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TERRAIN CRITERIA IN VEHICLE DESIGN

By

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June 1963

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OBJECTIVE

Present the elements of the terrain environment which affect vehicle performance and tabulate or indicate availability of data.

RESULTS

Data concerning soil strength are available in an adequate quantity to indicate the expected range of soil strength. There are not sufficient data to identify the range of geometric profiles nor the impact of vegetative cover.

RECOMMENDATIONS

Terrain design criteria should be presented in quantitative terms where possible. Additional data should be included in Military Characteristics as they become available.

ADMINISTRATIVE INFORMATION

This program was supervised and conducted by the Land Locomotion Laboratory, ATAC, under D/A Project No. 597-01-006, Project No. 5016.11.84400.

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ABSTRACT

A discussion of the elements of the terrain which affect vehicle performance is presented. The soil value data currently available are tabulated and a brief description of their application is provided.

Programs devoted to the description of terrain environments are reviewed.

ACKNOWLEDGEMENT

Mr. David Sloss prepared Appendix B, and his assistance is gratefully acknowledged.

SYMBOLS

k_c = Physical Soil Value associated with sinkage . . . . $\frac{lb.}{in.^{(n+1)}}$

k_ϕ = Physical Soil Value association with sinkage . . . . $\frac{lb.}{in.^{(n+2)}}$

n = Exponent of Sinkage

c = Soil Cohesion, psi

ϕ = Angle of Internal Friction, degrees

k = Tangent Modulus of Deformation, inches

LIST OF FIGURES

INTRODUCTION

A. Background:

In order to design any device it is necessary to have detailed prior knowledge of what the device is expected to accomplish. The more complex the device, the more detailed must be the design specifications or criteria. When a new vehicle is required by the Army, the criteria are established in the "Military Characteristics". These criteria have normally been stated in qualitative terms such as a requirement that a vehicle is to be mobile in mud, snow, or some other "difficult" soil or terrain environment.

The Army has long been aware that the use of qualitative definitions of the vehicle operating environment was not adequate. However, recognizing this fact did not produce a better means of specifying vehicle requirements simply because no one had more than a vague idea of what impact the terrain environment had on vehicle performance. Even today we do not know what elements of the terrain environment act most strongly on a vehicle nor is there general agreement on a means to identify the environment.

B. History:

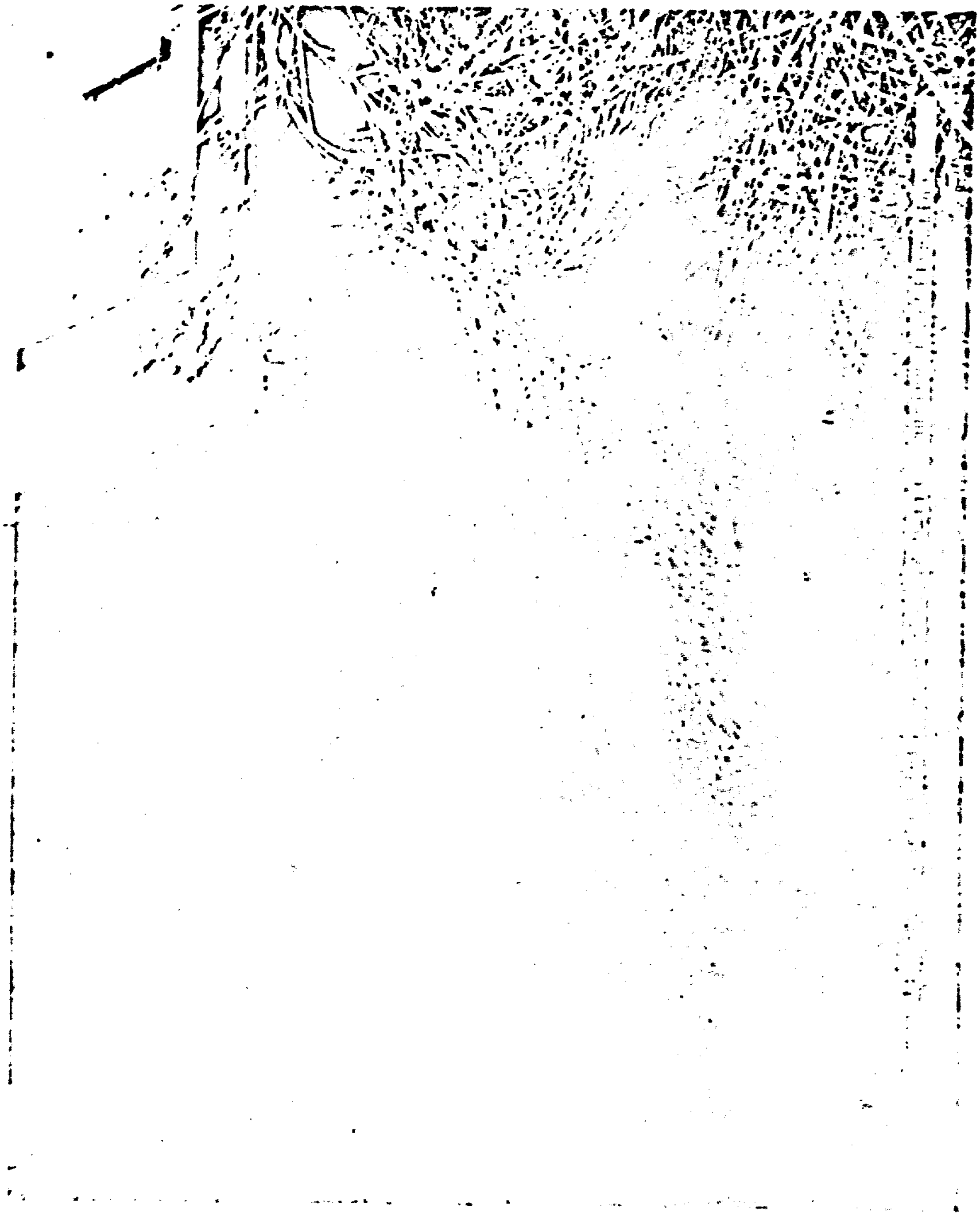
In 1941 the Army began its efforts to remove the mystery surrounding the off-road performance of vehicles. The Corps of Engineers was given the responsibility for the development of a means for vehicle performance evaluation. There was no great desire at that time to establish design criteria: the desire was simply to find a way to properly evaluate or predict performance if soil conditions were known. The outcome of this effort was the application of the Civil Engineer penetrometer test to soil and a correlation of performance to penetrometer reading[1]. The soil was identified by means of a cone index and a mobility index was developed that characterized vehicle performance. Essentially, the mobility index was established by a curve fitting procedure in which all of the assumed vehicle characteristics affecting mobility were juggled until an equation was found which fit the experimental results. This work produced a very useful evaluation tool but did not provide an insight into the interaction between a vehicle and the soil. Without such an insight it was not possible to determine how a vehicle should be designed. Rather, it gave an insight into how vehicles were designed.

The Ordnance Corps became concerned about the problem of vehicle design for off-road performance when it became evident that their off-road machines could not cope with the natural environment. However, the initial emphasis was placed on "mud mobility" since this was assumed to be the problem that had to be solved. This, of course, was not really believed by anyone since what was really meant was that the mud mobility was to be improved without any reduction in other elements of performance. This statement is offered as fact since it would be no great accomplishment to produce a vehicle capable of coping with almost any "mud hole" that it would meet. However, the machine would not be useful in a reasonably wide range of terrain condition. The demand for a universal vehicle has apparently been dropped since a paper was written[2], stating this boldly. Because it was to receive wide distribution the paper required concurrence by many channels within the Army. Since it received the necessary concurrences, one can only assume that the statement must be, or has been in the recent past, true. However, even if we don't demand a universal vehicle, we do demand at least a reasonable range of terrain types in which a vehicle can operate.

Although the Ordnance Corps' effort to improve off-road performance was originally devoted to mud mobility it soon became evident that a wide range of soil types and a multiplicity of terrain elements must be considered in establishing terrain design criteria. This was reflected in the work of the Land Locomotion Laboratory which attempted to generalize the problem. The approach taken was to identify the terrain elements in quantitative terms and to then develop equations relating the vehicle to the terrain. A soil value system[4], was developed which consisted of two parts: A physical soil value system and a geometric soil value system. The physical soil value system consists of a set of parameters that fit into a family of equations which describe the vertical and horizontal force-deformation curves. The force-deformation curves are obtained by means of an instrument called a Bevameter. The details of the instrumentation and the procedure for obtaining the soil values have been completely described in Reference 4 so will not be presented here. However, a description of the use of the parameters is given in Appendix A.

The geometric soil values describe the profile of terrain since it was observed that even if soil was strong, vehicle vibration limited vehicle speed to a low level. It is a relatively simple proposition to develop equations[5], describing the vibration characteristics of a vehicle once the vibration input is know. Admittedly, if the non-linearities of tire deflections, springs, dampers, or the effect of a heavy track on vibration can add a great amount of complication to the equations. However, if the equations produce general trends which are correct, the designer knows how to improve performance. He may not know the exact level of improvement without an experiment but he knows whether a given change represents an improvement or deterioration in performance.

Once the vibration or profile environment and soil strength characteristics were identified, it would seem reasonable that a vehicle designer would be in a reasonably good position to establish his design criteria. However, these two factors do not consider one very important facet of the environment: the effect of obstacles (6) in the form of vegetation[7]. It often occurs that soil is strong, profile is mild but vehicle performance is still limited by vegetation. For example, Figure 1 shows the effect of grass on the performance of a tracked vehicle. The grass shown in the photograph was approximately five



feet high and became packed into the suspension system of the vehicle to the point of immobilizing the vehicle. In Figure 2, we see a typical obstacle produced by vegetation in a jungle environment. The Corps of Engineers has been very active in the development of a technique to catalog vegetative environment as a part of the Military Evaluation of Geographic Areas System developed by Grabau[7].

It would appear that there are three prime elements of the terrain which limit vehicle performance: the soil, the soil profile, and the vegetation cover. This report represents a collection of the physical soil values and geometric profiles that have been obtained by the Land Locomotion Laboratory. Other than a cursary review in Appendix A, no attempt is made here to describe the application of the soil values since this has been done in earlier publications.

OBJECT

The object of the work reported was to collect and report the physical and geometric soil values that have been obtained by the Land Locomotion Laboratory and to indicate other sources of terrain design criteria.

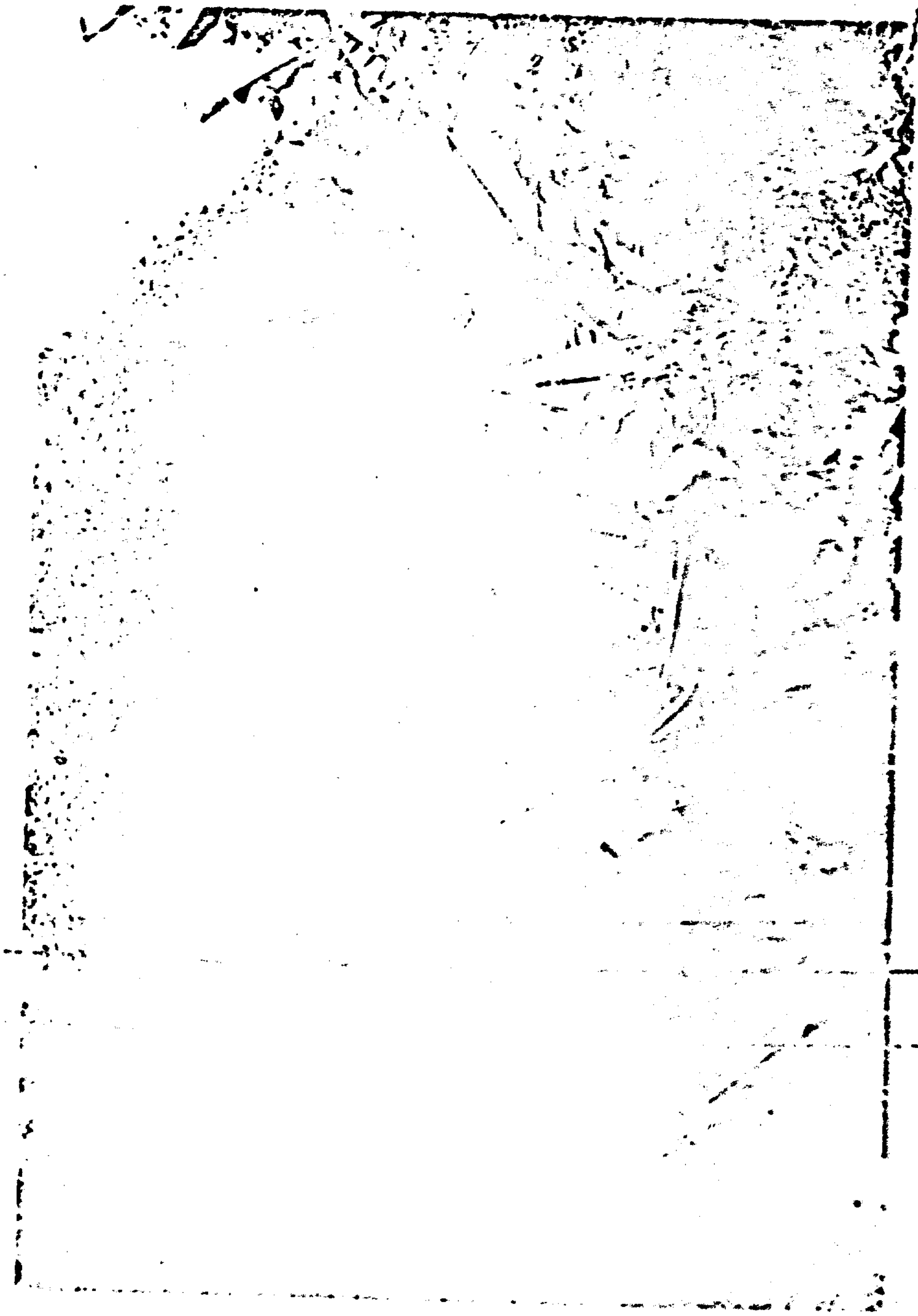


FIGURE 2

DISCUSSION

The physical and geometric values that have been obtained are included in Section VII. The major portion of current work devoted specifically to obtaining terrain design criteria is being conducted by the Advanced Research Projects Agency and the Waterways Experiment Station (WES) of the Corps of Engineers. These projects are reviewed below along with the studies of muskeg in progress in Canada.

The WES project is entitled The Military Evaluation of Geographic Areas and is concerned with a complete quantitative description of all elements of terrain. The discussion presented here is concerned primarily with the description of vegetation.

The progress to date of the vegetation analysis phase of the MEGA program at WES is the establishment of a workable descriptive vegetation classification. The system was devised by Dr. Dansereau of New York Botanical Gardens and has been used in Puerto Rico, Thailand, and portions of Central America. This classification accounts in a qualitative fashion for vegetal features such as height, crown shape, leaf characteristics, stem, branching, roots, armature, and distribution. The final description of an area is a combination of symbols in which these characteristics have been categorized.

The classification, although quite involved and rightly so considering the nature of vegetation, is free from Latin names and has the advantage that it can be used by a person with little or no biologic background. The avoidance of Latin names, however, neglects many of the subtle properties which presently have to be described symbolically in the classification.

The method of describing an area consists of selecting random points by statistical means such as a grid pattern and then measuring all the pertinent data at this point within a certain radius. Factors such as poisonous needles, edible fruit, limited visibility, etc., which may be applicable in some regions but not in others, are all incorporated in the description. WES also has a project in progress to determine the effects of tree spacing on vehicle mobility. The results of this study seem to indicate that this analysis is similar to a labyrinth problem.

Along with the vegetal description of a terrain, WES hopes to incorporate a "Family Factor Concept" in the study of obstacles in vehicle mobility. This concept basically implies that not one feature of the terrain alone is as important in the immobilization of a vehicle as the combination of several. The other significant terrain features considered are surface composition, microgeometry, macrogeometry, hydrologic geometry. Systems for macrogeometry classification are being worked on at Vanderbilt University, Marshall University, and the University of Tennessee. Microgeometry is being studied under contract at the University of Southern California and hydrologic geometry and surface composition is being handled at WES.

Project MERS (Military Environmental Research Studies) being conducted by ARPA is devoted to the definition of specific terrain environments. As a part of Project MERS, the techniques established for MEGA will be utilized along with the soil description used by the Land Locomotion Laboratory. It is anticipated that Project MERS will provide a major input into the establishment of terrain criteria since this is the first project in which all elements are being examined in the broadest terms possible.

A review of the classification of muskeg is presented primarily to demonstrate the feasibility of classifying vegetation.

Most of the world's land surface in the extreme latitudes toward the north, and in some cases, the south, is covered by an organic terrain known as muskeg. Muskeg is a term which has specific connotations with respect to both the surface and subsurface material. The work done in establishing a valid classification has been completed by N.W.Radforth of McMasters University. This system has been proven applicable in countries such as Alaska, Canada, Russia, Ireland, and parts of Chile. The classification is simple enough to be used by a non-biologist and has the prospects for direct correlations to engineering properties.

The surface classification of muskeg is divided into nine categories labeled from A to I. These categories are based on the vegetal features of woodiness, and stature. An area is identified by the letter of the most predominate category, followed by a second and third if necessary, but never more than three letters are used. This allows for many possible theoretical muskeg combinations, more than actually found in the field.

The subsurface portion of the muskeg, known as peat has been divided into sixteen categories numbered 1 to 16. These categories are lumped into three broader groups based on the visual nature of peat. Categories 1 to 7 are amorphous-granular, 8 to 11, are fine-fibrous, and 12 to 16, are coarse-fibrous. The categories are qualitatively defined, but work is progressing to evaluate them on a quantitative basis.

In conjunction with the surface and subsurface classifications of muskeg, an overall terrain evaluation of the muskeg reveals several definite topographic relationships.

These relationships are divided into sixteen contour types labeled "a" to "p". They include topography described as peat plateau, closed pond, gravel bar, and rock gravel plain, to name a few. Tables have been established which show in descriptive terms, at least, the correlation of topography to surface and subsurface conditions.

The most widely used method of muskeg mapping is with the use of airphotos. This is partly due to the accuracy and ease with which the airphotos can be used and partly due to the inaccessibility of much of the area to be mapped. Definite muskeg patterns have been identified at altitudes of 5,000 and 10,000 feet. These patterns are in turn related to the topography and muskeg coverage according to the Radforth system from which properties of the underlying peat can be inferred.

There was little in the way of previous experience to indicate what type of description would best describe terrain profile. The description would have to be statistical since the terrain geometry is a random phenomenon. Basically, the description had to rest on statistical properties sufficiently simple to be determined experimentally and yet sufficiently detailed so as to include a feature or features which would be significant in analyzing statistical vehicle dynamics.

It was decided to measure ground roughness initially in terms of the power spectral density.

To obtain the power spectral density, psd, of ground elevation (random function) along a straight line, or more precisely, to obtain an estimate of it, one proceeds as follows: measure and record the elevation at equidistant points along the line; compute the serial correlation from these data at selected intervals; the smoothed Fourier transforms of the serial correlation is the psd estimate - this is the analysis scheme according to the methods of Blackmann and Tukey[7]. The abscissa of the psd is in $(\text{length})^{-1}$ units, i.e., length frequency units and the ordinate is in $(\text{length})^2$ units.

The concept of the power spectral density of a random function has proven fruitful in a number of fields including spectroscopy, communication theory, turbulence, etc.. The validity of this concept rests upon the assumption that the underlying statistical mechanism which generates the fluctuation does not change as the abscissa increases and that estimates of the psd may be obtained from records of the fluctuation. One basic point must be stressed. Different segments of a record, i.e., different segments of a long survey record of elevation along a straight line, may appear different from one another. The psd estimates from these segments may also be different from one another. But as the length of each record and segment increases, these estimates will become closer and closer to one another. Ultimately, when the segments become infinite in length, they are assumed to coincide. Thus, differences in psd estimates are assumed to arise from the finite record length.

Of course, no records are of infinite length. None-the less, the concept of psd has proved useful in the areas mentioned; and thus, the assumptions just described have a practical validity. It is reasonable to expect that psd may prove useful in describing ground or terrain roughness over reasonable distances.

The selection of a method for specifying terrain profile made possible an attempt to answer the fundamental question: "What is the maximum speed of a particular vehicle model on terrain with a given psd?", or alternately, "How rough is a ride at a given speed with a given vehicle model on ground with a specified psd?" It is to be noted that a new point has been raised; namely, the criteria to be used to determine "maximum speed" or "rough ride."

Conversations with responsible personnel at various establishments established one point of importance. Most individuals held the position that the human driver or human cargo is one of the most significant factors in setting maximum speed or determining how rough a ride is. Further, the view was expressed that present vehicles could be driven much faster if only the driver would do so; mechanical breakage, if it was a limit, could be eliminated.

It became clear that the areas requiring basic research were:

a. Statistical description of rough ride based upon subjecting humans to random vibration environment.

b. Statistical description of terrain profile based upon survey data.

Both areas are presently being investigated. The subjection of humans to random vibration conditions, in its initial stages, is being carried out in a dynamic seat simulator. The initial stages of the test program are to determine the extent to which a subject can detect the relative roughness of simple vibration environments from two distinct power spectral densities that are of the nature of real terrain spectra. The statistical design of the experiment takes into account the fact that the sample run is of finite length and will be subject to the variability in amplitude that occurs when looking at only a small portion of a record that is statistically stationary. The ultimate goal is to determine those aspects of psd that determine quantitatively the limits of comfort a human will accept in being subjected to random vertical vibrational environments. The limits could then be used to determine how rough the seat motion would have to be in order to prevent the driver from going too fast.

In the other area, surveys of terrain profile have been initiated to determine psd estimates. Since the psd affords a quantitative method of describing terrain profile, one can deduce quantitatively the roughness of a profile having this psd in any specified frequency band. Hence, it becomes possible by use of psd to classify terrain according to these measures of roughness. It is therefore possible to classify the roughness of those areas of the world which are of strategic military importance.

Since there is no readily available data for studying the terrain as a surface, a survey on a field located in North Central Indiana, adjacent to Purdue University, has been conducted. The survey was taken along five concentric lines that divided a circle into equal sections, as shown in Figure 3. The length of the lines vary from 1,500 feet for line A, to 1,200 feet for line D. The elevations were taken at six-inch intervals along each line, thereby yielding a spectral resolution of one cycle per foot. These are presented in Figures 4 through 8.

Survey Plan, Plowed, Cultivated

and Grazed Field

Purdue University, North Central Indiana

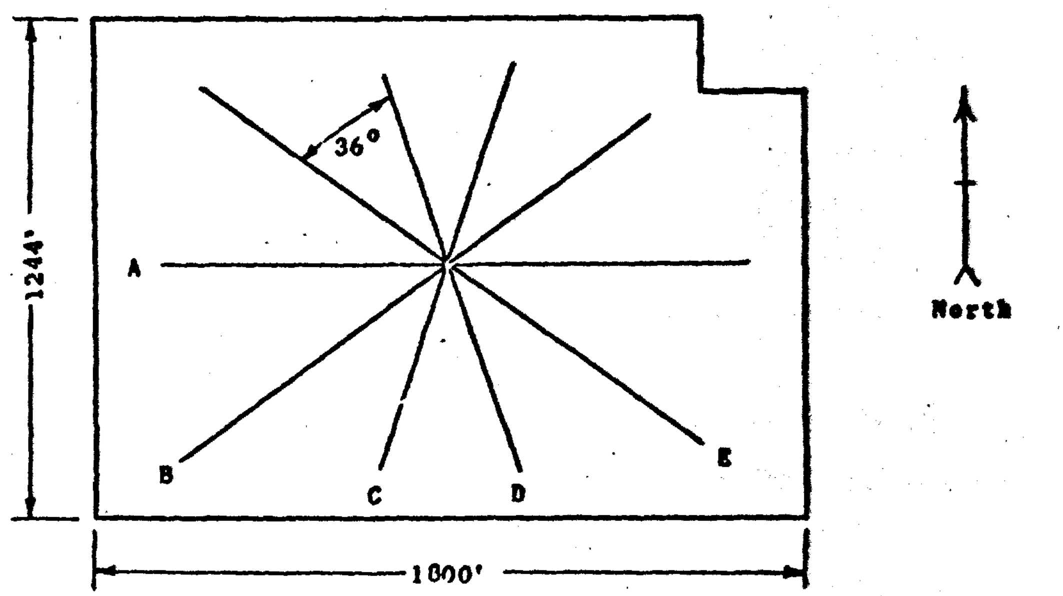


Figure 3.

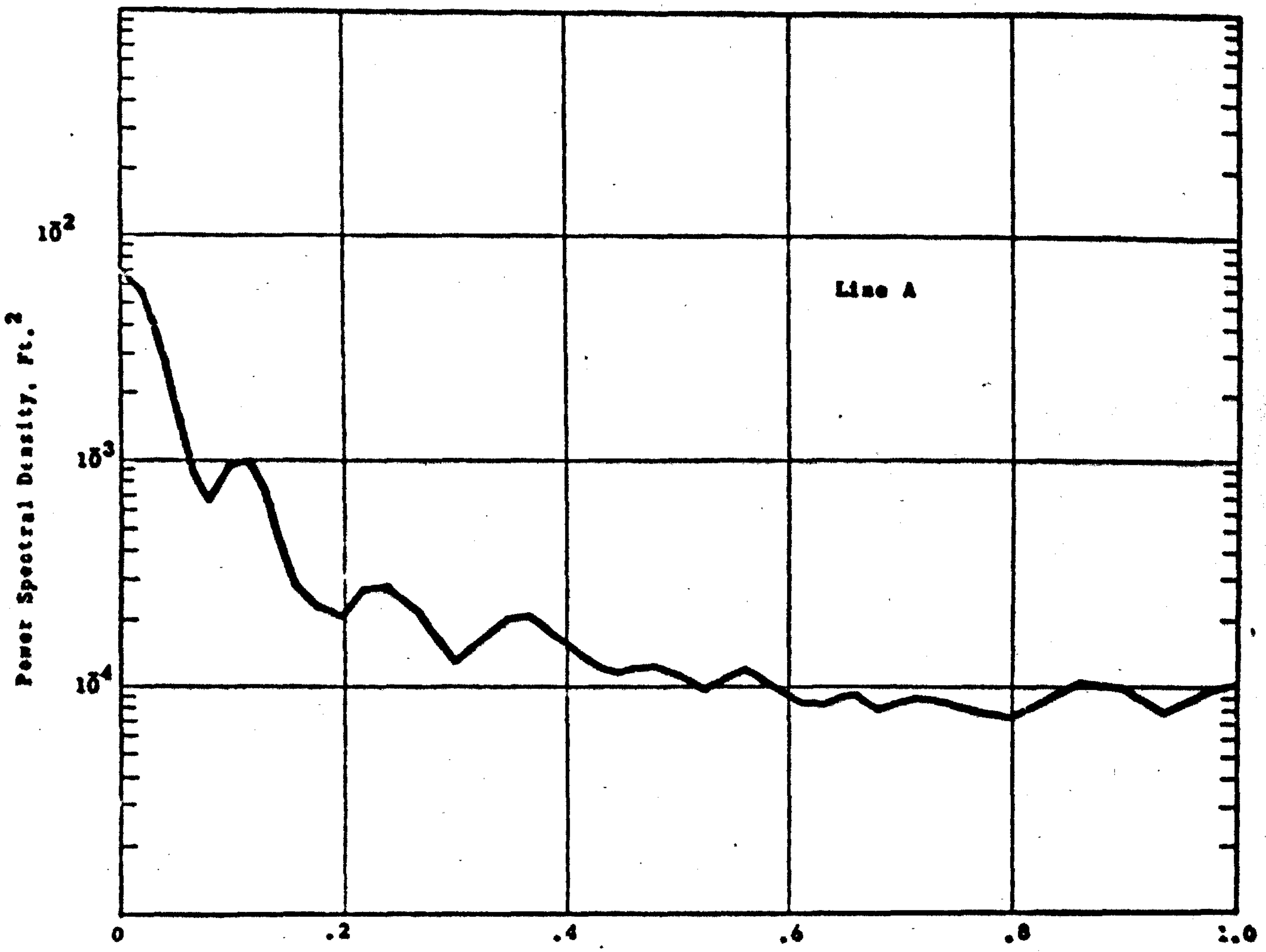


Figure 4: Frequency, C.P.F.

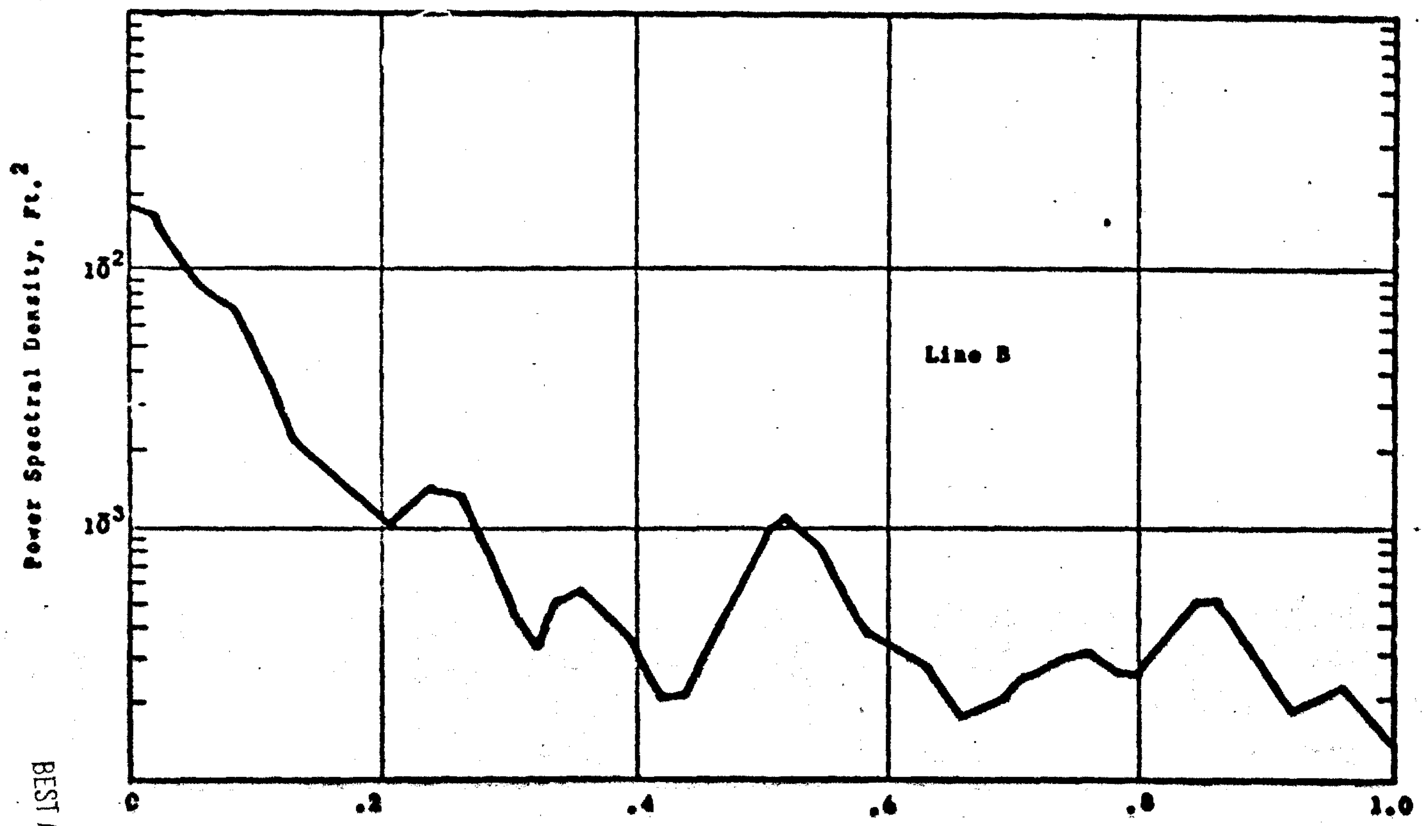


Figure 5: Frequency, C.P.F.

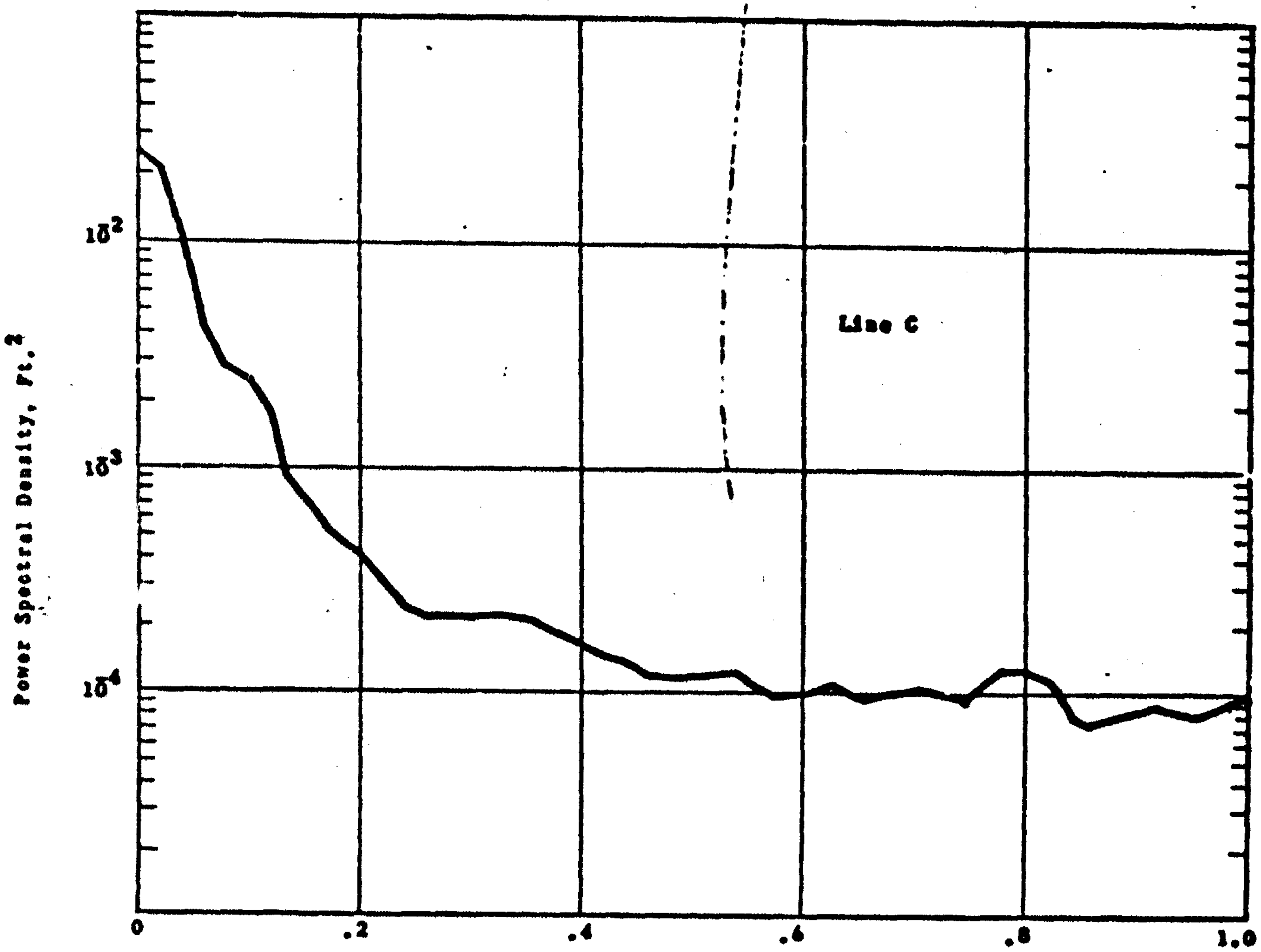


Figure 6: Frequency, C.P.F.

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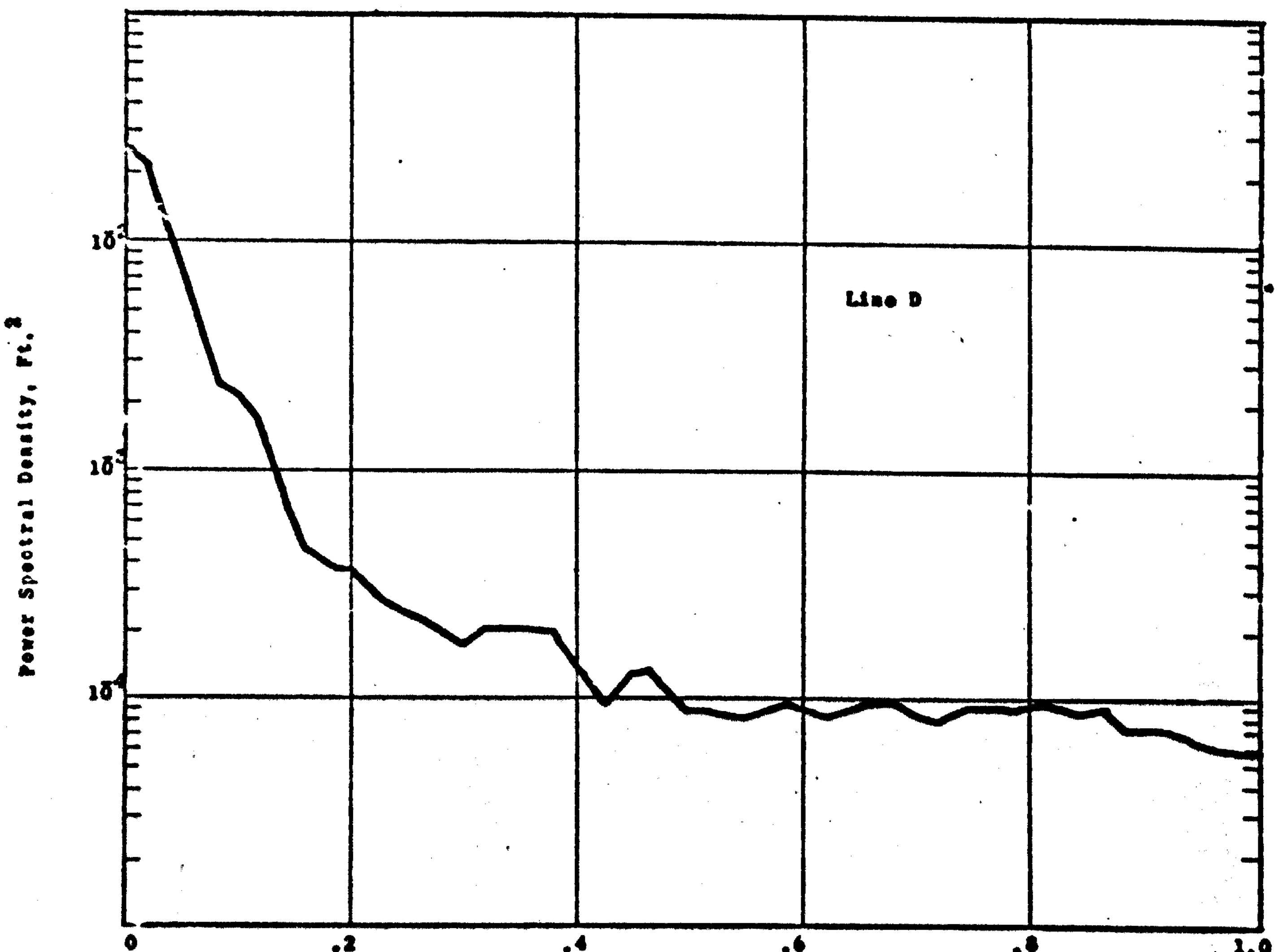


Figure 7: Frequency, C.P.F.

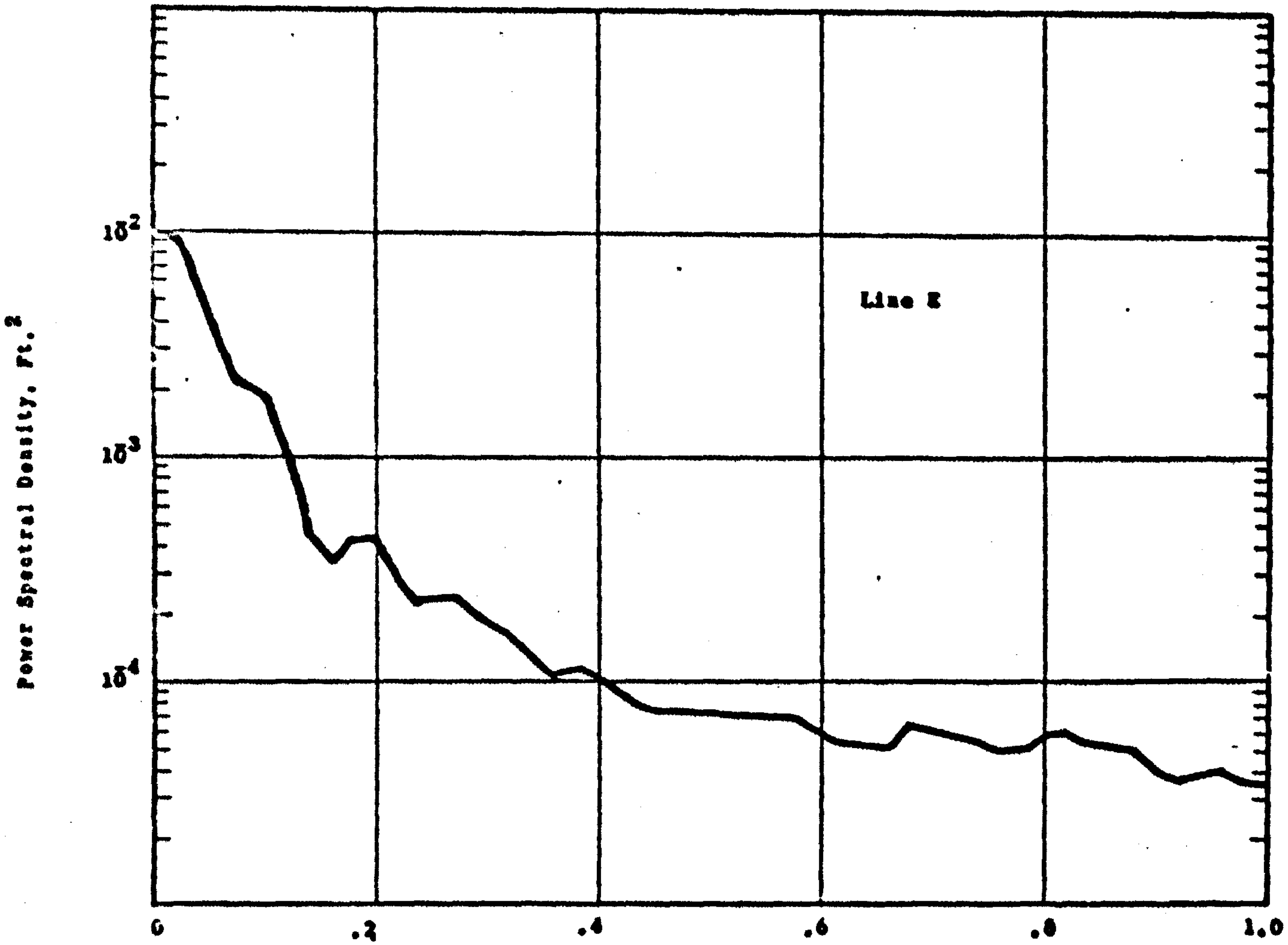


Figure 6. Frequency, C.P.F.

TEST EQUIPMENT

In order to obtain physical soil values, various Bevameters were utilized. The equipment shown in Figure 9 is representative of the equipment used. The use of the Bevameter is described in Reference 4.

Figure 10 shows the device used to obtain geometric profiles. A description of its use and characteristics is given in Appendix B.

RESULTS

The physical soil value data are presented in tabular form with the soil values listed along with soil type. The geometric soil values are given in a power spectral density function format.

As implied in previous sections, the collection of field data to give terrain a general description is divided into three areas: Soil strength, soil cover or vegetation, and terrain profile or geometry. Each category, in itself, is a major undertaking. The ultimate goal is to characterize or classify terrain over large areas so that a comprehensive description of the terrain will be available. In time, it is hoped that this description will be on a world-wide basis.

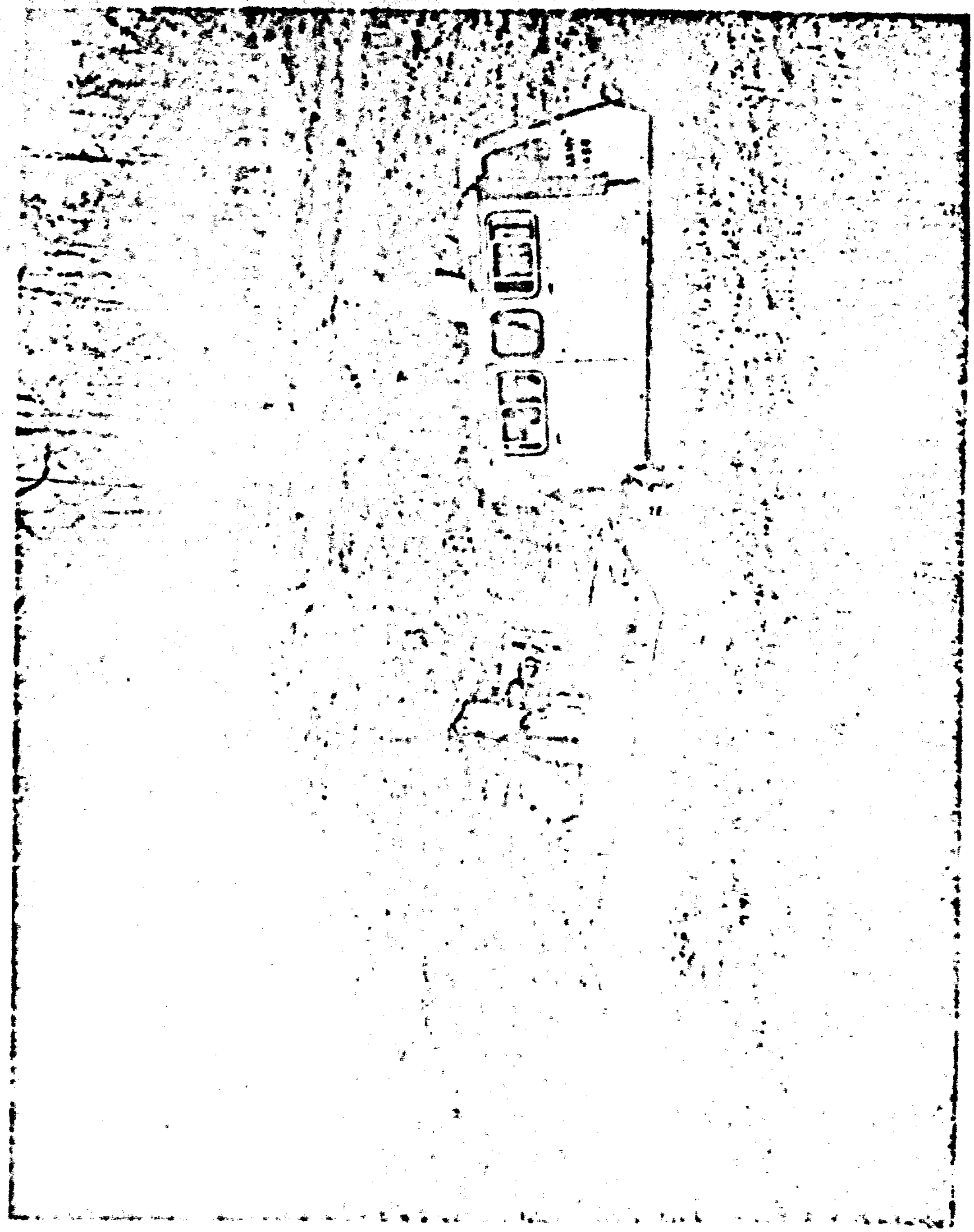


Figure 9: Bevameter Mounted on Polecat.

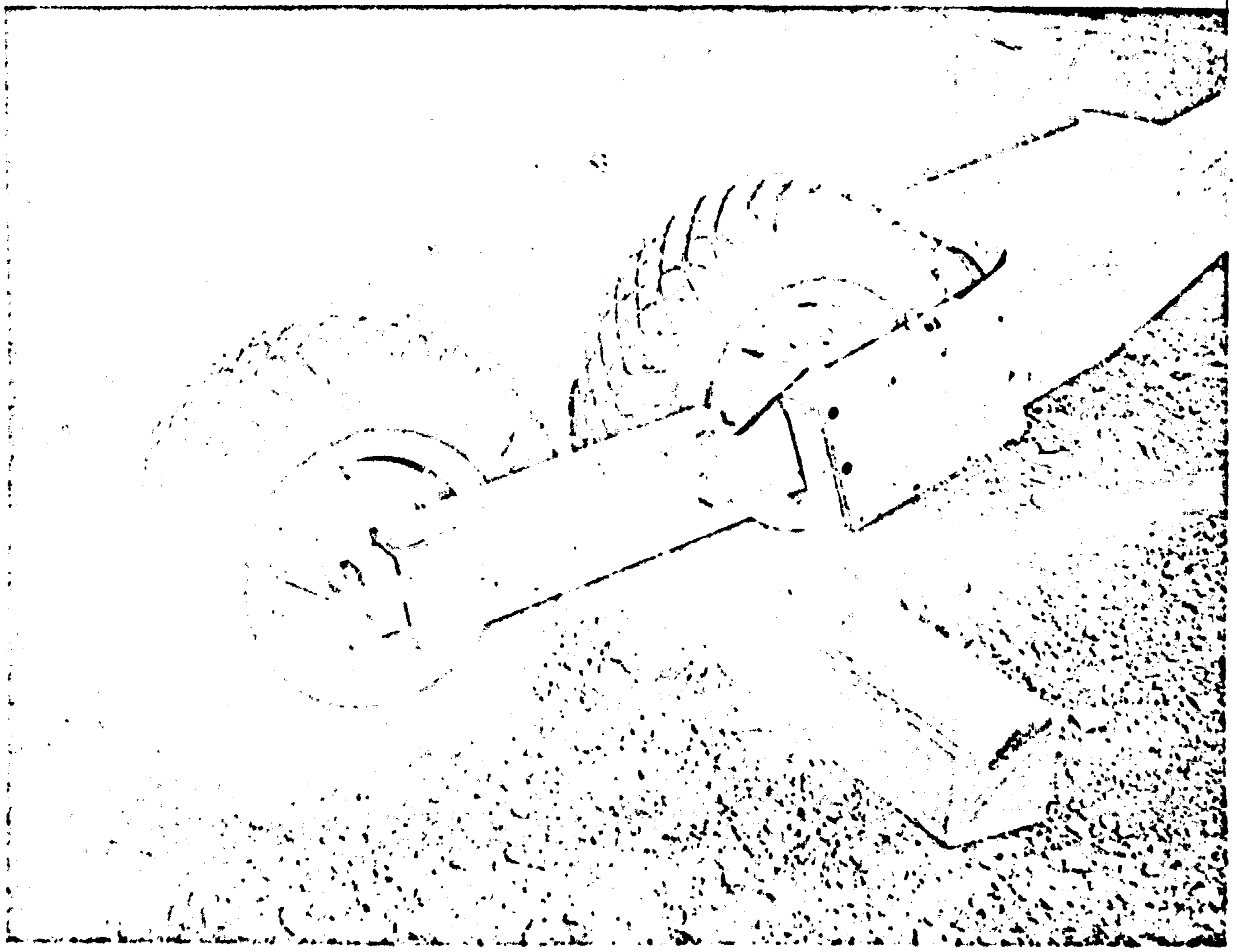


Figure 10: Profilometer for Measurement of Terrain Geometry.

In review, the strength of the soil, as described by the Land Locomotion Laboratory's Soil Value System, is composed of the vertical and horizontal components of soil strength. The vertical strength of soils is described by the parameters k_c, k_ϕ and n. These parameters are used to determine the sinkage of a loaded area and if this loaded area is a wheel or track of a vehicle, they are used to determine the wheel or track motion resistance. The horizontal or shear strength of the soil is described by the parameters c and ϕ. By combining the vertical and horizontal strength parameters of soils and applying them to vehicles, it is possible to determine the performance of the vehicle.

The soil strength parameters have been determined for various soils under controlled laboratory conditions as well as in the field. All measurements were obtained by the Bevameter, a device designed by the Land Locomotion Laboratory. The vertical parameters are determined by analyzing the load versus sinkage characteristics under circular and rectangular sinkage footings. The shear strength parameters are determined by the torque versus deformation relationship of a shear annulus at various normal pressures.

The following list is a tabulation of the soil strength values, first for the controlled condition and then for the field conditions:

CONTROLLED LABORATORY CONDITION

SOIL	MOISTURE CONTENT %	k_c	k_ϕ	n	c (psi)	ϕ Degrees
1. Michigan Loam	14	17.5	6.6	0.53	1.6	29.5
	16	9.5	5.6	0.50	1.9	27.5
	18	6.5	4.7	0.47	2.0	25.5
	20	4.5	3.7	0.42	1.6	23.5
	22	3.3	2.8	0.39	1.0	21.5
	24	2.2	1.8	0.35	0.0	19.5
2. Crystal Silica Sand Dry & Loose	-	0	3.3	1.0	0.05	28
3. Volclay Dry & Loose	-	0	1.0	1.34	0	32
4. Pumice Stone (Powder) Dry & Loose	-	0	1.05	1.15	0	32
5. Mason Sand Dry & Loose	-	0	3.5	1.0	0	27.5
6. Mississippi Buckshot Clay	38	11.7	3.7	0.12	2.9	11

FIELD CONDITIONS

SOIL	MOISTURE CONTENT %	k_c	k_ϕ	n	C (psi)	ϕ Degrees
1. Detroit Arsenal	Saturated	6.3	2.7	0.96	-	-
So. Side Bldg 219 Centerline, Mich.	50	3.2	4.4	0.42	-	-
	40	4.2	2.6	0.85	-	-
	34	13	3.1	0.28	-	-
	25	23	4.0	0.25	-	-
2. Miss. River Sand Bar Vicksburg, Miss.	3.0 (at 0-6" depth)	1.5	27.4	1.1	0.25	29
3. Area 25 Ft. Knox, Ky.						
Clay	24	5.2	0.2	0.75	1.0	18
Sandy Loam	15	7.0	7.6	0.87	0.40	20
Sandy Clay	15	2.3	1.3	1.3	0.85	10.5
4. Churchville Area, APG Maryland	33	0.90	1.7	0.33	0.75	11
	32	0.66	1.4	0.44	0.80	15
	29	1.6	2.7	0.63	0.90	23
	28	4.8	1.8	0.40	2.0	26
	26	1.6	2.8	0.58	2.1	26
Hard Pan	-	2.65	6.8	0.31	2.0	22

FIELD CONDITIONS, CONTD.

SOIL	MOISTURE CONTENT %	k_c	k_ϕ	n	C (psf)	ϕ Degrees
5. Erie Ord Depot, Port Clinton, Ohio	19	-	-	-	1.6	41
	24	-	-	-	2.8	31
	27	-	-	-	1.6	24
	29	-	-	-	2.2	18
6. Durden Creek ~~Area, WES,~~ Vicksburg, Miss.						
Silt with Vegetation	-	-	-	-	4.3	23.5
7. Rep. of Panama, SWAMP FOX II, Area	Area B	20.0	9.2	1.4	2.0	33
	Area D	0	47.0	1.2	3.2	29.0
	Area C	-	-	-	2.3	35.0
8. Fort Story, Va. Beach Sand	-	13.5	7.0	1.0	0.1	31.5
9. Fort Eustis, Va. Messick Marsh	-	21.0	7.0	0.82	0.42	31
10. Thailand Sara Buri S1	-	-	-	-	0.25	30.6
Sara Buri S2	-	-	-	-	0.40	31.2
Sara Buri S3	-	-	-	-	0.54	24.2
Korat K4	-	-	-	-	0.54	22.1
Korat K5	-	-	-	-	0.43	26.6

FIELD CONDITIONS, CONTD.

SOIL	MOISTURE CONTENT %	k_c	k_ϕ	n	C (psi)	ϕ Degrees
10. Thailand Contd.						
Bang Ping I	37.7 (0-6")	20	16	0.31	0.50	26.0
Bang Ping II	39.2 (0-6")	7.5	22	0.30	0.28	32.4
Bang PU 1A	55.4 (0-6")	18	25	0.16	0.63	29.0
Bang PU 8	40.3 (0.6")	-	-	-	0.50	31.4
Bang PU 10	60.6 (0-6")	-	-	-	0.60	29.9
Bang PU 11	42.9 (0-6")	14	21	0.21	0.43	32.9
Bang PU 12		19	17	0.19	0.20	32.0
Bang PU 13	47.8 (0-6")	15	16	0.16	0.44	36.9
11. Houghton, Michigan						
Snow Values -1957		3.6	0.3	1.0	0.18	18.2
1960		0.6	0.2	1.24	0	21.3
12. Ft.Churchill Manitoba,Can.						
Crusty Surface	-	-	-	-	0.35	23.
Sub-surface	-	-	-	-	0.23	20.
13. Greenland Ice-Cap, Mile 18, Nov. 1961						
0-3.5 psi Range		1.99	1.80	0.31		
3.5 psi Range		0	1.1	1.2	0.1	24.5

CONCLUSIONS

The work on this project was not intended to be conclusive in nature. The effort was devoted primarily to the collection of currently available terrain data. However, it is possible to offer a definite conclusion: The specification of vehicle characteristics can and must include a wide range of factors associated with the terrain. It is not possible ~~at this time~~ to establish which element of the terrain is of overriding importance or whether there is such a terrain element. However, ~~it is obvious that, as a minimum,~~ the soil strength characteristics, the geometric profile, and the vegetation obstacles must be specified in quantitative terms.

RECOMMENDATIONS

It is recommended that future Military Characteristics be stated in quantitative terms where possible. The current data only permit the identification of the soil strenth criteria but as Projects MERS and MEGA develop, the results of these projects should be incorporated in Military Characteristics.

APPENDIX A.

MOBILITY PERFORMANCE

In order to undertake mobility performance studies on a vehicle, the range of values of drawbar pull (DP) and drawbar pull per load (DP/W) with respect to a range of values in soil consistency (k) must be found.

Given the values of W or p, b, , in the case of tracked vehicles, and D in the case of wheeled vehicles, and a range of values for k_c, k_ϕ, n, c, and tan ϕ, values of DP and DP/W versus k may be found and graphed by evaluating the equations in the following procedure:

1. $k = (\frac{k_c}{b} + k_\phi)$

2. K_θ and K_x are dependent on the angle of internal friction with respect to the angle of inclination of the rupture plane and may be obtained from the graph appearing at the end of the Appendix A.

3. $z_{wheel} = \left(\frac{3W}{bk\sqrt{D}(3-n)}\right)^{\frac{2}{2n+1}}$ = Sinkage

$z_{track} = \frac{p}{K}^{\frac{1}{n}}$ = Sinkage

4. $\ell_{wheel} = 2\sqrt{z(D-z)}$ = Contact length

$$\ell_{track} = \text{Given}$$

5. $A = b\ell$ = Contact Area

6. $H = AC + W \tan \phi$ = Gross Tractive Effort

7. $R_c = \dfrac{bkz^{n+1}}{n+1}$ = Compaction Resistance

8. $R_b = b(zcK_\theta + \gamma z^2 K_\gamma)$ = Bulldozing Resistance

where γ = Soil density.

9. $DP = H - (R_c + R_b)$ = Drawbar Pull

10. $DP/W = \dfrac{H - (R_c + R_b)}{W}$ = Drawbar Pull per wheel or track load.

Although the values obtained give the values for DP and DP/W versus k for a track or front wheel of a vehicle, the DP and DP/W values for rear wheels may be different depending on whether one wishes to believe that the other wheels are encountering resistance, from bulldozing and compaction, or not. Test results appear to indicate that the rear wheels have the same motion resistance as the front wheels, even though the soil has been compacted and bulldozed by the front wheels. This result is based on very limited tests, but is obviously true when the vehicle is changing direction. However, the following possible assumptions may be made concerning the resistance encountered by the wheels in question:

(1) No compaction or bulldozing resistance is encountered: therefore, $DP = H$ and $DP/W = H/W$.

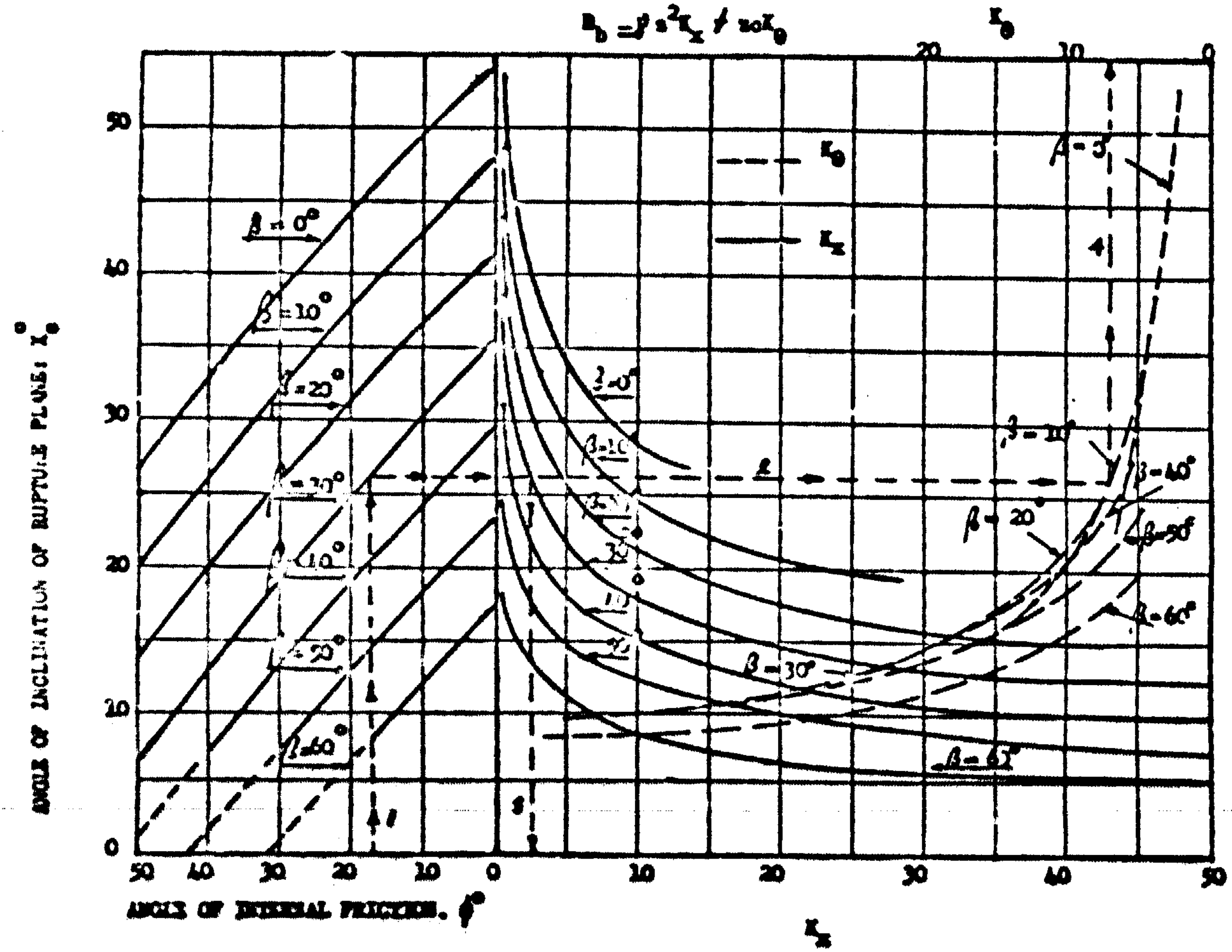
(2) Compaction but no bulldozing resistance is encountered: therefore, $DP = H - R_c$ and $DP/W = (H - R_c)/W$.

(3) Both compaction and bulldozing resistance is encountered: therefore, $DP = H - (R_c + R_h)$ and

$$DP/W = \frac{H - (R_c + R_h)}{W}$$

The assumption which is most nearly correct is left to the reader, since a completely verified theory is not available.

CHART FOR THE COMPUTATION OF K_x, K_θ KOEFFICIENTS OF THE GENERAL EQUATION FOR BULLDOZING RESISTANCE. (SEE EQUATION 17, PAGE 11 IN LL.REPORT NO.61.)



APPENDIX B.

TERRAIN PROFILE MEASUREMENT SYSTEM

By

David B. Sloss

BACKGROUND

Early in 1955, the University of Michigan, Engineering Research Institute, Ann Arbor, Michigan, began work on "Terrain Geometry Measurement". This work was done under the sponsorship of the Land Locomotion Laboratory, Detroit Arsenal, Center Line, Michigan. An extensive study was made of all existing methods of measuring terrain profile. A concept was selected based on this study. The present equipment resembles the concept closely. The differences are primarily mechanical design changes which were made to simplify and ruggedize the field equipment.

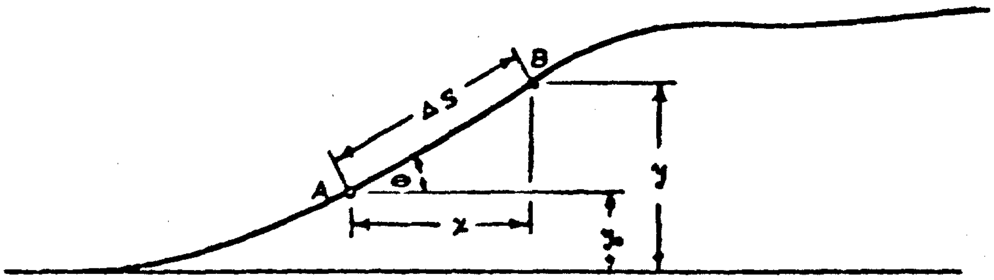
SYSTEM OPERATION (Slope Integration Method):

The equipment was designed around the slope integration method of terrain geometry measurement. This method is illustrated in Figure 11.

With reference to Figure 11, in order to determine the relative elevation of B to A, $(y - y_o)$ and the horizontal distance between the two points, x, it is necessary to measure the distance from A to B along the curve, s, and the angle, θ that the ground between A and B makes with a true horizontal drawn through point A.

SLOPE INTEGRATION METHOD

OF TERRAIN GEOMETRY MEASUREMENT



Elevation: $y - y_o = \int_0^s \sin\theta \, ds$

Horizontal Distance: $x = \int_0^s \cos\theta \, ds$

Δs = Total travel along curve

y = Elevation of ground for total travel, Δs, along the curve

y_o = Elevation of ground at start of run

x = horizontal distance for total travel, Δs, along the curve

θ = slope angle of ground

Figure 11.

SYSTEM DESIGN FOR FIELD USE:

In practice, the distance along the curve, s, is measured with a fifth wheel. The slope angle of the ground, θ, is measured with a tandem wheel device having a 12 inch wheel base. Therefore, θ, is the angle that the twelve inch wheel base makes with a true horizontal.

The details of the profile wheel are shown in Figure 12 The true horizontal is measured with a gyro. The gyro transmits a signal to the wheel base which positions a synchro relative to the true horizontal. A second synchro is mechanically connected to the wheel base. The slope angle of the ground, θ, is the difference between the two synchro angles.

SIGNAL GENERATED BY THE PROFILE WHEEL:

The wheel base angle is interpreted as a D.C. voltage between +2 and -2 volts. The voltage is positive for positive angles, zero for an angle of zero, and negative for negative angles. This voltage is monitored throughout the test run on an oscilloscope.

SYSTEM CALIBRATION:

Before the start of each test, the system is calibrated. Calibration consists of adjusting the system so that a specific voltage corresponds to a specific angle. For example, one volt could correspond to a wheel base angle of 20 degrees. Such a calibration is shown in Table I.

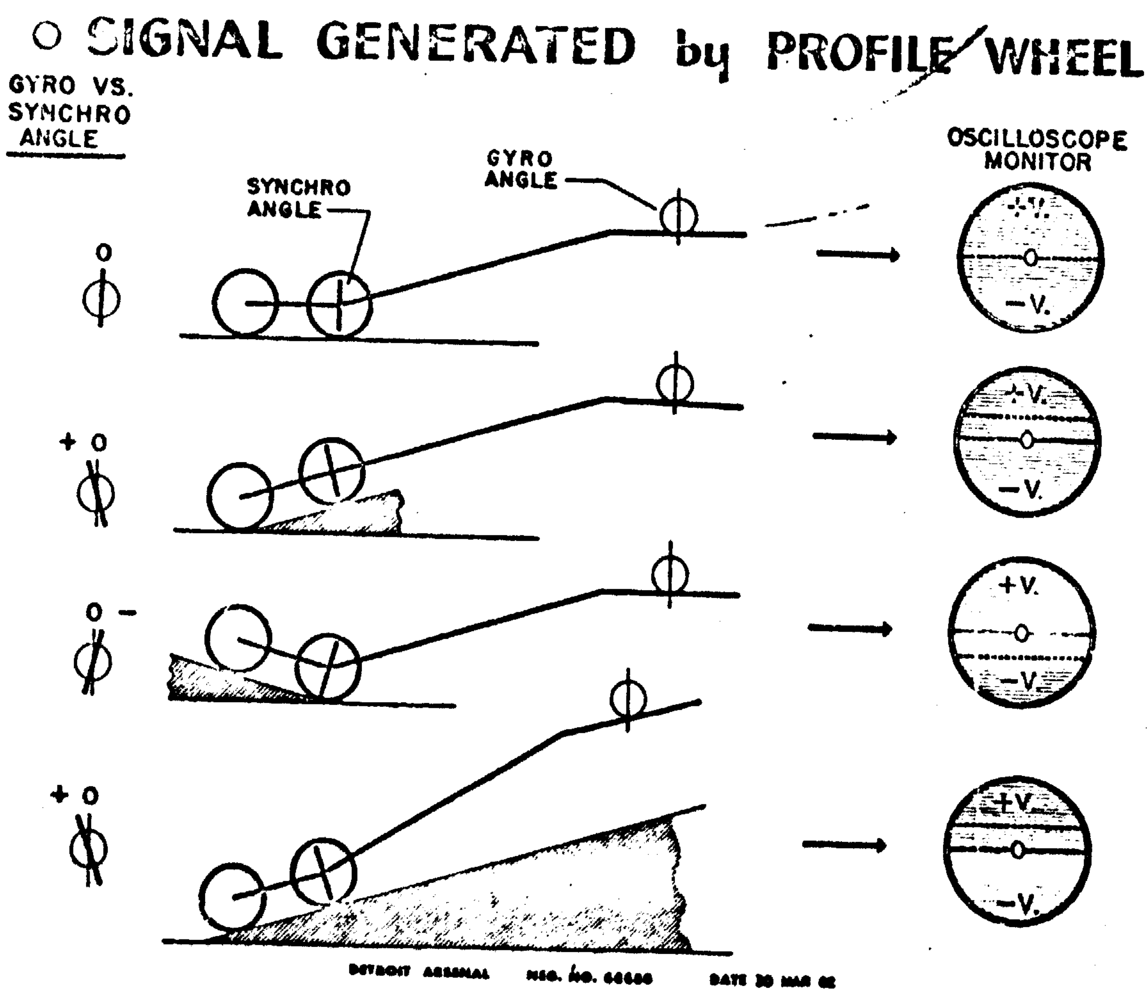

O SIGNAL GENERATED by PROFILE WHEEL
GYRO VS. SYNCHRO ANGLE
SYNCHRO ANGLE
GYRO ANGLE
OSCILLOSCOPE MONITOR
+V.
-V.

Figure 12.

TABLE I.

FOR CALIBRATION 1.00 VOLTS = 10°

1.00 Volt = 10°   X Volts = $\frac{\text{Sin } x}{.1736}$

θ	Sin θ	Voltage Proportional To Sin θ	Voltage Proportional To θ	Voltage Difference
0	.0000	.000	.000	.000
1	.0175	.101	.100	-.001
2	.0349	.201	.200	-.001
3	.0523	.301	.300	-.001
4	.0698	.402	.400	-.002
5	.0872	.502	.500	-.002
6	.1045	.603	.600	-.003
7	.1219	.703	.700	-.003
8	.1392	.802	.800	-.002
9	.1564	.901	.900	-.001
10	.1736	1.000	1.000	.000
11	.1908	1.099	1.100	+.001
12	.2079	1.197	1.200	+.003
13	.2250	1.296	1.300	+.004
14	.2419	1.390	1.400	+.010
15	.2588	1.490	1.500	+.010
16	.2756	1.585	1.600	+.015
17	.2924	1.685	1.700	+.015
18	.3090	1.780	1.800	+.020
19	.3256	1.870	1.900	+.030
20	.3420	1.970	2.000	+.030
25	.4226	2.439	2.500	+.061
30	.5000	2.880	3.000	+.120
35	.5736	3.310	3.500	+.190
40	.6428	3.710	4.000	+.290

INTERPRETATION OF THE GENERATED SIGNAL:

Technically, the signal generated by the synchro system is proportional to the sine of the angle rather than the angle. Table I shows, for a calibration of 1 volt = 20°, the voltage proportional to the sine of the angle is equal to the voltage proportional to the angle to within ± .05 volts for angles less than 30°. The system electrical resolution is ± .05 volts, and angles greater than 30° are seldom encountered in the field; therefore, in practice, the output voltage is treated as being proportional to both the sine of the angle and the angle. The function used is the one that is most convenient.

FIELD OPERATION:

Figure 13 shows how the system works in the field. The system is calibrated as described previously. As the wheel traverses the ground profile, a continuous record of the wheel base angle is recorded on one channel of an instrument type tape recorder. A measurement of the profile wheel's movement along the curve is recorded as a series of identical pulses. Each pulse represents a specific distance traveled along the curve. In Figure 13 the distance is 5-1/4 inches.

A voice channel is used to record calibration data and general information about the terrain being measured.

DATA REDUCTION (Raw Data Evaluation):

The raw data is read out on a brush recorder and examined for continuity and magnitude. The data is edited on the

DATA RECORDED BY PROFILE WHEEL

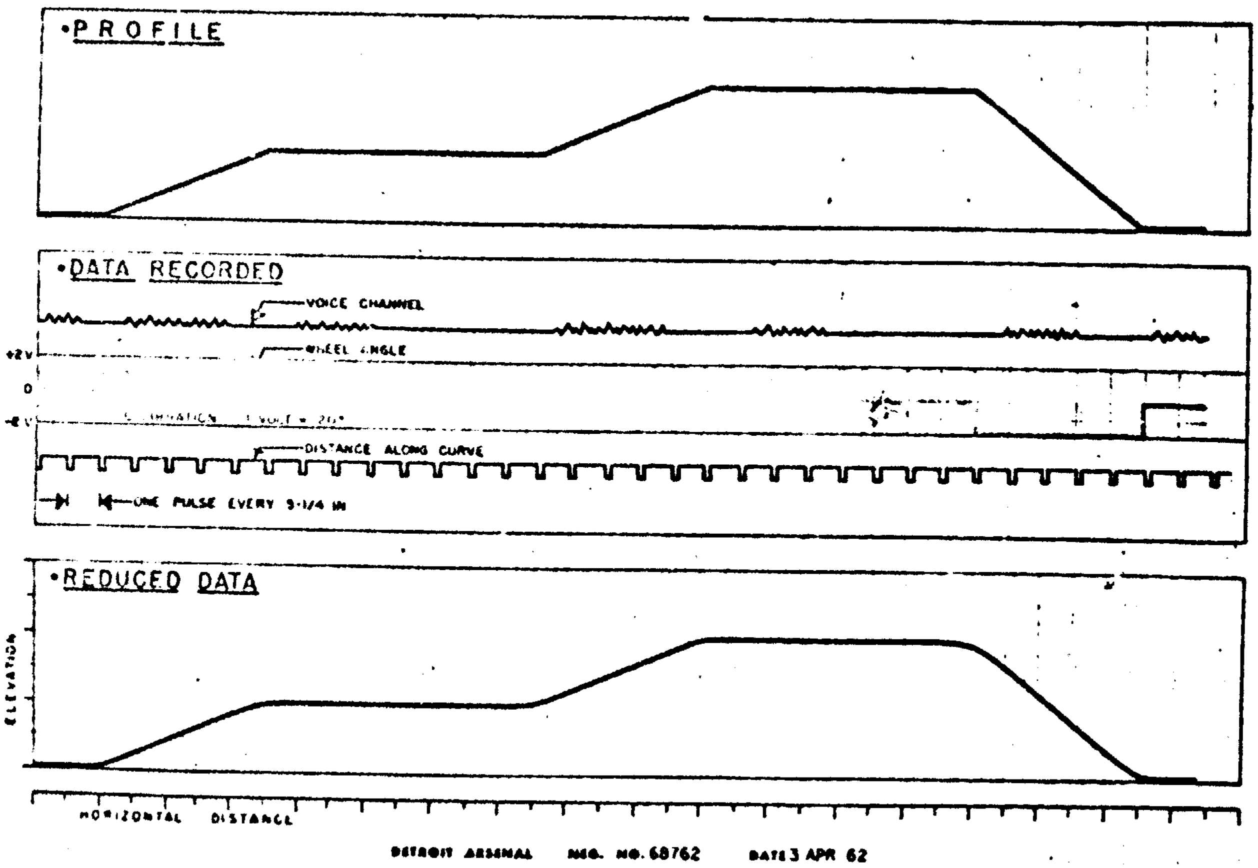


Figure 13.

basis of this examination and then the edited data is amplified in a PACE analog computer. The amplified signal is digitized in a special piece of equipment designed and built by Epsco. The end product of this stage of data reduction is an edited, digitized, magnetic tape suitable for use on our Burroughs Electrodata 205 digital computer.

DIGITAL COMPUTER DATA REDUCTION:

The data is operated on by the computer which solves for the elevation and horizontal distance as indicated in Figure 1. The computer output is usually in a form suitable for use on the PACE Data Plotter. The data plotter produces a profile curve similar to that shown in Figure 14.

DRIFT CORRECTION:

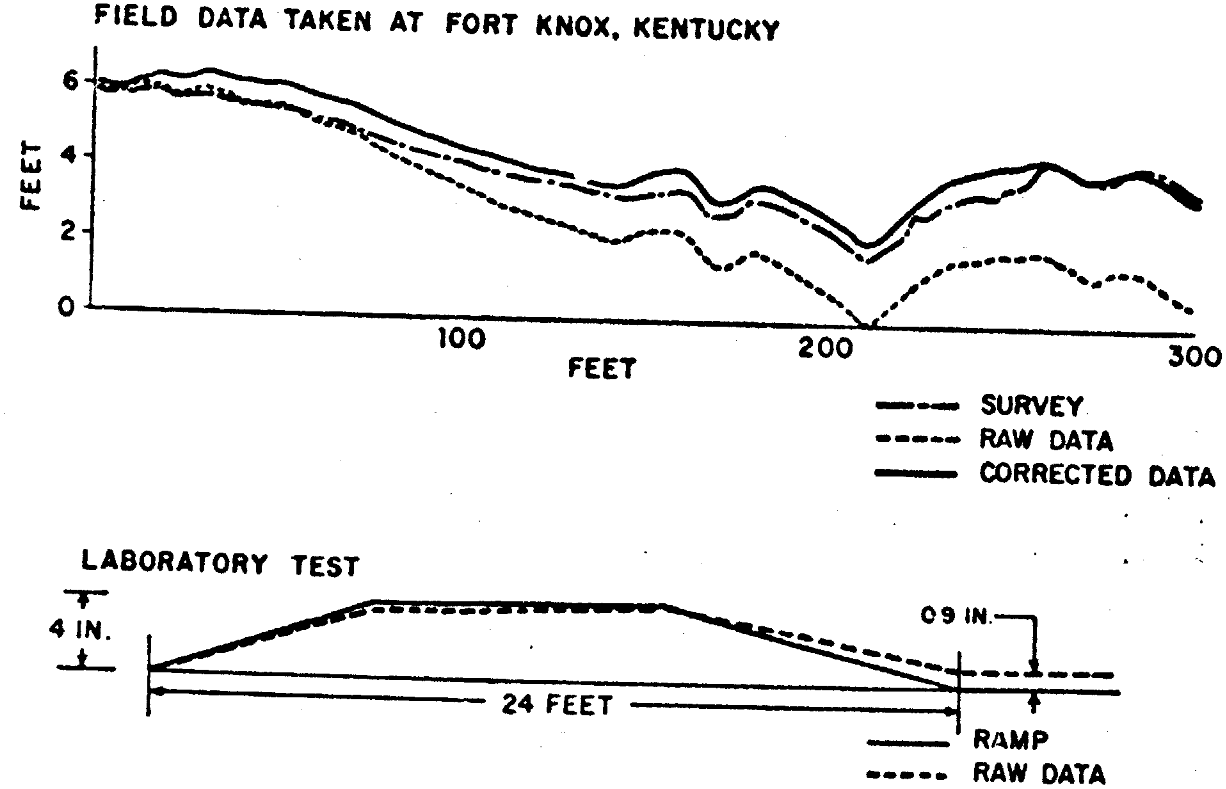
Figure 14 shows that the raw data exhibits a certain degree of drift. This drift is usually small, normally being less than two degrees. As Figure 4 indicates, this drift can be partially compensated for during the data reduction process. The correction process is relatively simple. Knowing the total elevation error at the end of the run, a correction factor is applied throughout the entire run to reduce the total elevation error to very near zero. It has been found that this process reduces the error at any point along the run to a minimum.

POSSIBLE EQUIPMENT MODIFICATION:

At present the data reduction and analysis process is somewhat time consuming. Consideration is being given to

PROFILE WHEEL

COMPARISON OF RECORDED DATA TO ACTUAL TERRAIN



DETROIT ARSENAL NEG. NO. [illegible] DATE 30 MAR 62

Figure 14.

modify the present equipment so that all or part of the data reduction can be done as it is acquired in the field.

USE OF THE DATA (Environment Description):

The ground profile is an important factor in describing the physical environment of a combat vehicle. Previous methods used to survey ground profile are time consuming and expensive. The terrain profile measurement system allows a rapid survey to be made of practically any test course in a relatively short time. It is also possible to repeat these measurements as required to determine profile change due to weather or vehicle traffic.

An important feature of the system is that the data is taken in a form that can be fed directly into a computer system for reduction and analysis.

As a survey device, the system is, therefore, capable of:

a. describing a specific test course

b. comparing two or more test courses.

c. measuring short or long term weather effects on the ground profile.

d. measuring the effects of vehicle traffic on the ground.

VEHICLE CONCEPT EVALUATION:

Vehicle concepts are now analyzed at ATAC with respect to their ride characteristics, using an analog computer. The computer input for this evaluation is the test course survey recorded on magnetic tape.

In the near future, it is intended to use the profile data in a computer program to predict concept fuel consumption and average speed over the various test courses.

SUSPENSION TEST AND ANALYSIS:

Procurement has been initiated for a device which will subject a suspension unit to loadings similar in magnitude and frequency to those the unit would encounter in the field. The ability of this device to subject a suspension unit to equivalent field testing in the laboratory makes it a useful research tool, as well as an endurance test machine.

The input control signal for the device will be the profile data of the test course survey recorded on magnetic tape.

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A discussion of the elements of the terrain which affects vehicle performence is presented. The soil value data currently available are tabulated and a brief description of their application is provided.

Programs devoted to the description of terrain environments are reviewed.

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