CONTRACT REPORT NO. 3-153

MOBILITY ENVIRONMENTAL RESEARCH STUDY MOBILITY TESTING PROCEDURES

by

R. A. Liston, T. Czako, P. Haley
W. L. Harrison, Jr., B. Hanamoto, and L. Martin

February 1966

Sponsored by

Advanced Research Projects Agency
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Service Agency
U. S. Army Materiel Command

Conducted for

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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ABSTRACT

Test procedures to be used for the evaluation of off-road vehicle mobility performance are presented. The development of a quantitative evaluation system represents an important step in the design of proper off-road vehicle tests. The procedures are presented as nine Annexes, entitled:

1. Drawbar-Pull
2. Torque
3. Vehicle Speed
4. Vehicle Sinkage and Trim
5. Resistance to Towing
6. Fuel Consumption
7. Load Distribution and Ground Pressure
8. Determination of Land Locomotion Soil Values
9. Determination of WES Soil Parameters

PREFACE

This report presents a review of procedures existing prior to the inception of Project MERS for conducting vehicle tests in natural terrain and includes an assemblage of test procedures for providing the necessary data to apply current terrain-vehicle relationships contributing to the evaluation of off-road mobility performance. The results of this study will be used in the development of a mathematical model for predicting ground mobility. The design of proper off-road vehicle tests represents an important step in the development of a quantitative vehicle performance evaluation system. This study was performed by the Land Locomotion Laboratory (LLL) of the U. S. Army Tank-Automotive Center, U. S. Army Materiel Command (AMC).

The study constitutes a portion of the Mobility Environmental Research Study (MERS), sponsored by the Office, Secretary of Defense (OSD), Advanced Research Projects Agency (ARPA), Directorate of Remote Area Conflict, for which the U. S. Army Engineer Waterways Experiment Station (WES) is the prime contractor and AMC is the service agent. The broad mission of Project MERS is to develop a significant research effort to study the physical environment, particularly as it affects the design and employment of materiel systems, with special emphasis being given to Southeast Asian environments. The funds employed for this study were allocated to WES through AMC under ARPA Order No. 400.

The annexes to this report contain seven individual test procedures for collecting the data required for vehicle evaluation purposes. The vehicle test procedures are given for quantitative and observational-type tests. The methods selected for predicting the effects of soil on vehicle performance are those currently used by LLL and WES and are presented in the two final annexes to this report.

LIST OF ANNEXES

No.	Title
1	Drawbar-Pull
2	Torque
3	Vehicle Speed
4	Vehicle Sinkage and Trim
5	Resistance to Towing
6	Fuel Consumption
7	Load Distribution and Ground Pressure
8	Determination of Land Locomotion Soil Values
9	Determination of WES Soil Parameters

PROCEDURES FOR OFF-ROAD VEHICLE TESTING

Introduction

1. The successful execution of current military operational concepts is largely dependent upon the cross-country capabilities of ground-contact tactical and logistical vehicles. It is evident that in order to increase the probability of full development and exploitation of current operational concepts, a more thorough knowledge of the physical environment and its specific effects on ground-contact vehicle performance is needed. It is also obvious that before a significant increase can be achieved in the probability of executing successful missions, this knowledge must be employed by the vehicle designer in optimizing the design of new vehicles for specific environments. Knowledge of the demands imposed by the physical environment and the meeting of these demands with properly designed vehicles offer the best solution to the problem.

2. The vehicle designer is concerned with optimizing the performance of a vehicle in the design phase by the selection (or design) of vehicle components to meet the design environmental and mission requirements. Thus, the vehicle designer must be ultimately provided with mathematical models from which vehicle performance can be predicted in a variety of terrain contexts in terms of several quantitative performance parameters such as speed, fuel consumption, ride quality, and costs.

3. Several performance parameters are required to encompass all the elements implied in an overall objective assessment of ground mobility. It is quite likely that one single performance parameter may rate one vehicle better than another in one particular type of terrain and poorer than another in a different type of terrain. The reverse may be true if another criterion is used to judge vehicle performance. It is therefore apparent that to obtain the most useful assessment of vehicle performance an analytical model of terrain-vehicle interaction must include several measures of vehicle performance in a range of selected environments. Once this has been achieved, decisions can be made on the requirements imposed by a specific environment under consideration.

General Background:

4. Recognizing the needs of the vehicle designer, the U. S. Army Engineer Waterways Experiment Station (WES) as a part of its Mobility

Environmental Research Study (Project MERS) included in its program plans* a major task for the development of a mathematical model for predicting ground mobility. This task was subdivided into five subtasks which would permit an orderly development of a mathematical model and at the same time permit the pursuit of several facets of the problem. These subtasks were as follows: (a) selection and description of test areas, (b) design of mobility tests, (c) tests of mobility in landform types, (d) verification of mobility predictions in terrain types of geographic regions, and (e) development of expression for ground mobility. Because of the experience and special capabilities in various fields of ground mobility of the Land Locomotion Laboratory (LLL) of the U. S. Army Tank-Automotive Center, WES solicited the assistance of LLL in formulating plans and assuming responsibility for pursuing agreed-upon work plans for some of these subtasks.

5. Several meetings were held among WES and LLL personnel to discuss possible approaches relative to the problem of quantifying off-road performance of ground vehicles and to agree on subtask work plans that were commensurate with the budget and time schedules of Project MERS. Most of the discussions were focused on the design of off-road vehicle tests since proper test procedures leading to the development of acceptable terrain-vehicle test designs represented the important steps necessary to the development of a quantitative vehicle performance evaluation system. From these discussions, it became apparent that although LLL and WES were in general agreement on the objectives to be achieved, some differences existed in the approaches to be followed and the data requirements to be used in the design of off-road vehicle tests. Test plans suggested by WES were based on a research approach which considered subdividing terrain in terms of individual factors known or hypothesized to have a specific effect on vehicle performance, whereas test plans suggested by LLL included a more general terrain description with an obvious advantage of requiring less time and effort in collecting data. With both types of plans having merit, it was decided to be in the best interest of Project MERS to pursue both.

Objective:

6. This report describes in some detail the most pertinent and widely used procedures for off-road vehicle testing in mobility research that existed prior to the inception of Project MERS. The objective of this report is to provide a convenient reference for engineers planning the conduct of tests for the purpose of evaluating vehicle performance and enhancing knowledge of vehicle-terrain relations.

*WES Operation and Funding Plans for OSD/ARPA Mobility Environmental Research Study (MERS), 26 March 1963.

Scope:

7. The test procedures described attempt to indicate the major elements to be considered in an evaluation of off-road vehicle performance. The procedures are by no means complete, and are intended to serve only as guides to ensure uniform data collection and application of acceptable quantitative terrain-vehicle relations which are only segments of a comprehensive mathematical model yet to be developed for predicting overall ground mobility.

8. The vehicle test procedures include those for two types of tests: (a) quantitative tests in which performance is measured in engineering terms, with the emphasis placed on the establishment of soil-vehicle relations, and with performance judged on the basis of minimum soil strength requirements and drawbar-pull-slip relations, and (b) observation tests in which a vehicle is operated in a natural environment, with the primary measure of performance being a comparison of its speed to that of a "reference" vehicle.

9. The methods selected for predicting the effects of soil on vehicle performance are those currently used by LLL and WES. A summary of the application of these methods including pertinent definitions, instruments and equipment, and soil measurements is given in WES Technical Report No. 5-625, "Environmental Factors Affecting Ground Mobility in Thailand, Appendix C: Soil Trafficability", dated May, 1963.

Presentation Order of Test Procedures

10. The data collection procedures are given in annexes to this report. Annexes 1 through 7 pertain to vehicle measurements, and Annexes 8 and 9 contain procedures for collecting soil parameters for the application of LLL and WES prediction systems, respectively, Application of data results or appropriate references are cited.

Quantitative Tests

11. The elements of the quantitative test procedure for determining the mobility characteristics of a vehicle are described in the following paragraphs.

General:

12. Quantitative tests entail three requirements which are necessary to determine the effects of terrain on vehicle operation.

Sufficient vehicle and soil measurements will be taken to permit the following determinations:

a. Excess traction that a vehicle can develop on paved and natural soil surfaces.

b. The motion resistance imposed on a vehicle by soft soil or obstacles.

c. Effectiveness of the propulsion members in utilizing soil strength and power available to them, as indicated by the drawbar-pull versus slip relations.

Vehicle Measurements:

13. The following measurements will be made in a manner such that a, b, and c above can be determined:

Drawbar-pull (1)

Output drive shaft torques and speeds (2)

Vehicle speed (3)

Vehicle sinkage (4)

Vehicle trim (4)

Resistance to towing (5)

Fuel consumption (6)

The number in parentheses following each vehicle measurement indicates the annex in which the measurement is discussed.

Observation Tests

14. These tests require a minimum number of measurements and consist of a series of operations over a range of representative terrain conditions. The tests are primarily comparative in nature. To increase the utility of the comparative tests, one of the vehicles participating in the test should be a conventional military vehicle of the same weight class as the vehicle or vehicles being evaluated. The performance of the standard vehicle will then serve as a yardstick since a trained observer will be able to establish the difficulty of the course on the basis of the performance of the standard vehicle.

15. Although the performance measurements may be kept to a minimum to include, for example, only average speed, number of immobilizations, and fuel economy, the test should not degenerate into a process of merely observing in general terms how a vehicle reacts to the impact of the off-road environment. Characteristics of the terrain and test vehicles should be observed on the same terms as for the quantitative tests. Characteristics of the terrain and vehicle should be measured when the measurement is reasonably simple to perform, such as turning radius of a vehicle, soil cone index, or size and spacing of trees. However, when a measurement is very complicated, such as determination of vehicle stability, the evaluation should be limited to the observation of the relative performance of the test and reference vehicles. Estimates of fuel consumption can be made by filling the fuel tank prior to the start of a test and refilling the tank at the end of a test run, measuring the amount of fuel used. When an immobilization occurs, the cause of the immobilization should be adequately described.

Terrain Conditions:

16. The terrain conditions selected for testing should be comparable to the design function of the vehicle. For example, a test plan to evaluate the performance of a vehicle designed to operate in a marsh should by all means include tests in marsh terrain. Where appropriate, variations in soil and obstacle characteristics on level and sloping terrain should be included in the selection of the test courses. Operation over disturbed and undisturbed soil should also be included where surface conditions change with traffic.

17. The observation test should be conducted on trails and strips of representative natural terrain. The test area should be long enough to include as many of the surface conditions as practical in a given area. The strip should be wide enough so that each vehicle being tested can make at least one pass over an undisturbed surface.

Test Criteria:

18. The following criteria should be considered in the design of test procedure and selection of suitable test courses.

a. Vehicles of similar mission assignment and of the same approximate size or payload capacity should be compared. Secondary comparisons can be made between the test vehicle and vehicles which may constitute a given operational unit.

b. The control vehicle used as a datum should have a performance sufficiently familiar to a layman to have general significance.

c. The tests should be designed to examine as many vehicle characteristics as possible, i.e., test areas should not be selected that demonstrate one characteristic favorably but exclude conditions that would demonstrate an unfavorable characteristic.

d. Conventional vehicles tested should include standard models only. The effect of modification of conventional standard models should be accomplished through separate tests.

e. The vehicles should be tested carrying their rated payloads. If test conditions or other considerations require testing at other than the rated payload, the payload used should be recorded. The gross vehicle test weight should always be recorded.

f. All vehicles should be in excellent mechanical condition.

g. The operators should be completely familiar with the operating characteristics of the vehicle. The effects of vehicle operators may be minimized by rotation of test and reference vehicle operators during the progress of the test.

h. The number of tests to be conducted should be sufficient to determine significant performance characteristics of the test vehicles.

Performance Evaluation:

19. Because the evaluation is basically qualitative, continuous observation of all vehicles throughout the test course is necessary. Considerations in the evaluation should include:

a. Average speed

b. Condition of vehicle and cargo on arrival

c. The ease or difficulty with which the course is negotiated by each vehicle.

Terrain Description

Introduction:

20. Tests involving performance rating, whether through direct measurements or observation, must incorporate a description of the test terrain in sufficient detail to be of value. It is necessary to classify terrain by means of a standardized description in order to convey

to others the conditions under which the test is conducted. Qualitative descriptions have proven themselves to be virtually useless since they can at best describe a general category of conditions.

General:

21. For evaluating off-road vehicle performance it is necessary to describe characteristics of terrains encountered in a test course by measurements made of surface profiles, including drainage features, soil, and vegetation. Measurements for constructing surface profiles are obtained by conventional surveying techniques. Profiles of test courses should include sufficient detail so that the magnitude and length of slopes and size and shape of surface obstacles are adequately defined. To properly describe the soil characteristics, measurements should be made of soil strength parameters, moisture content, density, and identification according to the U. S. Department of Agriculture and the Unified Soil Classification Systems. Of the soil characteristics identified, only soil strength measurements are required for evaluating soil trafficability; however, before methods for estimating trafficability for remote areas can be improved, such measurements are necessary. Soil strength is dependent to a large extent on moisture content and density, and differences in these properties occur in different soil types. Once sufficient data are available, data analyses can be made which will permit grouping soil types along with other soil and terrain data into units that exhibit similar ground mobility characteristics. The moisture content of a soil is dependent upon weather which is continually changing. For this reason it is very important that the time interval between a vehicle test and the collection of soil strength, moisture content, and density data be kept to a minimum. Special equipment and techniques are used to make these soil measurements. Conventional measurement equipment and techniques are used to measure vegetation characteristics. These measurements should include height, size, and spacing of individual plants. A description of the instruments and procedures for collecting and reducing data for applying the LLL and WES vehicle evaluation systems is given in Annexes 8 and 9, respectively.

Terrain Data Collection Guide:

22. The degree of detail to which the terrain data in an area selected for test purposes should be defined is rather difficult to establish, however, it is reasonable to assume that the decision should be made on the basis of economics because considerable time and cost are involved in collecting data and preparing appropriate maps. If a need exists for conducting a large number of tests and a determination has been made that advance information concerning the range in variation and location of specific terrain conditions would result

in a more efficient selection of test courses, then it may be desirable to prepare detailed maps of significant terrain attributes. If testing is conducted on an infrequent basis, it is best to reconnoiter the area, select specific test courses, and restrict the data collection to the area occupied by the test courses. The following tables list the minimum terrain information desired for quantitative and observation-type vehicle tests.

Quantitative Tests

1. Soil Information:

   a. Strength:

      (1) LLL soil parameters (c, ϕ, and vertical load-deformation curves.

      (2) Rating cone index

   b. Moisture content

   c. Density

   d. Classification

      (1) U. S. Department of Agriculture (USDA) System

         (a) Great Soil Group

         (b) Soil Series

         (c) Phase

         (d) Type

      (2) Unified Soil Classification System (USCS)

2. Ground Surface Profile.

3. Vegetation

Observation-Type Tests

1. Soil Information:

   a. Strength, rating cone index

   b. Moisture content

   c. Density

   d. Classification

      (1) U. S. Department of Agriculture (USDA) System

         (a) Great Soil Group

         (b) Soil Series

         (c) Phase

         (d) Type

      (2) Unified Soil Classification System (USCS)

2. Ground Surface Profile

3. Vegetation

ANNEX 1: DRAWBAR-PULL

I. INTRODUCTION:

Drawbar-pull is a basic measure of vehicle performance either on or off-the-road. It is a conveniently obtained quantity essential to a vehicle comparison or evaluation program. Drawbar-pull is determined by similar procedures for either tracked or wheeled vehicles.

II. DEFINITION:

Drawbar-pull is defined as the available tractive effort in excess of that necessary to propel the vehicle at a given constant speed on a level surface. It is a measure of the force available to accelerate the vehicle, climb grades, and pull towed loads.

III. PURPOSE:

The purpose of drawbar-pull measurement is to determine available excess traction which the vehicle can develop on a given surface.

IV. TYPE OF TESTS:

a. Hard Surface Tests:

Hard surface tests are conducted on level pavement to determine the overall efficiency of the vehicle. Efficiency is taken as the ratio of measured drawbar-pull and theoretical (rim pull, sprocket or wheel) drawbar-pull. The efficiency is a measure of losses which include internal suspension frictional losses, external rolling resistance and, at higher speeds, aerodynamic drag. The measured drawbar pull is limited by the power plant, transmission, suspension efficiency, and the traction that the wheels or tracks can develop on a given surface. Theoretical drawbar-pull may be computed from data supplied by the vehicle manufacturer and assumes no traction limitation. Required data include the engine torque curve, gear ratios and efficiencies in the various drive line components, and the rolling radius of the tire or pitch radius of the drive sprocket. The measured drawbar-pull is established from the average of several tests.

In hard surface tests, the test vehicle is operated throughout its range of gear ratios and at small speed increments to provide data for the drawbar-horsepower speed curves. Drawbar load can be provided by any convenient system. Experience has shown that a dynamometer vehicle is the most useful loading device. A dynamometer vehicle should be sufficiently large to assure that the test vehicle can achieve 100% slip and should have adequate space for instrumentation and test personnel. However, a dynamometer vehicle is not essential to a drawbar test. It is only necessary that a device be used that can apply a variable load and has provision for the measurement of drawbar load.

A drawbar-pull test should include continuous records for the following measurements:

(1) Drawbar load (lb.)

(2) Engine, wheel, or track, sprocket speed (rpm)

(3) Vehicle speed (mph)

b. <u>Soft Soil Tests:</u>

The determination of drawbar-pull for soft soil operation follows similar procedures as for paved surfaces with the exception that there is no interest in the effect of transmission range. The soil is the controlling element in soft soil operation so that the relation between drawbar-pull and slip is of primary interest.

The determination of drawbar pull in soft soil requires measurement of the following:

(1) Drawbar load (lbs.)

(2) Vehicle speed (mph or ft./min.

(3) Wheel or sprocket speed (rpm)

(4) Vehicle sinkage (in.)

(5) Vehicle trim (degrees)

(6) Soil strength parameters

Instrumentation and recording devices will vary depending on the accuracy desired, the magnitude of the test program and the funds available to support the test program. It is necessary that instrumentation adequately cover the expected range of measurements to be taken without sacrifice of sensitivity or accuracy.

V. PROCEDURE:

a. Preparation of the Vehicle:

In the case of the hard surface tests, the engine should be tuned and adjusted for maximum performance according to the manufacturer's specifications. Throttle linkage, transmission linkage, and brakes should also be adjusted according to manufacturer's specifications. The transmission clutch and band adjustments must be checked. In the case of the soft-soil test, the precise adjustment of power train components is not as significant as for the hard surface test since the soil and suspension to a large extent control the test results.

Each vehicle component requiring lubrication must be checked and/or lubricated with the proper quantity and grade of lubricant.

Track tension should be checked and adjusted if necessary.

Tire inflation pressure should be set for optimum off-road performance.

Periodic inspection of the vehicle must be made during testing to insure optimum performance.

b. Instrumentation:

Description of the instrumentation for the measurement of most test variables appears in annex form in the test procedure. Instrumentation requirements for the conduct of a drawbar-pull test will be covered in detail in this annex only for those instruments not discussed elsewhere. A typical drawbar-pull test setup is shown in Figure 1-1.

c. Drawbar Load:

Any of the several types of load measuring devices can be used so long as the appropriate load range is maintained. A standard, commercial load cell using strain gauges is economical and adequate. Because of the wide variety of load ranges available, the load cell is a convenient instrument on which to base an instrumentation system.

Hydraulic dynamometers that are rugged and accurate are commercially available. The hydraulic system has the advantage of permitting immediate read-out so that the dynamometer vehicle operator can observe the load he is applying to the test vehicle. The hydraulic dynamometer has the disadvantage that a permanent record is not produced. If a permanent test facility or dynamometer vehicle is being considered, a combination load cell hydraulic dynamometer should be given serious consideration. The dynamometer vehicle operator should control the load by observing the hydraulic read-out and the test engineer should maintain control of the test by means of the permanently recorded strain gauge measurement.

d. Vehicle speed:

It is quite possible to measure vehicle speed by recording the time required to traverse a measured distance. However, the use of a fifth wheel to measure speed substantially reduces the complexity of the test procedure since a continuous reading of speed is obtained. The alternate technique of measuring time and distance requires such close coordination between the measurement of speed and drawbar-pull that it is quite clumsy.

e. Engine, Wheel, or Track Sprocket Speed:

In order to compute wheel or track slippage, it is necessary that actual and theoretical vehicle speed be known. Theoretical vehicle speed is obtained by measuring the motion of the driving elements. The engine speed can be measured if the transmission has a lockup so that there is no slippage between the engine and final drive. Normally, it is more accurate and simpler to measure the speed of the drive sprockets on a tracked vehicle or driving wheels on a wheeled vehicle. Any convenient measuring system can be used but experience has shown that a tach-generator arrangement produces the most reliable data. No standard attachment is available so a bracket must be fabricated for each vehicle to be tested. The speed of both drive sprockets on a tracked vehicle must be measured. The speed of all driving wheels on a wheeled vehicle must be measured unless the vehicle is equipped with no-slip differentials. In this latter case, only the speed of sets of driving wheels need be measured.

f. Vehicle Sinkage:

It is not necessary to measure vehicle sinkage except for documentary purposes or for verification of the analytical prediction of vehicle sinkage. The measurement of vehicle sinkage is described in Annex 4.

g. Vehicle Trim:

The measurement of vehicle trim is of value in that an extreme trim attitude will reduce the performance of a vehicle. If a vehicle does not perform as well as anticipated, the measurement of the trim behavior may provide a clue as to the source of poor performance. The measurement of vehicle trim is described in Annex 4.

h. Soil Strength Parameters:

The measurement of drawbar-pull in soft soil without an identification of soil properties by some numerical means is virtually useless and may be misleading. The soil properties should be measured by a method that will permit the correlation between soil properties and vehicle performance. Two useful systems are presented in Annexes 8 and 9.

i. Hard Surface Tests:

The hard surface drawbar test is conducted on a level, straight, paved surface. The test vehicle, properly prepared and instrumented, is driven prior to testing until all components reach normal operating temperature. The test vehicle is coupled to the dynamometer vehicle and operated throughout the range of speed and transmission ratios established prior to the test. An adequate number of readings should be obtained so that smooth curves of drawbar-horsepower versus speed can be plotted for each gear ratio. Wheeled vehicles should be operated with the maximum number of axles driving. Vehicles equipped with automatic transmissions should not be operated at engine speeds near or at transmission shift points unless a manual selector enables the operator to lock the transmission in gear.

After establishing a steady state condition during a test run, data should be recorded for at least three vehicle lengths.

j. Soft Soil Tests:

The soft soil test site selection depends mainly on the type of soil conditions required or desired. At the chosen test site, a smooth flat area with at least a 500 ft. straightaway wide enough to accommodate the test vehicle should be selected. The soil should be uniform throughout the test lane. To obtain desired ranges of soil strength, the test lane can be prepared by thoroughly working or mixing soil and water to a depth of 20 to 24 in. until a high degree of homogeneity is obtained. Processing of the soil requires specialized equipment because of the depth of uniform soil required. A gyrotiller with tines rotating about a vertical axis has been the most useful apparatus for the processing of soil in the field. It is recognized that it may not be economically feasible to construct equipment adequate for processing soil. The alternative to soil processing to obtain a desirable strength range is the selection of test sites in areas where seasonal difference in soil strength occurs. Processing of the soil is required after each pass of the test vehicle in order to restore the soil to its original condition to obtain reproducible data. Water, when required, should be applied as evenly as possible. When conducting drawbar-pull tests in snow, processing of the snow is not feasible and a sufficiently large area is required to permit several tests to be conducted. In practice, this requires a 10,000 sq. ft. uniform snow field.

Uniform soil strength, the result of good processing techniques or careful site selection is essential to the production of reproducible test results. If uniform soil conditions cannot be produced because of a lack of soil processing equipment or for other reasons, it is necessary that many soil strength measurements be made to obtain representative average soil property values. The variations of the soil properties can also provide a guide to the number of vehicle tests that must be conducted in order to obtain a representative drawbar-pull measurement.

Vehicle operating techniques are similar to those used on paved surfaces. However, for determining maximum tractive effort in most soils, the drawbar load must be sufficient to induce 100% slip condition. From a practical viewpoint, the maximum drawbar pull at 100% slip is of little interest. For most applications, the test engineer is interested in the drawbar-pull at slip rates less than 80%. In conducting the test, it is normal procedure to begin the run with no load at the drawbar. The test vehicle is allowed to reach a constant, predetermined engine rpm. which will provide a truck or wheel speed of about 2 mph. The gear range is important only in that the test vehicle must be capable of developing full track slip (100%) in the soil while maintaining a constant engine rpm. Once a constant rpm is reached, load is applied to the test vehicle incrementally. As each increment of load is applied, it is kept constant for a period of approximately 10 seconds. The load is increased until the 100% slip is reached.

VI. DATA ANALYSIS:

Drawbar pull is one of the essential measurements used in evaluating the traction performance of a vehicle and is very useful when making vehicle comparisons. The data are generally presented as maximum drawbar-pull developed or as a curve of drawbar-pull/weight versus slip (Figures 1 and 2). Possibly a more revealing curve would be efficiency versus slip where efficiency is defined as the drawbar work output and equals drawbar-pull/weight x 1 - slip

(Reference: Dickson, W. J., "Some Fundamental Soil/Vehicle Mechanics and a Method of Evaluation of the Soil/Vehicle System". Canadian Armament Research and Development Establishment, Valcartier, Quebec, 1961). This plot is shown in Figures 1-3. This curve has the advantage of indicating the optimum performance point for the test vehicle in a particular soil.

Fig. 1-1. Arrangement of Vehicles for Drawbar Pull Test

(1) Test Vehicle
(2) Articulated load-instrumentation vehicle (dynamometer vehicle)

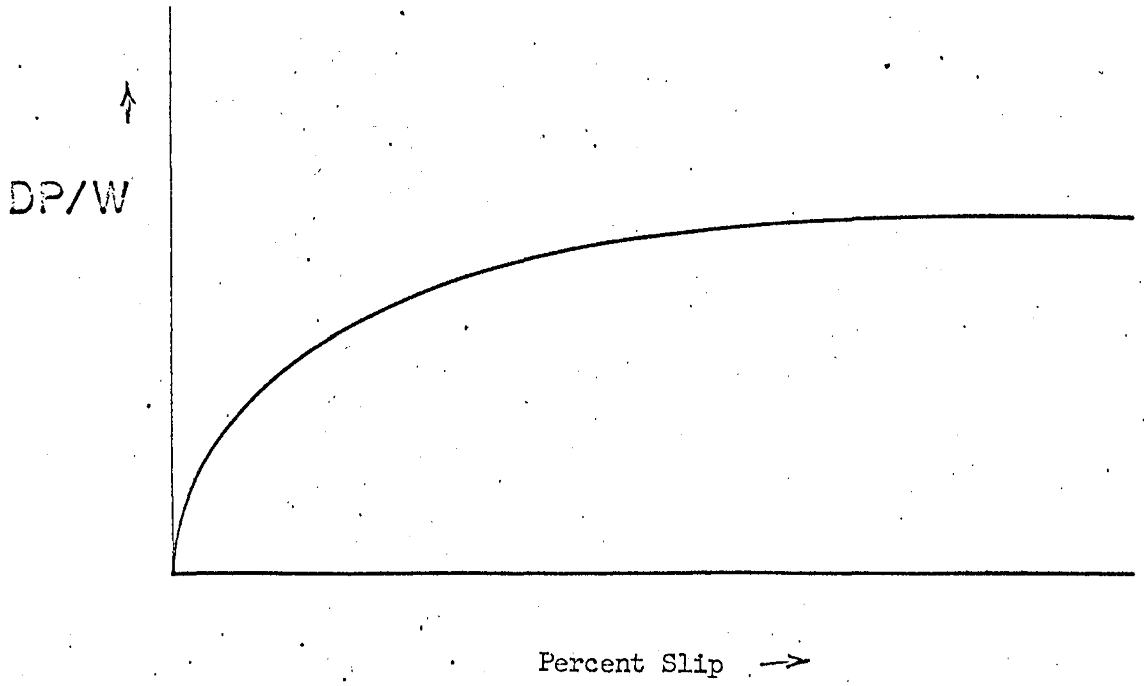


Fig. 1-2. Example of Drawbar Pull Coefficient - Slip Relation

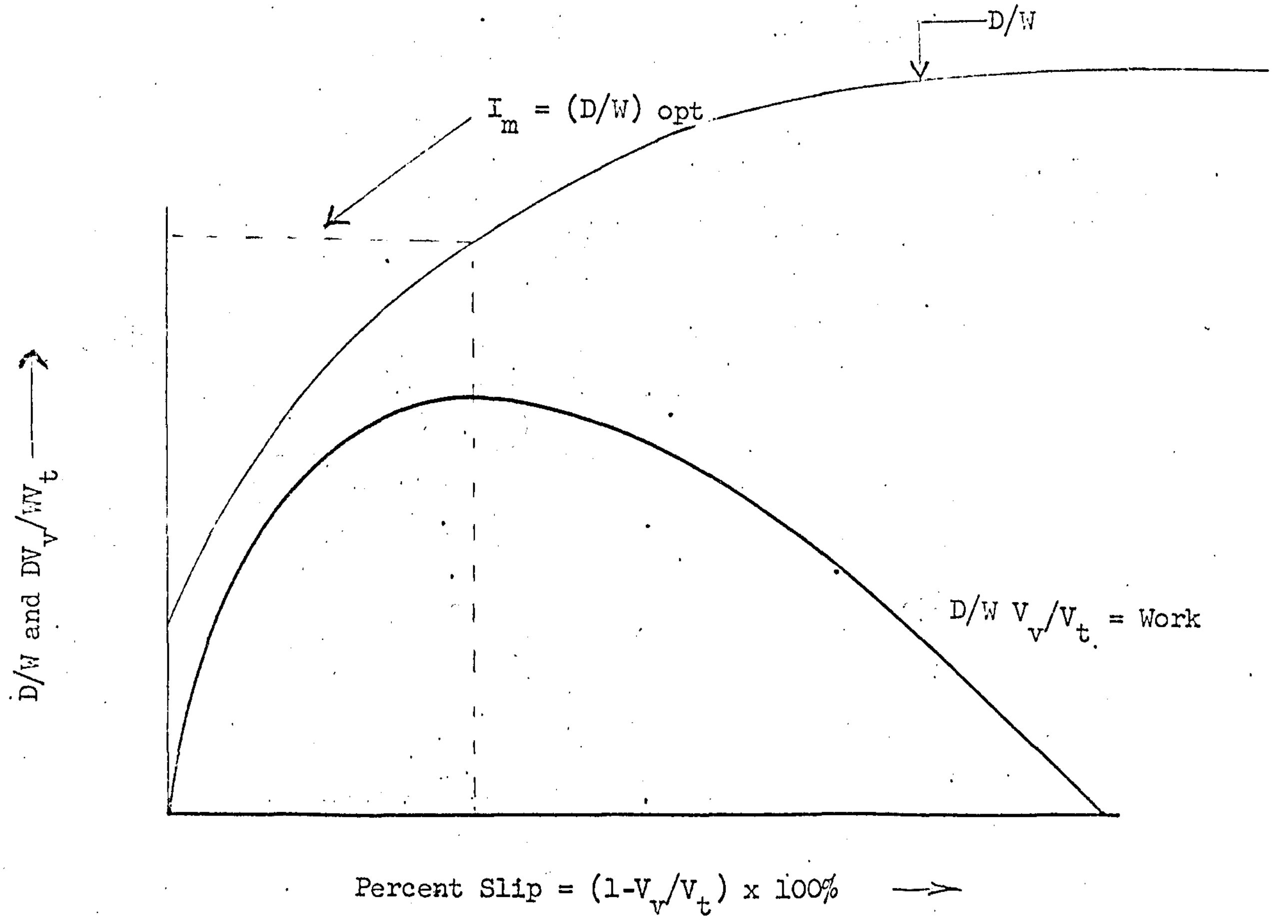


Fig. 1-3. Determination of Mobility Index (I_m)

ANNEX 2: TORQUE

I. INTRODUCTION:

In order to conduct a thorough evaluation of vehicle performance, a measure of output torque is essential. The torque applied to a wheel or drive sprocket is of no immediate interest since the reading itself only provides a knowledge of the efficiency of transmission and other driving elements between the engine and the final drive. However, when output torque measurements are combined with drawbar measurements, it is possible to obtain values for the losses in the suspension and the motion resistance caused by soft soil or in overriding vegetation. It must be recognized that the measurement of torque is a difficult and relatively expensive task and should not be considered as a part of a routine vehicle evaluation. However, when mobility evaluation is a part of a vehicle development program, the measurement of output torque is essential to a full understanding of the source of a deficiency in performance.

The use of the output torque measurement requires that measurements be made on both hard surfaces and in soft soil. Further, the measurement in soft soil should be made simultaneously with drawbar pull for maximum utilization of data. The measurement of torque independent of drawbar-pull provides an index of losses due to ground resistance, wheel or track slippage, and suspension clogging. The hard surface tests permit the development of the relation between torque and track or vehicle speed. The curve that is obtained from this test serves as a base line indicating internal resistance which are the suspension losses caused by such things as friction in the various elements and acceleration of the track. It is obvious that almost an identical result could be obtained by disconnecting the final drive or axles towing the vehicle at an equivalent group of speed intervals. By measuring the towing force necessary to produce a constant speed, the suspension losses can be identified. The only difference between the two sets of readings would be caused by the torque reaction when the vehicle is driven instead of towed.

When combined with the soft soil test results, the hard surface torque measurement permits the identification of motion resistance developed by the soil. The difference between the traction that the output torque should produce and the drawbar-pull can be attributed to three losses: (1) internal resistance;

(2) soil motion resistance; and (3) suspension losses caused by accumulation of soil or other surface materials. The internal resistance is obtained from the hard surface test. The suspension losses caused by accumulation of extraneous material is obtained from the 100% slip point. If track or wheel speed is constant at 100% slip, the difference between the gross traction, as measured by the output torque, and the drawbar pull is equal to the sum of the internal resistances and the losses caused by accumulated material. The motion resistance is equal to the difference between gross tractive effort and the sum of the suspension losses.

II. DEFINITION:

Output torque is the torque applied to the final driving elements of a vehicle such as a wheel or sprocket.

III. PURPOSE:

The output torque is used to determine resistance to motion on both hard (paved) surface and soft soil or in overriding vegetation. The resistance to motion is subdivided into ground losses and suspension losses permitting identification of sources of performance deficiencies.

IV. APPARATUS:

When possible, torque is measured by means of a commercial torque-meter mounted between the final driving element and the input to the final drive. However, in most cases, it is necessary to apply strain gauges to the shafts leading to the final drive or to the axles. Slip rings are required to feed the strain gauge signals to a recorder so that the installation is quite expensive and time consuming. Because each installation is unique, no standard instrumentation procedure is offered for the measurement of torque. The measurement of track or wheel speed is identical to that used in the drawbar pul test, Annex 1. Torque measurement is of little use unless measured concurrently with speed measurement. The reader is thus referred to Annex 3.

V. PROCEDURE:

a. Hard Surface Tests:

The output torque should be measured on a level paved surface over the vehicle speed range. Steady state speed should be maintained for a minimum of ten seconds, or until the torque readings become constant. The speed increments should be chosen to result in a reliable torque-speed curve.

b. Soft-Soil Tests:

(1) The output torque is measured in soft soil concurrently with drawbar pull. The procedure for the drawbar pull test, therefore, controls the procedure used to measure torque. See Annex 1.

(2) If a vehicle has been instrumented to measure output torque, a valuable addition to the observation-type test can be obtained by measuring torque during the test. It must be observed, however, that the results of the measurements are more useful for design than evaluation purposes. A history of power requirements related to obstacle configuration would permit establishment of design criteria. However, one objective of this recommended practice is to develop such data.

VI. DATA TABULATION AND PRESENTATION:

a. Output torque data from the hard surface tests should be presented as torque versus speed curves.

b. The presentation of the soft-soil results can follow any pattern desired by the test engineer. It is suggested that the data follow both a graphical and tabular format:

(1) The output torque should be presented graphically plotted against wheel or track speed.

(2) The soil motion resistance should be presented graphically against wheel or track slip.

(3) The suspension internal resistance and resistance due to accumulated material should be tabulated since these values tend to be relatively independent of track or wheel speed at the speeds at which drawbar tests are conducted.

c. For observation-type tests, the output torque signal should be identified with the terrain conditions. The torque data may be presented as torque required to overcome an obstacle versus obstacle type. A useful presentation technique is the use of a double plot: one curve identifying the terrain profile and the second curve identifying the torque level associated with each point on the profile.

ANNEX 3: VEHICLE SPEED

I. INTRODUCTION:

There are many situations in which vehicle speeds are taken as the primary measure of vehicle performance. For example, when identifying the off-road performance of a vehicle operating over a cross-country course, a logical measure of performance is "speed made good", i.e., a straight-line distance between two points divided by the time required to complete the course. In other circumstances, the actual vehicle speed must be measured in order to be included as a variable. An example is the development of drawbar pull versus speed data. The method used to determine vehicle speed depends upon the final use of the measurement, the accuracy required, and the particular test situation which may prescribe the measuring method to be used.

II. DEFINITION:

Vehicle speed is the rate of travel, i.e., the total distance traveled divided by the time to traverse the distance.

Vehicle speed made good is defined as the straight line distance between two points divided by the time required to move between the two points.

III. PURPOSE:

Vehicle speed is measured as a test variable or as the primary performance evaluation criterion. In the conduct of cross-country or train operation tests one of the most useful criteria of performance is vehicle speed. It is normal to consider speed made good rather than vehicle speed because the latter value may have little significance as an indicator of vehicle performance in cross-country conditions. For example, one vehicle may be capable of moving at a higher rate than a second vehicle but if the second vehicle has other characteristics that permit it to take a shorter route, the second vehicle may arrive at the destimation before the faster moving vehicle.

Speed is, of course, also measured as the primary variable in various gear ranges.

In several types of tests, speed is a "secondary" variable. It is measured to permit the establishment of the variation with speeds of the primary variable of interest. For example, the measurement of resistance to propulsion is made throughout the speed range of a vehicle to determine the relationship between losses and speed. In this example, speed is of no interest in itself; speed is measured in order to record the variation of the parameter of interest.

IV. APPARATUS:

Because of the wide variation in methods of measuring vehicle speed, instrumentation details will not be specified. Time and distance must be measured by some means. Time may be recorded by means of an electronic counter, a stop watch, an event marker on a paper recorder, or any similar device. The length of the time to be counted will establish the sophistication of the measuring apparatus.

Distance can be measured by means of a standard automotive fifth wheel; by measuring the distance prior to the test and timing the run to traverse the distance; by measuring the distance on a map for large distances; or by any conventional method which produces a measurement sufficiently accurate for test requirements.

The measurement of both time and distance are considered sufficiently well known to make a detailed description superfluous.

V. PROCEDURE:

a. Measurement of Average Speed:

Because of relatively long distances involved in cross-country operations and because the primary factor of interest is usually comparative performance, the measurement of cross-country speed can be relatively simple. If speed is to be based on actual distances traveled, the distance can be measured by means of the odometer on one of the test vehicles and this distance taken for all vehicles in the test. Time can be measured by means of stop watch readings of starting and stopping time.

If "speed made good" is to be taken as the performance measure, it is necessary to have adequate map coverage to provide a distance measurement within $\pm$ 2% . If maps are not available, it is necessary to resort to standard surveying methods to establish the straight-line distance. The cost and effort of this measurement is not considered justifiable unless the test course is to be used on a repetitive basis.

b. Measurement of Actual Speed:

When a test requires that actual speed be measured, a higher order of accuracy is required than for the measurement of average speed. When concerned with actual speed, the test engineer usually must have an immediate speed read-out since speed must be maintained at a specific level.

The most common method of measuring actual speed is by means of a fifth wheel attached to the rear of the test vehicle. The fifth wheel drives a standard Weston Meter (Tach-generator) which reads directly in miles per hour.

If a fifth wheel is not available, the test engineer may be forced to operate on the basis of the test vehicle speedometer. Under this circumstance, the speed reading should be checked by an alternate method. The speedometer can be used to provide immediate read-out to maintain a constant speed level and the actual speed level established by the time required to complete a measured distance. In order to reduce error caused by the averaging process, the measured distance should be kept short - of the order of 100 feet. Time can be measured by means of a stop watch.

If a high degree of accuracy is required in the measurement of vehicle speed, it is possible to obtain commercial units normally applied to racing events such as drag-racing or to police work. The former units likely exceed the requirements of vehicle testing. Photocells and counter-chronographs are used to obtain time with an accuracy of ± .01 seconds. Speed can be measured and read directly by setting the photocells at known distances and converting the counter-chronograph reading to mph rather than time units.

The police-type of radar has adequate accuracy as attested by the acceptance of its results as legal evidence. The system can provide a reading of speed taken over a very short distance which can be a definite advantage when attempting to establish a given speed level. The advantage is lost, however, unless the read-out equipment is mounted on the test vehicle. It should be possible to mount the radar equipment on the test vehicle and shoot at a fixed target on the course and thus provide both accurate speed readings and immediate read-out for the test engineer or vehicle operator.

ANNEX 4: VEHICLE SINKAGE AND TRIM

I. INTRODUCTION:

The measurement of vehicle sinkage and trim during soft-soil drawbar pull tests assist in the description and analysis of performance. Motion resistance is proportional to both sinkage and trim and gross traction can vary significantly with trim. Since motion resistance and gross traction determine drawbar pull, it is necessary that sinkage and trim be measured in order to understand and interpret the results of a drawbar pull test.

II. DEFINITIONS:

a. Vehicle sinkage is the deformation or rut depth created by the vehicle traction element after completing one or a specified number of passes. It is the result of the vertical deformation of soil due to the loads imposed on it by the vehicle traction elements. Sinkage can be taken as either static or dynamic sinkage. Static sinkage is the deformation of the soil caused by the vehicle weight when no forward motion of the vehicle occurs. Dynamic sinkage is the soil deformation produced by vehicle weight and by the disturbance of the soil resulting from the shearing action of the tracks or wheels, that is, the slip-sinkage phenomenon. Many soils produce approximately equal static and dynamic sinkages but granular materials, such as sand or snow, may produce dynamic sinkages several times as great as the static sinkage. Dynamic sinkage is the appropriate measurement for the analysis of drawbar pull data since this is the depth to which the vehicle actually sinks during operation.

b. Vehicle trim is the attitude that a vehicle assumes relative to the ground surface as it moves over the surface.

III. PURPOSE:

a. Measurement of vehicle sinkage during off-road tests permits the computation of motion resistance and ground pressure if the soil strength characteristics are also measured. Motion resistance is proportional to the work involved in causing the soil to deform to a depth equivalent to the vehicle dynamic sinkage. The ground pressure is proportional to static sinkage unless vehicle trim is in excess of 5^{o}. For small trim angles, average ground pressure can be computed using the pressure-sinkage relationship of the soil and the static sinkage of the vehicle.

b. Vehicle trim is measured in order to identify non-uniform ground pressure distribution which results from weight transfer because of the trimmed attitude. In addition, increase in motion resistance caused by sinkage associated with weight transfer can be identified. A severe trimmed attitude is a source of deterioration in performance to either wheeled or tracked vehicles because of the resulting adverse weight distribution. The measurement of trim, along with sinkage, should therefore be considered as fundamental to an off-road vehicle evaluation.

IV. APPARATUS:

Equipment used for measuring vehicle sinkage and trim consists of sets of outriggers with a means to establish a ground reference point and potentiometers to measure vehicle attitude relative to the ground as shown in Fig. 4-1. In order to measure both sinkage and trim it is necessary that two such units be used: one at the front of the vehicle and one at the rear. Sinkage is taken as the reading of the rear unit and trim is obtained from the difference of the two readings. The arrangement in Fig. 4-1 is a relatively sophisticated installation approach for permanent test facilities. A more typical arrangement is shown in Fig. 4-2, which is a temporary installation that can be used for a large number of vehicles. In addition to presenting an example of a temporary arrangement, Fig. 4-2 is an example of the use of skis for the measurement of trim and sinkage in weak soil or snow in which small wheels would be useless. Despite the apparent difference, the instruments are quite similar in that they both measure the difference between the ground surface and known points on the vehicle by means of a potentiometer which records the motion of an outrigger.

The installations shown in the figures are not the only acceptable methods for the measurement of sinkage and trim but are likely the most economical. One technique consists of the use of one outrigger to measure the sinkage of one point and a gyroscope to measure vehicle trim. The use of this system produces readings that are likely more precise than required and is not recommended. The use of a photographic technique utilizing a pre-exposed grid has received considerable support but has the disadvantage of awkwardness in data reduction and relatively high cost.

The use of a scale to measure the depth of rut to determine sinkage has the advantages of simplicity, low cost and immediate availability of data. However, it is not feasible to measure trim with a scale so that this convenient technique should only be used when the test vehicle is operating in soil conditions producing negligible trim.

V. PROCEDURE:

The procedure for measuring vehicle sinkage and trim is as follows when an arrangement similar to that shown in Figure 4-2 is used:

a. Attach the outriggers to the vehicle.

b. Calibrate the potentiometers.

c. Zero the potentiometer outputs on hard surface so that the zero point is equivalent to zero sinkage.

d. Conduct vehicle test as prescribed.

Sinkage and trim measurements are almost always taken as part of data for another test since sinkage and trim data are of little interest as isolated pieces of data.

VI. DATA TABULATION AND PRESENTATION:

When using an arrangement similar to Fig. 4-1 or 4-2, the measurements are recorded as continuous traces of the sinkage of the two points of the vehicle. The distance between the two ground contact points is known so that the trim can be established by determining the difference between the two sinkage readings and computing trim by use of geometric relationships.

The sinkage and trim can be presented as continuous traces as shown in Fig. 4-3 or numerical results can be tabulated. Trim would thus be given in degrees and sinkage values would be given in inches for the front, center, and rear of the vehicle.

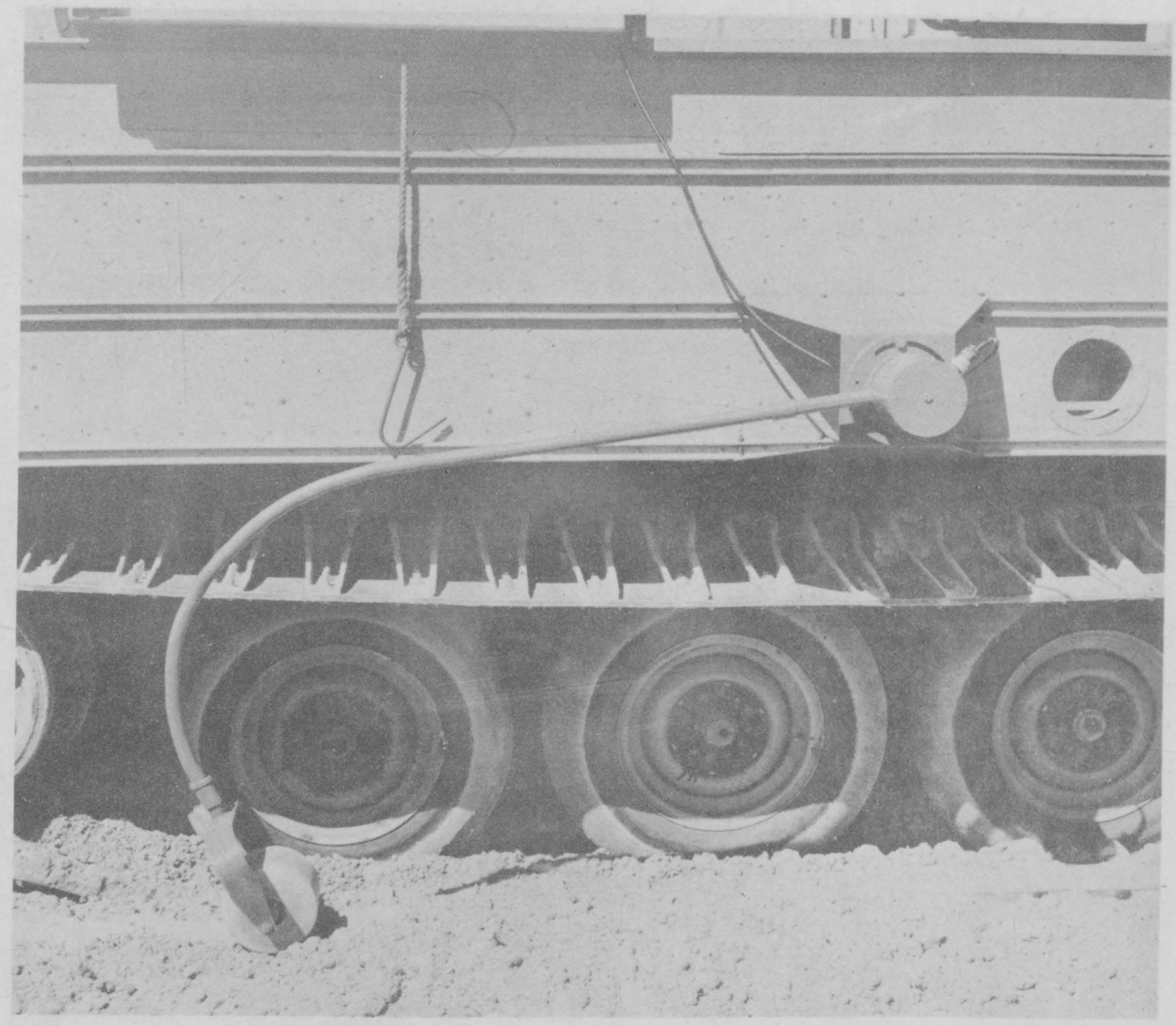


Fig. 4-1. Arrangement of Potentiometers Used to Measure Vehicle Attitude Relation to Ground Surface

Fig. 4-2. Example of Ski-Potentiometer Arrangement Used to Measure Vehicle Sinkage and Trim.

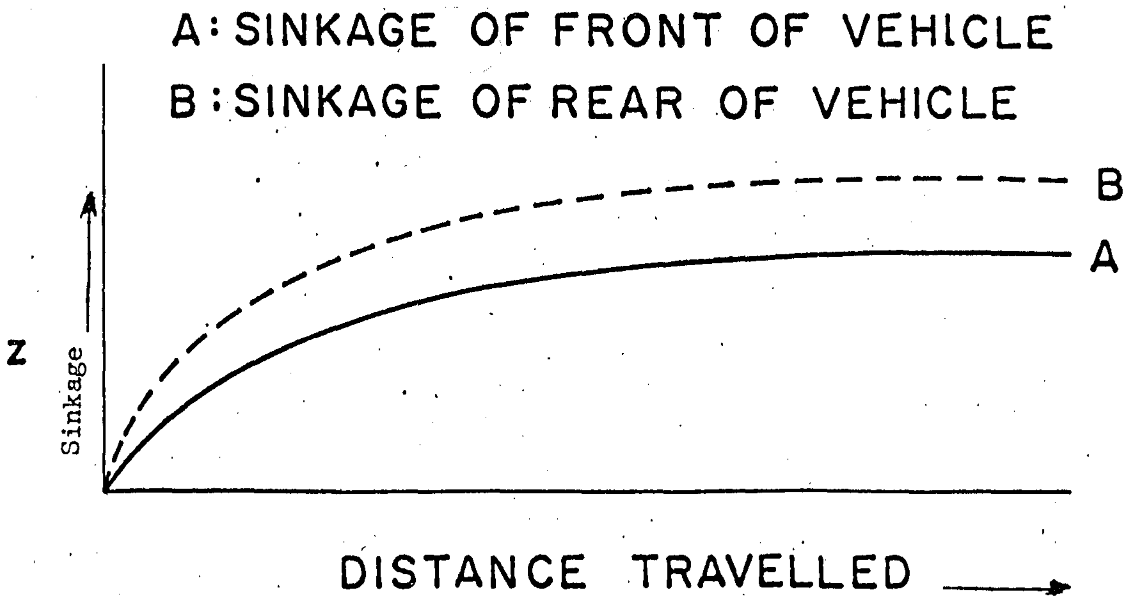


Fig. 4-3. Examples of Continuous Traces of Sinkage Measurements

ANNEX 5: RESISTANCE TO TOWING

I. INTRODUCTION:

Resistance to towing and resistance to propulsion on a hard surface are basically measures of the internal losses in a vehicle suspension system. The losses associated with the vehicle suspension system are significant from an efficiency standpoint and to serve as input data for determining motion resistance when conducting soft-soil performance evaluations. It is normal procedure to measure towing or propulsion resistance on hard surfaces. However, measurement of the resistance values in soft soil can provide valuable insight into the behavior of a vehicle operating in soft soil, particularly if the vehicle has a suspension system with poor self-cleaning characteristics. In many cases more realistic measurements of resistance can be obtained with torque measurements.

II. DEFINITION:

a. Resistance to Towing: Resistance to towing (sometimes called rolling resistance) is defined as the force required to tow the vehicle at a fixed, constant speed on a level surface.

b. Resistance to Propulsion: Resistance to propulsion is defined as the force required to propel the vehicle at a fixed, constant speed on a level surface.

III. PURPOSE:

Resistance to towing and propulsion are measured to permit the establishment of the suspension and power train efficiency as represented by the losses due to friction, vibration of running gear components, and inertia of the rotating elements. Because of the significant contributions of the inertia and vibration components, it is normal to conduct the resistance measurements over the complete operating speed range for the vehicle being tested.

The force required to overcome losses is a reliable index of the efficiency of a vehicle suspension and drive system. Experience has shown that there is no direct correlation between soft soil performance and hard surface resistance to towing. However, excessive losses in a suspension system produce obvious penalties so that the establishment of the suspension-drive train efficiency is required for the complete evaluation of a vehicle. Furthermore, resistance values determined on hard surface provide a basis for approximating components of motion resistance attributed to soft soil. These components include soil compaction and suspension clogging. Resistance to propulsion values measured in soft soil permit more flexibility in isolating these losses than resistance to towing measurements. It is desirable that resistance measurements be taken in the soft soil in which drawbar pull is measured.

IV. APPARATUS:

The equipment and instrumentation necessary for the measurement of resistance to propulsion and towing consist of:

a. Resistance to Towing:

(1) Dynamometer vehicle or any vehicle capable of towing the test vehicle at its maximum operating speed or 30 mph, whichever is lesser.

(2) Fifth wheel or equivalent apparatus for the measurement of vehicle speed.

(3) Load cell or hydraulic dynamometer.

(4) Soil strength test equipment when conducting soft-soil tests. See Annex 2.

b. Resistance to Propulsion:

(1) Torquemeters or strain-gaged final drive and axle shafts.

(2) Fifth wheel or road speed and generators for sprocket or wheel rpm.

(3) Recording equipment to accept the output from the torquemeters.

V. PROCEDURE:

a. Data to be Recorded for Resistance to Towing:

(1) Towing force required.

(2) Vehicle speed.

(3) Soil characteristics for soft-soil tests. See Annex 2.

b. Data to be Recorded for Resistance to Propulsion:

(1) Vehicle speed.

(2) Sprocket or driving wheel torques and speeds.

(3) Soil characteristics for soft-soil tests. See Annex 2.

c. Hard Surface Resistance to Towing:

(1) Prior to conducting the test, the test vehicle should have track tension or tire inflation pressures adjusted to design specifications. Lubrication of the drive-line and running gear should be checked for proper level and lubricant type.

(2) Operate the vehicle for a sufficient period of time to insure that the lubricants are at normal operating temperatures.

(3) To measure resistance to towing, the final drive is disconnected on tracked vehicles and driving axles removed on wheeled vehicles. If this is a time consuming process, it is necessary that the vehicle be towed upon removal of the driving elements to re-establish proper lubricant temperatures.

(4) The dynamometer or towing vehicle is attached to the test vehicle by means of the load cell or dynamometer. Assure that load cell or dynamometer and speed measuring device are properly connected to the recording equipment and proper zero established.

(5) Tow the test vehicle on a straight, level track at constant speed and record the towing load. Repeat over the complete speed range of the test vehicle in 4 mph increments, or less if necessary, to establish a smooth curve relating towing force to speed.

(6) Step 5 may be repeated for tracked vehicles after removing the tracks to establish the contribution of the track to the losses. This measurement is not necessary but may be useful to provide design information.

d. Hard Surface Resistance to Propulsion:

(1) Prior to conducting the test, the test vehicle should have track tension or tire inflation pressures adjusted to design specifications. Lubrication of the drive-line and running gear should be checked for proper level and lubricant type.

(2) Operate the vehicle for a sufficient period of time to insure that the lubricants are at normal operating temperatures.

(3) To measure resistance to propulsion the vehicle is operated under its own power over a level paved surface at constant speeds in increments of 1 to 4 mph to establish a smooth curve over the complete speed range. The smaller increments of speeds are essential in the low road speed range. Data to be recorded is final drive or axle shaft torque and speed and road speed.

e. Soft Soil Resistance to Towing:

(1) Soft soil towing tests require a prepared soil course having homogeneous strength characteristics that can only be obtained from uniform moisture conditions and processing of the soil as discussed in Annex 1 for drawbar-pull test.

(2) The test follows the same procedure as presented in Steps 1 - 6 for the hard surface tests. However, it is not practical to measure the resistance to towing over the complete speed range of the test vehicle. Measurements at an average speed of two (2) mph and four (4) mph is adequate.

(3) In order to identify soil characteristics, the soil strength and moisture content should be measured as described in Annexes 8 and 9.

f. Soft Soil Resistance to Propulsion:

(1) The soft soil conditions outlined for resistance to towing are desirable.

(2) The same measurements will be taken as for hard surface testing.

(3) Soil characteristics will be defined as indicative for resistance to towing.

VI. DATA ANALYSIS AND PRESENTATION:

The data are presented in the form of a curve relating resistance to towing or propulsion in pounds versus vehicle speed. In the case of hard surface tests, no particular analysis is necessary beyond the comparison of test results with the results of previous tests of similar vehicles.

When analyzing the results of soft-soil tests, it is necessary to establish the effect of the soil on the towing resistance. The contribution of total resistance due to soil approximates the difference between the towing force in soft soil and the hard surface towing force. This same relation holds true for resistance to propulsion.

ANNEX 6: FUEL CONSUMPTION

I. INTRODUCTION:

Vehicle fuel-consumption rate information can be used to: judge the acceptability of a vehicle's off-road performance; determine whether or not a vehicle meets specified consumption rates; and provide the vehicle user with data for computing fuel requirements for tactical operations.

II. DEFINITIONS:

Fuel consumption in this discussion will be expressed in gallons/hour. Measurements will be computed at standard temperature and pressure conditions.

III. PURPOSE:

The purpose of measuring vehicle fuel consumption rate under standard test conditions is to establish vehicle fuel requirements and vehicle range.

IV. APPARATUS:

The determination of fuel quantity used by a vehicle may be accomplished by filling the fuel tank to a given level using an ordinary metering gas pump or by measuring the amount of fuel flowing to the engine during operation. If the metering pump is accurate to within one ounce, the first method is reliable within a one percent error when the consumption rate is at least 10 gallons/hour, and the time duration involved in the test is not less than 1/2 hour. Most gasoline metering pumps are calibrated to measure fluid volume flow. By knowing the temperature of the gasoline at the metering pump and in the fuel tank, the corrected volume (at Standard Temperature and Pressure) and the weight can be computed. Measuring the quantity or rate of fuel flowing to an engine during operation can be accomplished by using a suitable burette arrangement or a flow meter.

A burette arrangement generally has a limited capacity but provides the most accurate determination of the quantity of fuel used. The burette is arranged so that the instant the fuel supply from the vehicle is stopped, the engine begins to draw fuel from the burette. The weight or corrected liquid measure can be computed from the quantity of fuel used from the burette. The fuel consumption rate can be computed by knowing the time taken for the measured fuel quantity to be drawn from the burette.

Several kinds of flow meters are commercially available to measure fuel flow to an engine. A flow meter that will give accuracy within ± 1% should be used.

The selection of a timing device will depend on the proposed length of the test. For a test of less than five minutes duration, an accurate stop watch should be used. For tests of longer duration, an electric timer having an error not in excess of 1/4 second in one minute is adequate.

V. PROCEDURE:

a. Idle Tests:

(1) Make applicable electrical, fuel, and speed regulation adjustments on the engine to meet recommended settings.

(2) Use a burette or flow meter arrangement for measuring the quantity of fuel used.

(3) Operate vehicle at the chosen idle speed until the engine reaches the proper operating temperature.

(4) Measure fuel used during a 5-minute time period.

(5) Compute fuel consumption rate in gallon/hour. State volume measurements at standard temperature and pressure.

(6) Repeat Steps 1 through 5 for all recommended idle speeds.

b. Paved Level Road Tests:

Fuel consumption rate of vehicles carrying rated load under these conditions is an indication of minimum consumption rate or maximum economy. Tests are conducted as follows:

(1) Make electrical, fuel, and speed regulation system adjustments on the engine to achieve maximum economy.

(2) A burette or flow meter can be used to measure fuel consumption rate for these tests.

(3) Operate vehicle until engine reaches proper operating temperature.

(4) Measure fuel used and time required to travel over, at least, a two-mile level paved course.

(5) Establish the fuel consumption rate for at least four speeds in each gear range.

c. Standard Course Tests:

The variation in types of standard test courses allow only a general statement of recommended procedure. Test results should include a detailed description of the courses, such as profile, length, surface material, etc.

(1) Make electrical, fuel, and speed regulation system adjustments on the engine to achieve a reasonable trade-off point between maximum economy and maximum power.

(2) Operate vehicle until engine reaches operating temperature.

(3) Fill fuel tank to pre-established level to permit determination of fuel usage if flow-meter is not used.

(4) With vehicle carrying rated load, determine fuel consumption rate by recording the time required to negotiate the test course. Upon completion of operation on course, refill the fuel tank to the original level and record the amount of fuel used.

ANNEX 7: LOAD DISTRIBUTION AND GROUND PRESSURE

I. INTRODUCTION:

Many of the equations which relate vehicle performance to soil properties require load distribution and ground pressure as fundamental input data. In order to describe test results analytically, knowledge of actual load distribution or gound pressure must be available or else these data must be assumed. The measurement of ground pressure is a difficult process so that it may be preferable to infer pressure from sinkage. If the relation between pressure and sinkage is known for a given soil, it is possible to estimate the ground pressure. An analytical solution based on a pressure computed by this procedure is of limited value since it is based on a circular argument.

II. DEFINITIONS:

a. The term load distribution refers to the division of a vehicle's weight among the running gear elements (road wheels or tires).

b. The average ground pressure is the unit load (lb./in.^{2}) along the soil-running gear interface. The average ground pressure is obtained by dividing the total vehicle weight by the ground contact area of the traction elements.

c. The nominal ground pressure is based on a ground contact area whose length and width are established by agreement.

d. The specific ground pressure is based on actual contact area measured on a hard surface.

III. PURPOSE:

a. In evaluating vehicle suspension systems or predicting soft soil mobility characteristics, it is necessary to determine the static load distribution and the ground pressure. The load distribution influences the life of suspension and running gear parts and can serve as a general guide for the evaluation of a suspension. The effect of load distribution can be considered primarily from a negative viewpoint, that is, an excessive imbalance in weight distribution can produce a significant adverse effect.

b. Ground pressure and load distribution are fundamental to the analytical evaluation of off-road mobility characteristics. The ground pressure distribution must be known in order to properly compute the tractive effort that a vehicle can develop. In addition, the sinkage of a vehicle is directly related to the ground pressure. Since motion resistance is proportional to sinkage, the necessity for the measurement of both load distribution and ground pressure is apparent. It should be pointed out, however, that the measurement of both load distribution and ground pressure may be too difficult to be justifiable on the basis of the value of the data for most routine tests. If the performance of a vehicle differs significantly from predictions and expectations, the measurement of load distribution and ground pressure will produce data on which an explanation can be based.

IV. APPARATUS:

To measure the load distribution of a wheeled vehicle, platform scales can be used. Small, portable scales are available on the commercial market which are specifically designed for the measurement of wheel loads. These devices are rugged and accurate.

The measurement of the load distribution of a tracked vehicle is considerably more difficult than for a wheeled vehicle because of an absence of standard measuring apparatus. If one assumed that the track does not upset the load distribution significantly, it is possible to remove the track and treat the vehicle as if it were a wheeled vehicle. Experience has demonstrated, however, that for the accuracy required, the load distribution can be obtained with the tracks installed.

The measurement of ground pressure is not a direct measurement. The normal procedure is to measure contact area. Ground pressure is then obtained from the contact area and load distribution. Therefore, equipment used for the establishment of ground pressure actually measures contact area. On hard surfaces, the contact area is measured by means of an impression of the tire or track print. The impression can be obtained by covering a section of the tire or track with ink, or paint, and lowering the vehicle onto a sheet of paper placed on the hard level surface. The impression that is left on the paper can be measured by any convenient method to obtain the contact area.

The measurement of contact area in soft soil requires the use of plaster of Paris or any similar material to obtain an impression of the contact surface left in the soil. It is necessary that the soil have cohesive properties in order to use this technique.

V. PROCEDURE:

The load distribution of wheeled vehicles or tracked vehicles with the track removed can be determined by means of platform scales. In order to obtain a correct reading, a separate scale should be used for each wheel.

To obtain a precise measurement of load distribution without removing the track on a tracked vehicle requires the construction of specialized apparatus. However, experience has shown that reproducible readings cannot be obtained by means of any measurement system so far developed because of inherent vehicle characteristics. It is, therefore, suggested that adequate accuracy can be obtained by driving the vehicle onto a platform scale in such a way that the load for each wheel can be determined.

There is no standard procedure for the measurement of ground pressure under a track or a wheel. The measurement of the pressure distribution along the contact length of a wheel is so difficult that it can only be considered as a laboratory procedure. To establish the ground pressure of a vehicle, the ground contact area is measured and the average pressure established by dividing the wheel or track load by the contact area.

In order to measure tire contact area, one of two procedures have been used depending on whether the measurement was made on a soft or hard surface. On hard surfaces the following procedure is followed. The wheel or track is removed from the surface by means of a jack or hoist. The contact surface is coated with ink or paint. Paper is placed on the hard surface and the vehicle lowered onto the paper. The vehicle is lifted and the paper removed. The contact area can be measured by means of a planimeter or any standard approximation techniques for the measurement of irregular area.

To measure the contact area of a wheel in soft soil, a successful procedure has been developed using plaster of Paris to make a cast of the footprint. In order to use this procedure, however, it is necessary to lower the vehicle onto the soil and then lift the vehicle off of the soil. The indentation in the soil is then filled with plaster of Paris and the hardened cast measured to establish the contact area. In order to use this technique, it is necessary that the soil have adequate cohesion to prevent the soil from flowing after the wheel has been removed from the soil.

Because of the large area involved with most tracked vehicles, it is possible to establish the contact area by simply measuring the track "footprint".

The nominal ground pressure is normally used instead of the actual ground pressure. Nominal ground pressure can be calculated under a tracked vehicle by assuming a track length equal to the distance between the centers of the front and rear road wheels.

The nominal ground pressure for tires can be estimated by dividing the load by 0,7 x R x b, where b is the section width and R is the radius of the undeflected tire. (Reference: Project Wheeltrack I, A Joint Comparative Mobility Evaluation, Vol. I, Annex A, Vehicle Mobility Characteristics, ATAC, Detroit, Michigan, 1959 and U. S. Rubber Tire Company, letter dated 21 February 1963).

ANNEX 8: DETERMINATION OF LAND LOCOMOTION SOIL VALUES

I. INTRODUCTION:

Land Locomotion Soil Values are a necessary documentation of vehicle test conditions. Equations describing vehicle mobility are based on soil reactions to loaded wheels or tracks moving over the soil. The soil values define the vertical and horizontal stress-strain relations of soil and establish the relationships between soil reaction and load. If the soil values are known, the performance of any vehicle or concept may be evaluated so that the source of differences in performance between vehicles can be identified.

II. DEFINITION:

The Land Locomotion Soil Values are obtained from two separate tests: a vertical load-sinkage test and a horizontal shear stress-deformation test. The three parameters obtained from the first test, 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.

III. PURPOSE:

The Land Locomotion Soil Values are used for:

a. Documenting soil properties during vehicle tests.

b. Making analytical evaluations of vehicles and vehicle concept performance in selected soil conditions.

c. Providing vehicle design engineers with input data for designing off-road vehicles with a predetermined level of performance.

IV. THEORETICAL BACKGROUND:

The pressure-sinkage relationship of soils resulting from vertical loads producing soil deformation can be described by the equation:

$$p = \left(\frac{k_c}{b} + k_\phi\right) z^n \qquad \text{. . . . . 1.}$$

where: p = the pressure on a footing (psi)

z = the sinkage of the footing (inches)

b = the width of the footing (inches)

k_c, k_ϕ = sinkage moduli

n = sinkage exponent

The horizontal shear stress-deformation relation produced by a horizontal deformation of soil can be described by a modification of Coulomb's equation. An expression describing the relation between shear stress and deformation is:

$$s = (c + \tan \phi)(1 - e^{-j/K}) \quad \text{. . . . .} \quad 2.$$

where: s = shear stress (psi)

p = normal pressure (psi)

j = soil particle deformation (inches)

c = cohesion (psi)

ϕ = angle of internal friction (degrees)

K = tangent modulus 1/in.

V. APPARATUS AND PROCEDURES:

a. Load-Sinkage Equipment:

A schematic of typical equipment required to obtain a load-sinkage curve is shown in Fig. 8-1. This equipment shown includes a hydraulic cylinder, a rotary potentiometer or helipot, a load cell or transducer, two sinkage footings, and an X-Y Plotter. Any device which permits the recording of the load-sinkage relation is adequate but experience has shown that the equipment described produces the most reliable test results.

The load-sinkage device should have the following capabilities:

(1) The loading device, i.e., the hydraulic cylinder, should be capable of a minimum of 35 psi footing pressure, a

sinkage rate of 60 in./min., and a total travel of 18 inches.

(2) The sinkage measuring potentiometer should have a minimum travel of 18 inches and an accuracy of ± 2%.

(3) The load cell should measure the load with an accuracy of ± 2%.

The load-sinkage curves are obtained by using the hydraulic cylinder to force a footing into the soil. The load and sinkage are continuously measured and recorded on the X-Y plotter.

b. Load-Sinkage Test Procedure: The load-sinkage test should be conducted as follows:

(1) By means of trial sinkage tests, select a circular footing which will sink at least 4 inches when loaded to 35 psi. If the trial tests indicate that the minimum plate size (2-inch diameter) is required to achieve this result, discontinue the test. If the soil is so strong that the minimum plate is required, the sinkage test has little significance.

(2) Remove the surface vegetation directly under the sinkage footing.

(3) Lower the sinkage footing to the soil level. The footing must be in full contact with the soil before soil deformation is started. When an uneven contour is present, the soil must be smoothed with care taken to avoid compaction which would affect the soil strength.

(4) Apply the load and record load and sinkage on the X-Y plotter. The maximum load shall be limited to that which results in 35 psi footing pressure or 12 inches of sinkage, whichever occurs first.

(5) Retract the cylinder, lifting the footing clear of the soil, and move a distance of at least five times the footing diameter and repeat Steps 1 through 4.

(6) Steps 1 through 5 must be repeated using two footings with a minimum size difference of 1 inch diameter for footings less than seven inches in diameter and a minimum of two inches for footings greater than seven inches in diameter.

c. Load-Sinkage Data Reduction:

Typical data, as recorded in the field on an X-Y Plotter are shown in Fig. 8-1. The soil parameters k_c, k_ϕ, and n can be obtained as follows:

(1) Plot the pressure (p) and sinkage (z) data for the footings on logarithmic paper, Fig. 8-2.

(2) Draw parallel straight lines through the data points of sinkage two inches and greater.

(3) The sinkage exponent 'n' is the slope of this line.

(4) Extend the straight lines until they intercept the one-inch sinkage line denoted as a_1 and a_2 as shown in Fig. 8-2. a_1 and a_2 are identical with the respective quantities of $\frac{k_c}{b}$ + k_ϕ. Equation (1) can be written:

$$a_1 = \frac{k_c}{b_1} + k_\phi \; ; \quad a_2 = \frac{k_c}{b_2} + k_\phi \qquad \ldots\ldots 3.$$

where b_1 and b_2 are the radii of the sinkage footings and k_c, and k_ϕ the sinkage moduli.

By solving Equation 3 simultaneously, the unknown k_ϕ and k_c values can be determined as follows:

$$k_\phi = \frac{a_2 b_2 - a_1 b_1}{b_2 - b_1}$$

$$k_c = \frac{(a_1 - a_2)\; b_2 b_1}{b_2 - b_1}$$

In case a straight line cannot be drawn through the data after they have been plotted on logarithmic paper, then the straight line should be drawn through the data that are in the same range of ground pressures as the vehicle under consideration. This method will then reflect the proper soil strength for that vehicle.

In a measurement type test, such as drawbar pull, the location of the load-sinkage tests should be as close as possible to the vehicle test lane to insure that the measured soil strength is representative of the soil in which the test is conducted.

When a large area, rather than a single test lane, is to be classified, a sufficiently large number of measurements must be taken to produce a 'stable' standard deviation. A 'stable' standard deviation is taken as the standard deviation associated with a sample size such that a plot of the standard deviation versus sample size approaches a constant value. An alternate approach to the treatment of data for an area is to record all measurements for a given plate size in one plot. When a definite trend of values is identifiable, an average line can be drawn and this average taken as the 'mean value' for the plate.

d. Shear Test Equipment:

A typical shear test device is shown schematically in Fig. 8-3 and consists of a power source, a transmission, a shear head shaft, a shear head, a normal load applicator, and associated instrumentation.

The shear device should have the following capabilities and features:

(1) The power source-transmission combination should rotate the shear head at approximately 10 rpm.

(2) The shear head shaft must have complete freedom of motion in the vertical direction at all times.

(3) The cylindrical mount should be shaped to minimize soil contact with the mount when sinkage is encountered during a test.

(4) The normal loading system should maintain a constant load throughout the test.

(5) The inside diameter of the shear annulus should be a minimum of 5 inches. An annular ring with dimensions of inside diameter of 5.25 inches, outside diameter of 7.30 inches and area of 20 square inches, is suitable for shear tests in most soils.

The shear head is comprised of a cylindrical shaped mount and an annular ring, Fig. 8-4. The annular ring is grousered to assure soil-on-soil failure strength. When adhesion between rubber on steel and soil is to be measured, the face of the ring is covered with the rubber or no grousers are used.

Instrumentation needed for a shear test consists of:

(1) A system to provide a measure of the horizontal shear stress beneath the annular ring.

(2) A system to provide a measure of the horizontal deformation beneath the annular ring.

(3) A recording device.

A torque sensing element is used to obtain a signal which is proportional to the shear stress. An angular position sensing element is used to obtain a signal which is proportional to the soil deformation. An X-Y plotter is normally used to record the two signals.

e. Shear-Deformation Test Procedure:

Shear tests are conducted to record horizontal stress-deformation relationships. Determination of c, ϕ and K requires a number of shear tests, each with different normal loads. The normal loads should produce pressures over a minimum range of 0 to 10 psi but should include expected vehicular ground pressures. All the tests are conducted in the same manner except for the magnitude of the normal load. The sequence of steps of a test is as follows:

(1) Remove the surface vegetation directly below the annular ring.

(2) Remove any foreign material from the annular ring.

(3) Apply the desired normal load.

(4) Adjust recording instrument.

(5) Rotate the shear head until the shear stress reaches a constant value or until a constant rate of increase in shear head sinkage occurs. This constant value is defined as the ultimate shear stress.

(6) Move to a new site which is at least three outside annular diameters removed and repeat Steps 1 through 5 with a different normal load. The procedure should be repeated to obtain a set of shear readings consisting of four different normal loads. A Minimum of three sets of shear readings should be taken.

f. Shear-Deformation Data Reduction:

When a shear stress-deformation curve shows a definite leveling trend, ultimate shear stress is defined as shown in Fig. 8-5. However, under some soil conditions, the shear stress-deformation curve does not level off, but eventually reaches a constant rate of increase. In the latter case, the shear stress at one-half a revolution of the shear head is arbitrarily defined as the ultimate shear stress.

To compute c and ϕ, plot the ultimate shear stress as a function of normal pressure as shown in Fig. 8-6. Draw the best straight line through the array of points. The intersection of the line and shear stress axis is the cohesion c, and the slope of the line is the tangent of the angle ϕ.

The tangent modulus of deformation K is defined as the abscissa of a point determined by the intersection of a line drawn through the origin and tangent to the beginning of the shear stress-deformation curve, and a line drawn tangent to the straight portion of the end of the shear stress-deformation curve, Fig. 8-5.

The parameter K can be determined from a shear stress-deformation curve that levels off or from one that reaches a constant rate of increase. The dimension of K is inches.

To determine representative soil values of an area, the number of samples should be established by using the 'stable' standard deviation method. This is recommended since it is difficult to obtain a large number of repetitions of the shear test.

When excessive sinkage of the shear head occurs, the sides of the cylindrical mount often come in contact with the soil. The soil in contact with the cylindrical mount increases the rotational resistance encountered by the shear head, and an erroneous value of the ultimate shear stress is obtained.

Assuming the rotational resistance encountered by the cylindrical mount in contact with the soil increases linearly with increasing sinkage, a correction factor can be determined and applied to the experimental results. The correction factor is determined in the following manner.

(1) Determine the ultimate shear stress S_{s1} at the soil surface. This can be accomplished by using a very small normal load which will give low pressure.

(2) After completing a shear test in which the shear head has sunk to a depth of approximately one-half the height of the cylindrical mount, reduce the normal load to the magnitude used in Step 1, but do not disturb the position of the shear head. Determine the indicated shear stress S_{s2} at this position with the reduced normal load.

(3) The data from Steps 1 and 2 are then plotted as in Fig. 8-7.

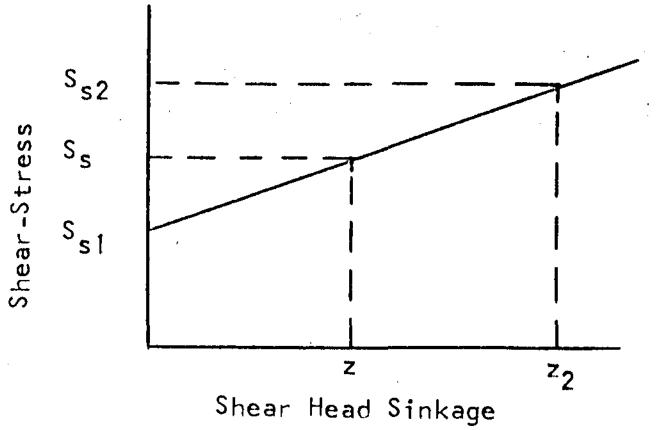


Fig. 8-7

The sinkage, z_2, is that which occurred in Step 2. The change in shear stress between a minimum load at the soil surface, Step 1, and a minimum load at sinkage z_2, Step 2, is designated S_s. It is assumed that the increase in torque required to rotate the shear head is linear with sinkage. Therefore, for any shear head sinkage between 0 and z_2 inches the measured shear stress should be reduced by the amount in Fig. 8-7 corresponding to the measured sinkage. For example, suppose the shear head sinkage was equal to z inches. Then the corresponding shear stress S_{s2} psi should be subtracted from the measured value to get the corrected shear stress.

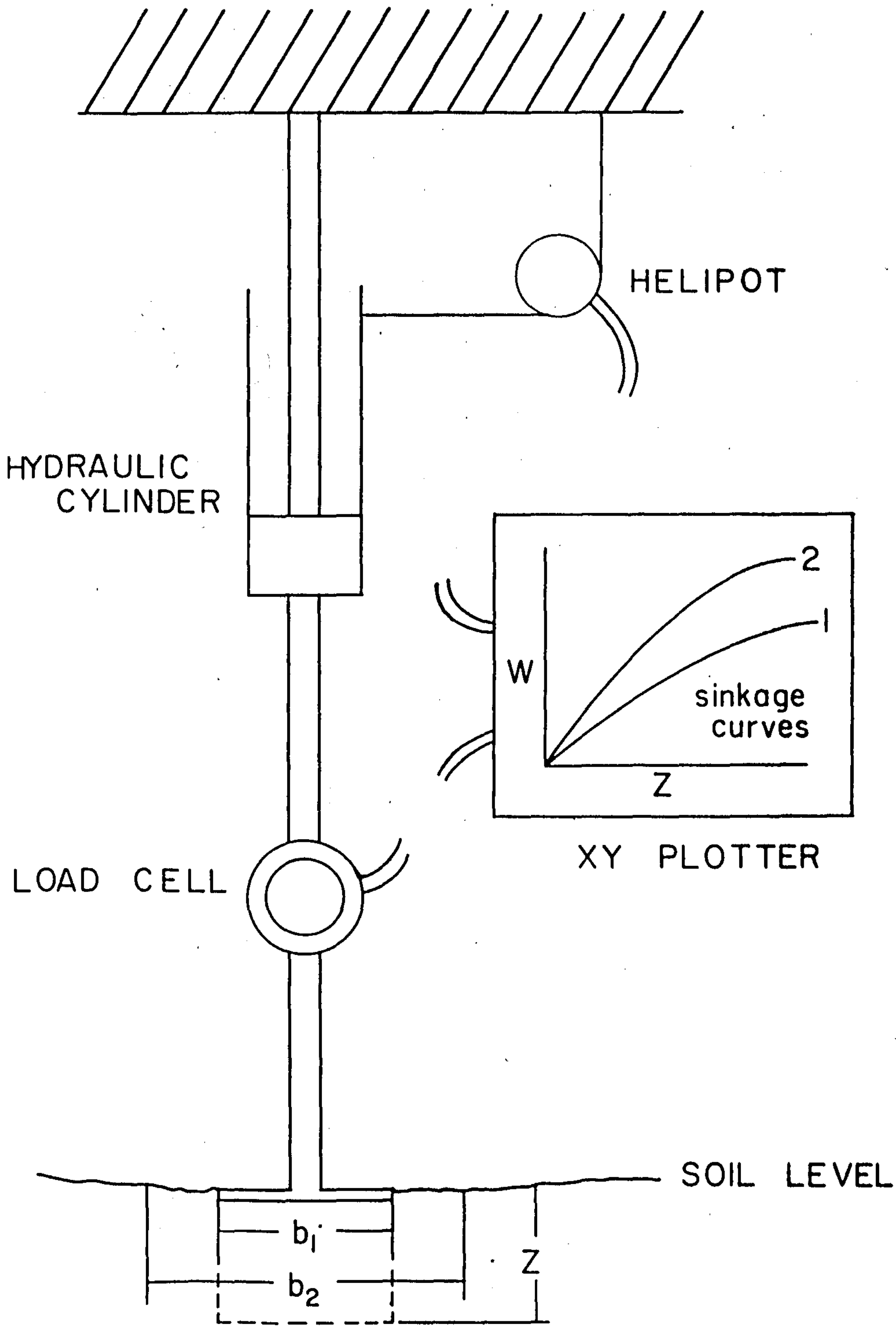


FIGURE 8-1.

Schematic of Equipment Required to Obtain a Load-Sinkage Relation.

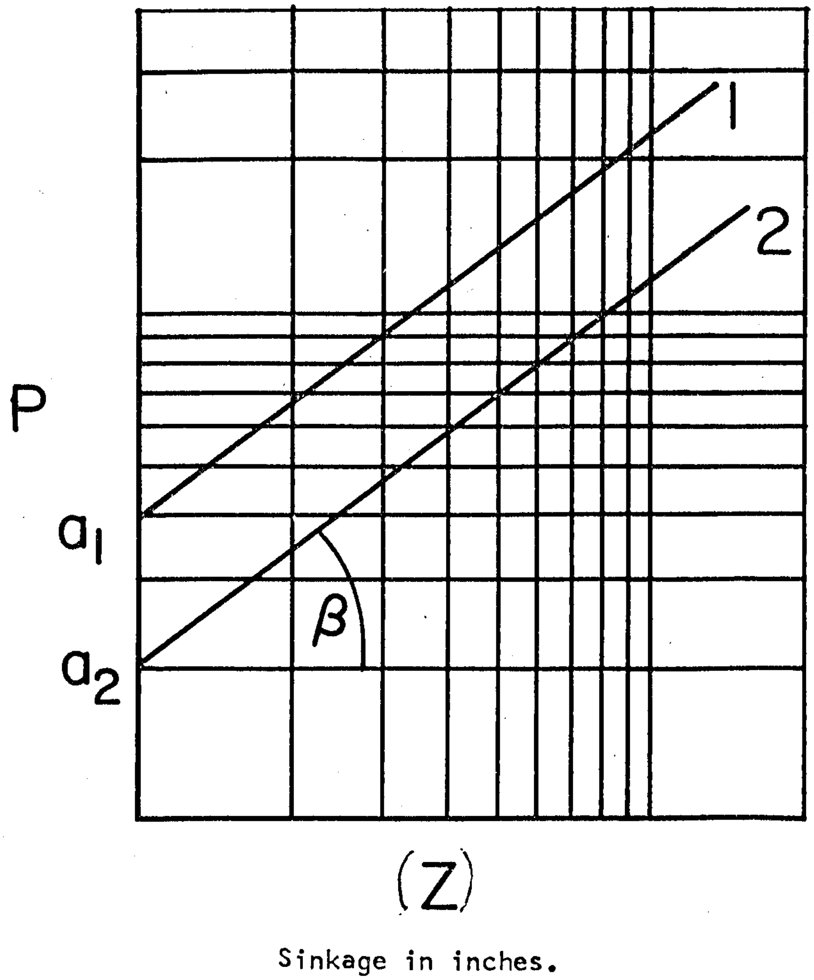


Fig. 8-2: Pressure-Sinkage Relation for Two Different Sized Plates.

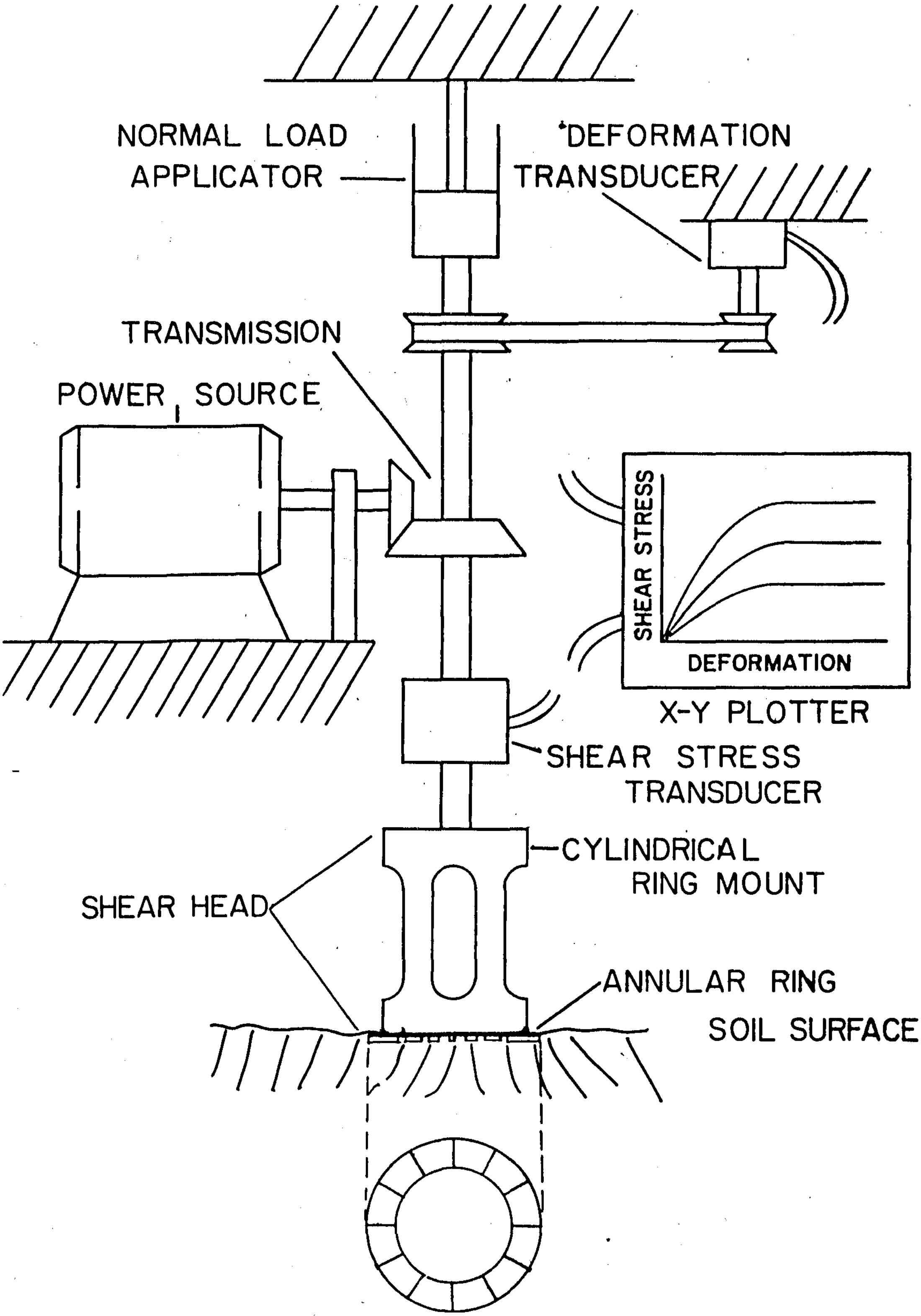


FIG. 8-3. SCHEMATIC OF A SHEAR TEST DEVICE

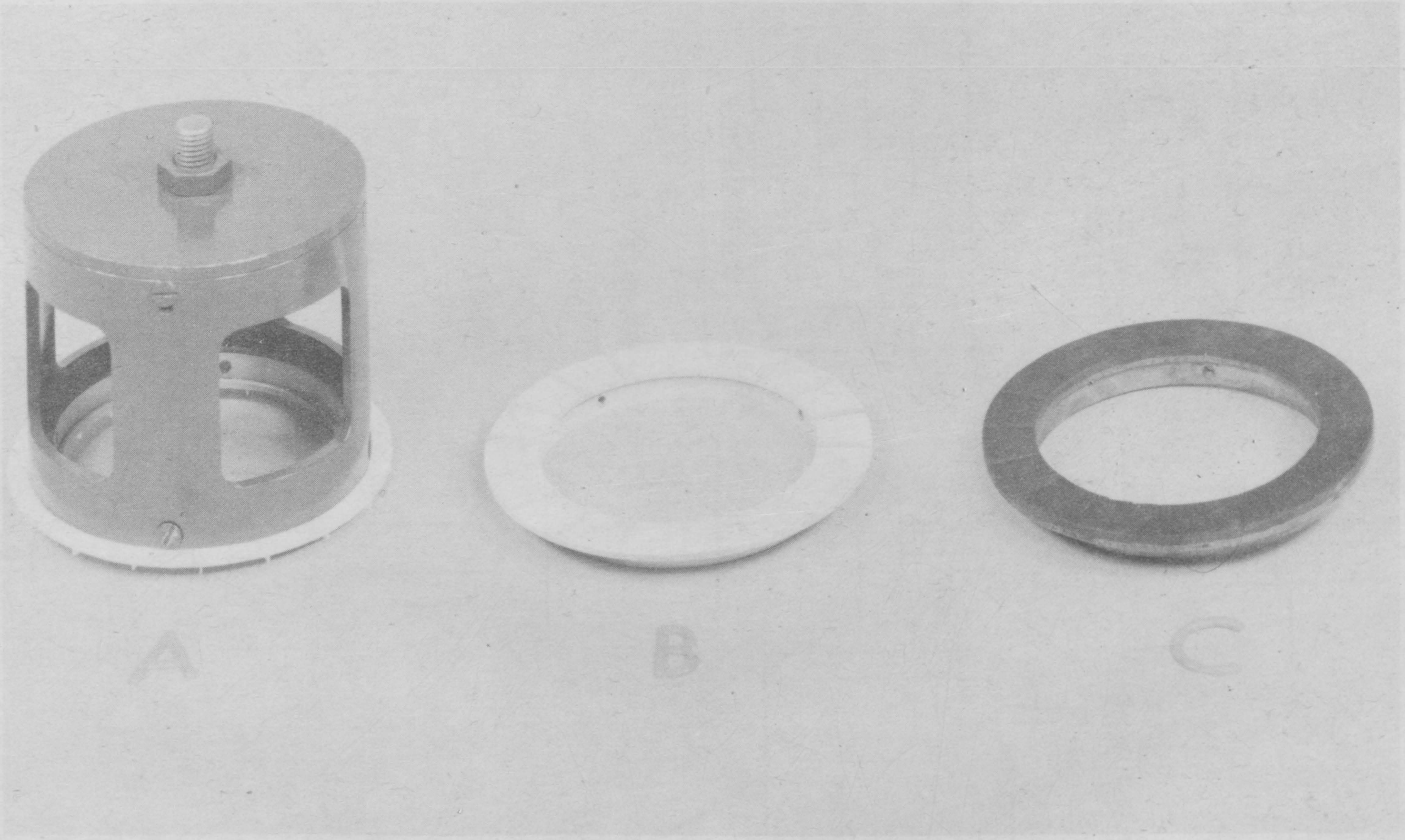


Fig. 8-4. Shearhead Components Parts.

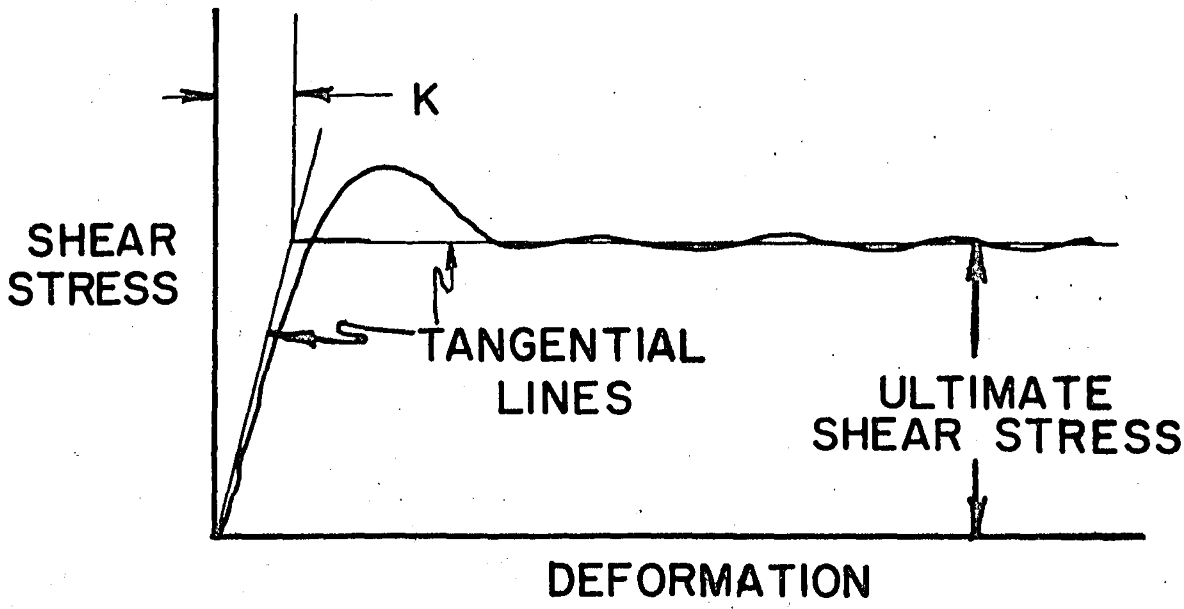


FIG. 8-5. ULTIMATE SHEAR STRESS AND K

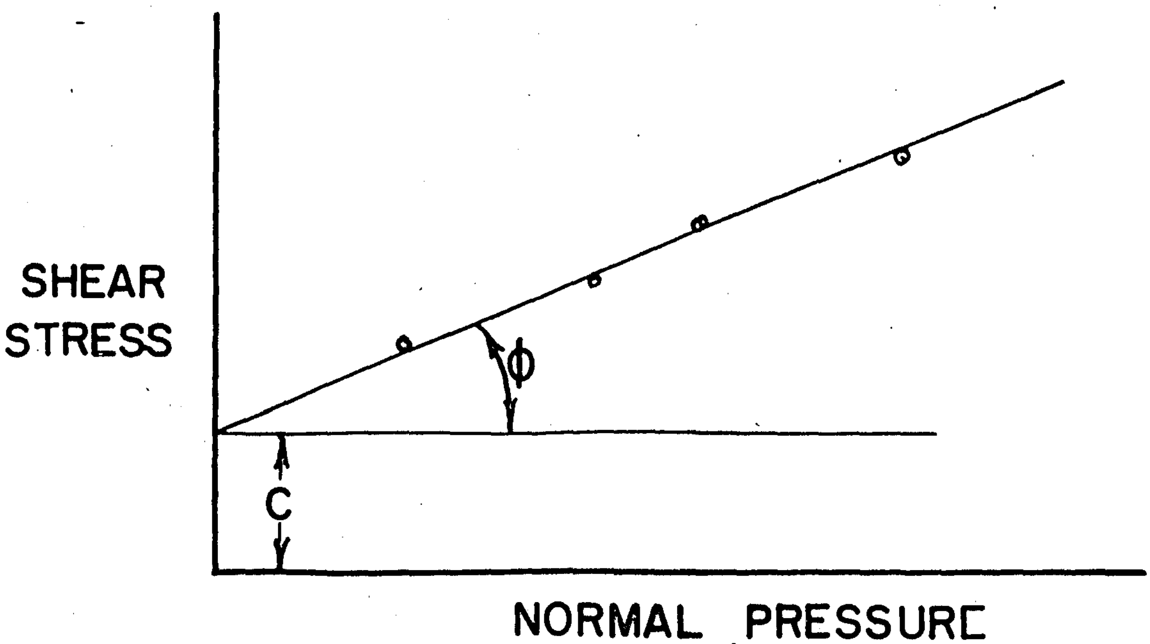


FIG. 8-6. DETERMINATION OF C AND φ

ANNEX 9: DETERMINATION OF WES SOIL PARAMETERS

I. INTRODUCTION:

The WES soil trafficability prediction method is based on the strength that a soil will develop under traffic. The method includes a determination of the effects of soil on a go - no go basis for 50-pass traffic for fine-grained soil and 1-pass traffic for coarse-grained soil, and in terms of drawbar-pull and slope-climbing ability. The soil parameter has also been used to develop a soil classification scheme and a mapping scheme for soil trafficability purposes. The equipment used to measure soil strength and the techniques for evaluating soil trafficability are discussed briefly in this Annex. Detailed descriptions thereof are contained in Department of the Army Technical Bulletin ENG 37, Soil Trafficability, U. S. Government Printing Office, Washington, D. C., July 1959; and WES Technical Memorandum No. 3-240, 14th Supplement, "Trafficability of Soils, A Summary of Trafficability Studies Through 1955", Vicksburg, Mississippi, December, 1956.

II. DEFINITIONS:

Terms used in connection with WES soil trafficability studies are as follows:

a. Soil terms:

(1) Fine-grained soil: A soil of which more than 50 per cent of the grains, by weight, will pass a No. 200 sieve (smaller than 0.074 mm in diameter).

(2) Fines: Grain sizes that will pass the No. 200 sieve (smaller than 0.074 mm in diameter).

(3) Coarse-grained soil: A soil of which more than 50 percent of the grains, by weight, will be retained on a No. 200 sieve (larger than 0.074 mm in diameter).

(4) Sand: A coarse-grained soil with the greater percentage of the coarse fraction (larger than 0.074 mm) passing the No. 4 sieve (4.76 mm).

(5) Sand with fines, poorly drained: A sand that contains some fines and is slow-draining when wet. Such sands behave similarly to wet, fine-grained soils under vehicular traffic.

(6) Liquid limit: The liquid limit is generally conceded to represent the moisture content at which the characteristics of a mixture of soil and water change from plastic to liquid.

(7) Plastic limit: The plastic limit is generally conceded to represent the moisture content at which a mixture of soil and water begins to take on plastic properties (i.e., undergoes appreciable deformation with little change in volume).

(8) Plasticity index: The numerical difference between the liquid and plastic limits. The numerical value of the plasticity index is generally a good indication of the plasticity or clayeyness of a soil; highly plastic clays generally have high plasticity indexes, less plastic clays have lower plasticity indexes.

(9) Moisture content: The ratio, expressed as a percentage, of the weight of water in the soil to the weight of the solid particles.

(10) Density: The unit weight in pounds per cubic foot. Unless specifically stated otherwise, the density is the dry unit weight.

b. Trafficability terms:

(1) Bearing capacity: The ability of a soil to support a vehicle without undue settlement.

(2) Traction capacity: The ability of a soil to provide sufficient resistance between the soil and the tread or track of the vehicle to furnish the necessary forward thrust.

(3) Critical layer: The layer of soil that is regarded as being most pertinent to establishing a relation between soil strength and vehicle performance. For freely draining or clean sands, this is usually the 0- to 6- in. layer. In fine-grained soils and in sands with fines, poorly drained, it is usually the 6- to 12- in. layer. However, the critical layer may vary with weight of vehicle and soil strength profile.

c. Strength terms:

(1) Cone Index (CI): An index of the shearing resistance of soil obtained with the cone penetrometer. The cone index is considered to be a dimensionless number representing the resistance of a medium to penetration of a 30-degree, right-circular cone of 0.5 sq. in. base area. The number, although considered dimensionless, is actually the number of pounds of force exerted on the handle divided by the area of the cone base in square inches.

(2) Remolding Index (RI): A ratio that expresses the change in strength of a fine-grained soil or a sand with fines, poorly drained, that may occur under traffic of a vehicle. (The procedures used to obtain this value are described in paragraphs 8 and 9.)

(3) Rating Cone Index (RCI): The product of the measured cone index and remolding index for the same layer of soil. This index is valid only for fine-grained soils and for sands with fines, poorly drained.

d. Vehicle terms:

(1) Pass: One trip of the vehicle over the test course.

(2) Immobilization: For self-propelled vehicles, failure to complete a substantial number of passes (50) across a test course. For trailers, sinkage to the extent that the axle or under carriage drags prior to completing a substantial number of passes (25).

(3) Towed load: A constant load applied at the drawbar of a vehicle being tested.

(4) Towing force: The force required to move a towed load at a constant speed.

(5) Vehicle Cone Index (VCI): The minimum cone index that will permit the vehicle to complete 50 passes.

(6) Mobility Index: A dimensionless number which results from a consideration of certain vehicle characteristics.

III. PURPOSE:

The WES indices (VCI and RCI) permit evaluating vehicle performance in terms of minimum soil strength required to permit a vehicle to successfully complete a prescribed number of passes on level soil, drawbar-pull, and slope-climbing ability.

IV. EQUIPMENT AND TEST PROCEDURES:

A description of the equipment used to obtain soil strength measurements is given in the following paragraphs:

a. Cone Penetrometer:

(1) Equipment: This is a field instrument (Fig. 9-1)

consisting of a 36 in. long shaft with a 30-degree cone of 1/2 sq. in. base area mounted on one end and a proving ring with dial gage and handle mounted on the other end. The force required to move the cone at a constant rate through a plane of a given material is indicated on the dial inside the proving ring. This force is considered to be an index of the shearing resistance of the penetrated material and is called the cone index of the material in that plane. A capacity load of 150 lb. deflects the ring 0.1 in. and gives a cone index reading of 300.

(2) Procedures: The procedures for measuring cone index are as follows:

(a) Zero the dial indicator while the instrument is suspended by its handle.

(b) Place the cone point on the ground surface and position with hands on the handle as shown in Figs. 9-2a and 9-2b.

(c) Apply force on the handle until a steady downward movement of 6 ft./min. is achieved. The instrument should be vertical at all times.

(d) Take the first reading at the surface when the base of the cone is flush with the ground surface and at 3 in. vertical increments to a depth of 18 in., and then at 6 in. vertical increments to a depth of 30 in., when possible. When the soil strength exceeds the capacity of the instrument or the maximum reading which an instrument operator can obtain, a plus sign is indicated by each reading.

(3) Data Reduction: An example of a convenient field data sheet is shown in Fig. 9-3. At each site a number of readings are required to obtain a meaningful average strength value. At least 10 sets of CI measurements are required to characterize a small area properly. In averaging CI a plus sign is placed after the average value if one or more readings exceed the maximum of the instrument operator or the instrument itself. After averages have been determined for the individual depths measured, averages are determined for the critical layer using all the readings taken within that layer. For example, the 6-, 9-, and 12-in. readings are used to obtain an average for the 6- to 12- in. depth.

b. Remolding Tests: The equipment and procedures used to perform a remolding test are described in the following paragraphs:

(1) Equipment: The following equipment is required to perform this test:

(a) A piston-type sampler (Fig. 9-4) for use in securing soft soil samples. The design of the sampler is such that constant-volume samples can be taken; a constant can be used to obtain density of samples quickly.

(b) Remolding cylinder of the same I.D. as the soil sampler mounted vertically on a base.

(c) A cone penetrometer with an 18 in. shaft having 1 in. markings for the first 6 in. and markings at 6 in. intervals thereafter.

(d) A 2-1/2 lb. drop hammer which travels 12 in. on an 18 in. section of a cone penetrometer shaft fitted with a circular foot on one end and a handle on the other end.

(2) <u>Procedures</u>: The procedures to be used are as follows:

(a) Set the soil sampler in a vertical position, unlock the piston rod by turning the knurled hand counterclockwise (Fig. 9-5a). Place one hand on one end of the horizontal handle and with the other hand grasp the disk handle on top of the piston rod and force the sampler at a uniform rate into the soil until a 6 in. long sample is obtained. Lock the piston rod by turning the knurled handle, twist the sampler, and remove the sampler from the soil.

(b) Unlock the piston rod and carefully extrude the soil sample from the sampler into the remolding cylinder mounted on the base by pushing downward on the disk handle (Fig. 9-5b). The sample in the remolding tube is pushed to the bottom with the drop hammer.

(c) Measure cone indices of the soil in the tube at the surface of the soil and at 1 in. vertical increments to a depth of 4 in. (Fig. 9-5c). If at least three readings cannot be obtained with the 1/2 sq. in. end area cone, resample and use the 0.2 sq. in. end area cone and a 3/8 in. diameter shaft. If the soil sampled is fine grained, place the foot of the drop hammer on the soil in the tube and allow the hammer to "free fall" from a height of 12 in. a hundred times (Fig. 9-5d). Remeasure CI as above. If the soil is coarse grained with fines, the sample is remolded by bouncing on firm ground the remolding cyclinder and base with the sample inside 25 times from a height of 6 in. Remeasure the cone indices as above. Care must be exercised in remolding coarse-grained soils with fines to ensure that water is not excreted from the remolding cylinder during the remolding process. This can be accomplished by placing a small (about 1 in. high) clay plug on the bottom of the remolding tube after the remolding tube has been loaded with a test specimen and inserting a rubber stopper in the top of the tube prior to bouncing the tube.

(d) Remolding index (RI) tests are measured for at least the critical layer, which for most military vehicles is the 6- to 12 in. depth. Sampling points are selected by examining the cone index data. The portion of the test site that has the lowest cone index profile is selected fro remolding test. If moisture content and density samples are taken, they should be taken within close proximity (about 1 ft.) of the remolding sampling point. If the next 6 in. layer of soil is weaker than the layer considered to be critical, remolding index is also measured for the subsequent 6 in. soil layer. RI measurements are made only in fine-grained soils or in poorly drained wet sands containing some fines. It is not necessary to measure RI in clean sands such as those normally found in deserts and beaches.

(3) Data Reduction:

(a) The field data form shown in Fig. 9-3 is convenient for recording and tabulating data. The RI is determined by dividing the sum of the five CI readings taken after remolding by the sum of the five readings taken before remolding. A CI value of 300 or the maximum reading indicated on the cone penetrometer dial is assigned to each layer that cannot be penetrated. If two or more CI readings cannot be obtained in the soil placed in the remolding cylinder, an RI value of 1.00+ is assigned to that soil layer and indicated as the average RI.

(b) For each RI determination, at least two tests are run on soil samples taken from an area that does not exceed about 1 sq. ft. If the difference in RI values obtained in the first two tests exceeds 0.12, an additional test is run. If the value of the third test is within 0.12 range of either of the two previous tests, these two tests are used to determine an average RI, otherwise, all three tests are used to obtain an average RI.

V. USE OF SOIL STRENGTH MEASUREMENTS FOR TRAFFICABILITY PURPOSES:

a. Fine-grained soils and sands with fines, poorly drained:

(1) In fine-grained soils and in sands with fines, poorly drained, CI and RI measurements are necessary to define soil trafficability. The CI provides an index of the in-situ or undisturbed shear strength of the soil prior to vehicular traffic.

It, by itself, is inadequate for predicting the soil strength during or after repeated traffic by a vehicle because repetitive traffic invariably remolds the soil, thus altering its strength. The probably effect of vehicular traffic on soil strength is obtained from the RI, which indicates the direction and magnitude of the strength change that can be anticipated under vehicular traffic. An RI less than 1.00 denotes a strength loss as a result of remolding; and an RI greater than 1.00 indicates a gain in strength. For example, a wet silt may retain only 25 percent of its undisturbed strength once it is subjected to repetitive vehicular traffic.

(2) The trafficability of fine-grained soils and sands with fines, poorly drained, is therefore defined in terms of a value called the rating cone index (RCI) which is the product of the CI and the RI for the same soil layer. In general, the soil layer between the 6- and 12 in. depths is critical for most military vehicles operating in such soils. However, the depth of the critical layer varies with the strength profile of the soil and the vehicle type and weight (See references cited in paragraph 1).

b. Coarse-grained soils:

For coarse-grained soils or clean sands, CI measurements alone are adequate to quantify trafficability. Usually, clean sands possess adequate strength to support vehicles without critical sinkage, but because of the loose nature of surface sand, traction is the limiting factor. In most clean sands the first pass is critical, and subsequent passes are made with less difficulty. For these reasons, the soil layer between the surface and the 6 in. depth is considered the critical layer for most military vehicles.

VI. EVALUATION OF SOIL TRAFFICABILITY:

a. Fine-grained Soils and Sands with Fines, Poorly Drained:

(1) The ability of a given vehicle to complete 40 to 50 passes traveling in a straight-line path over a level area or to execute severe maneuvers in fine-grained soils or sands with fines, poorly drained, is assured if the RCI of the soil in the critical l yer in that area is equal to or greater than the vehicle cone index (VCI) assigned to that vehicle. In general, an RCI equal to 75 percent of the VCI indicates sufficient soil

strength to permit one or two straight-line passes of the vehicle or severe maneuvering for one pass. If the RCI is greater than the VCI of a given vehicle, the additional traction resulting from the excess soil strength can be used to accelerate the vehicle, negotiate slopes, or tow a load.

(2) The VCI's for most military vehicles are tabulated in several publications (See references cited in paragraph 1). The referenced publications also contain formulas for computing mobility indexes and means of relating them to VCI's, and the relation of drawbar-pull, slope, and towing force to soil strength. Military vehicles also have been placed in categories on the basis of the VCI requirements to aid in classifying vehicle performance, as shown in the following tabulation. Each category shown identifies the minimum soil strength required for operations of the vehicles in that category.

Category	VCI Range	Standard Military Vehicles
1	20-29	M29 Weasel, M76 Otter, and Canadian Snow-Mobile are the only known military vehicles in this category.
2	30-49	Engineer and hi-speed tractors with comparatively wide tracks and low contact pressures.
3	50-59	Tractors with average contact pressures, tanks with comparatively low contact pressures, and some trailed vehicles with very low contact pressures.
4	60-69	Most medium tanks, tractors with high contact pressures, and all-wheel-drive trucks and trailed vehicles with low contact pressures.
5	70-79	Most all-wheel-drive trucks, a great number of trailed vehicles, and heavy tanks.
6	80-89	A great number of all-wheel-drive and rear-wheel drive trucks, and trailed vehicles intended primarily for highway use.

Category	VCI Range	Standard Military Vehicles
7	100 or greater	Rear-wheel-drive vehicles and others that generally are not expected to operate off-roads, especially in wet soils.

(3) The range of RCI of maximum interest from the trafficability standpoint is from about 15 to 100. Only a few lightweight, tracked military vehicles, such as the Weasel and the Otter, and special-purpose, tracked commercial vehicles can negotiate areas for which the RCI for the critical layer is as low as 20 to 25. Likewise, only a few special vehicles with high-ground-contact pressures require soil strength greater than 100 RCI to permit "going". These limits usually make it possible to classify large land areas as being above or below the critical range for a given category of vehicles.

(4) The probable vehicle performance in terms of slope-climbing ability or drawbar-pull that can be expected when the soil strength requirements exceed the minimum required for a given vehicle can be obtained from a relation of these performance parameters, vehicle characteristics, and excess soil strength expressed as RCI. Force required to tow vehicles also can be related to RCI and vehicle characteristics (Figs. 9-6 and 9-7). These relations, along with soil strength (RCI) and minimum soil strength required (VCI), can be used to determine the load which a prime mover can successfully tow.

b. Coarse-Grained Soils:

Studies being conducted on clean sands have not yet progressed to the point of quantifying trafficability. Results thus far indicate that tracked vehicles usually experience little or no difficulty in traversing level clean sand areas. The effect of soil strength on vehicle performance (in terms of drawbar-pull and slope-climbing ability) of a given tracked vehicle is small; however, a significant difference in performance exists among vehicles having different types of track systems (Fig. 9-8). A wide range in wheeled-vehicle performance occurs as a result of changes in tire pressure, number of tires, and tire size. Examples of the effect of tire pressure and tire size on vehicle performance are given in Figs. 9-9 and 9-10, respectively.

VII. DATA REQUIREMENTS FOR SOIL CLASSIFICATION PURPOSES:

In addition to the soil strength measurements, site data and additional soil data are required for the establishment of a meaningful soil classification scheme for soil trafficability purposes. These requirements are discussed in the following paragraphs:

a. Site Description Data:

Information on location of test site, topographic position, slope, land use, vegetation, depth of surface water, and depth to water table is required. Those items that require clarification are discussed in the following paragraphs.

(1) Topographic Position:

A topographic classification consisting of 13 categories is used to identify the topographic position of each site. These categories are: upland flat (UF); upper slope (US); middle slope (MS); lower slope (LS); terrace (T); terrace slope (TS); bottomland flat (BF); bottomland depression (BD); natural levee (NL); stream bottom (SB); tidal flat (TF); drainage ditch (DD); and beach (B). In addition, sites that are surrounded by dikes to retain surface water for rice-field irrigation are identified as paddy (P). All of the above-listed categories except TF, DD, P, and B are illustrated in Fig. 9-11.

(2) Slope:

Slope is measured to the nearest percent with a suitable instrument.

(3) Vegetation:

Vegetation observations are recorded in terms of general classes such as grass, brush, and trees, supplemented with height and density information where trees are encountered. Information as to the size at breast height and spacing are recorded. For cultivated areas, the type of crop is indicated.

(4) Surface and Groundwater:

The depth of surface water at a test site and the depth to the water table as indicated by sample holes are observed and recorded.

c. Soil Data:

Soil data collected to define characteristics pertinent to trafficability studies should include soil depth, organic-matter content, soil classification, moisture content, density, and specific gravity. Representative bulk soil samples are taken from the 0- to 6- in. and 6- to 12- in. layers, and occasionally from the 12- to 18- in. layer, for laboratory determination of organic content, grain-size distribution, Atterberg limits, and specific gravity.

d. Organic-Matter Content:

Organic-matter content is determined by means of a modified Walkley rapid-dichromate oxidation[1*], and the values are expressed as percentages by weight. When the organic-matter content is determined to be more than 5 percent by the Walkley method, the loss-on-ignition method is used, following modified procedures of the Association of Official Agricultural Chemists.[2]

e. Grain Size, Atterberg Limits, and Specific Gravity:

Standard U. S. Army Corps of Engineers Laboratory procedures are used in determining these soil properties, except that the liquid limit of some low-plasticity or nonplastic soils cannot be determined with the standard procedures, and a modified procedures is used to make tests on these soils.

f. Soil Classification:

The U. S. Army Corps of Engineers Unified Soil Classification System (USCS) and the U. S. Department of Agriculture (USDA) Soil Classification System are used. The procedures followed in classifying soil are discussed in detail in References 3, 4, and 5. The USDA soil textural classification is given in Figure 9-12. A summary table of the USCS is given in Table 9-1. Auxiliary laboratory procedures are given in Table 9-2.

g. Soil Moisture Content-Density Samples:

A 2- in. diameter trafficability sampler is used to obtain moisture content-density samples. When the soil is too firm to allow penetration in 3- in. vertical increments with the trafficability sampler, a disturbed soil sample for the prescribed depths is taken for moisture content determination. At each site, one sample each for moisture content-density determination is taken from the same soil column at depth increments of 0 to 3, 3 to 6, 6 to 9, and 9 to 12 in. Occasionally samples are taken from the 12- to 15- in. and 15- to 18- in. depths.

*Raised numerals refer to similarly numbered items in List of References at end of this Annex.

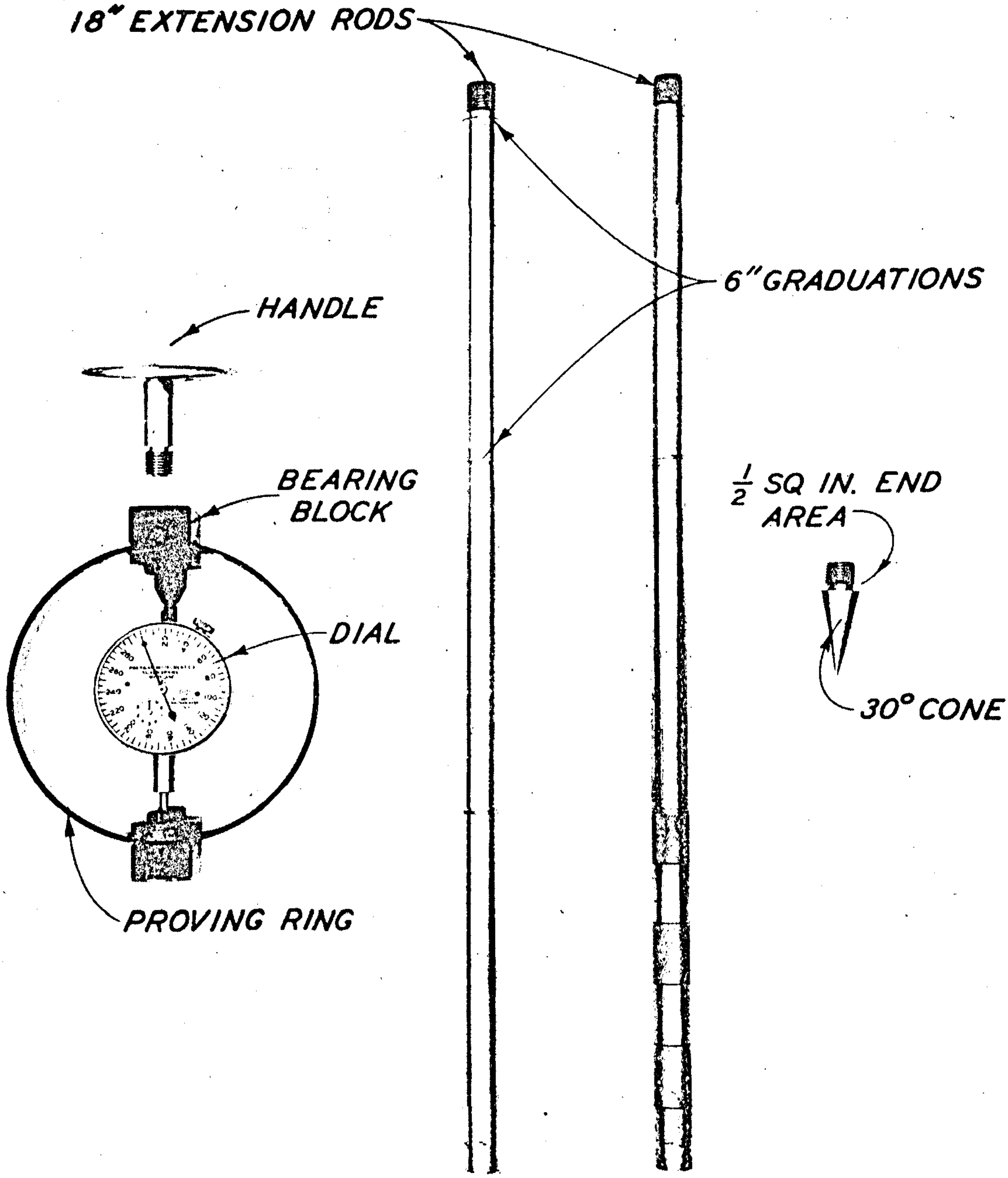


Fig. 9-1: Cone Penetrometer Disassembled.

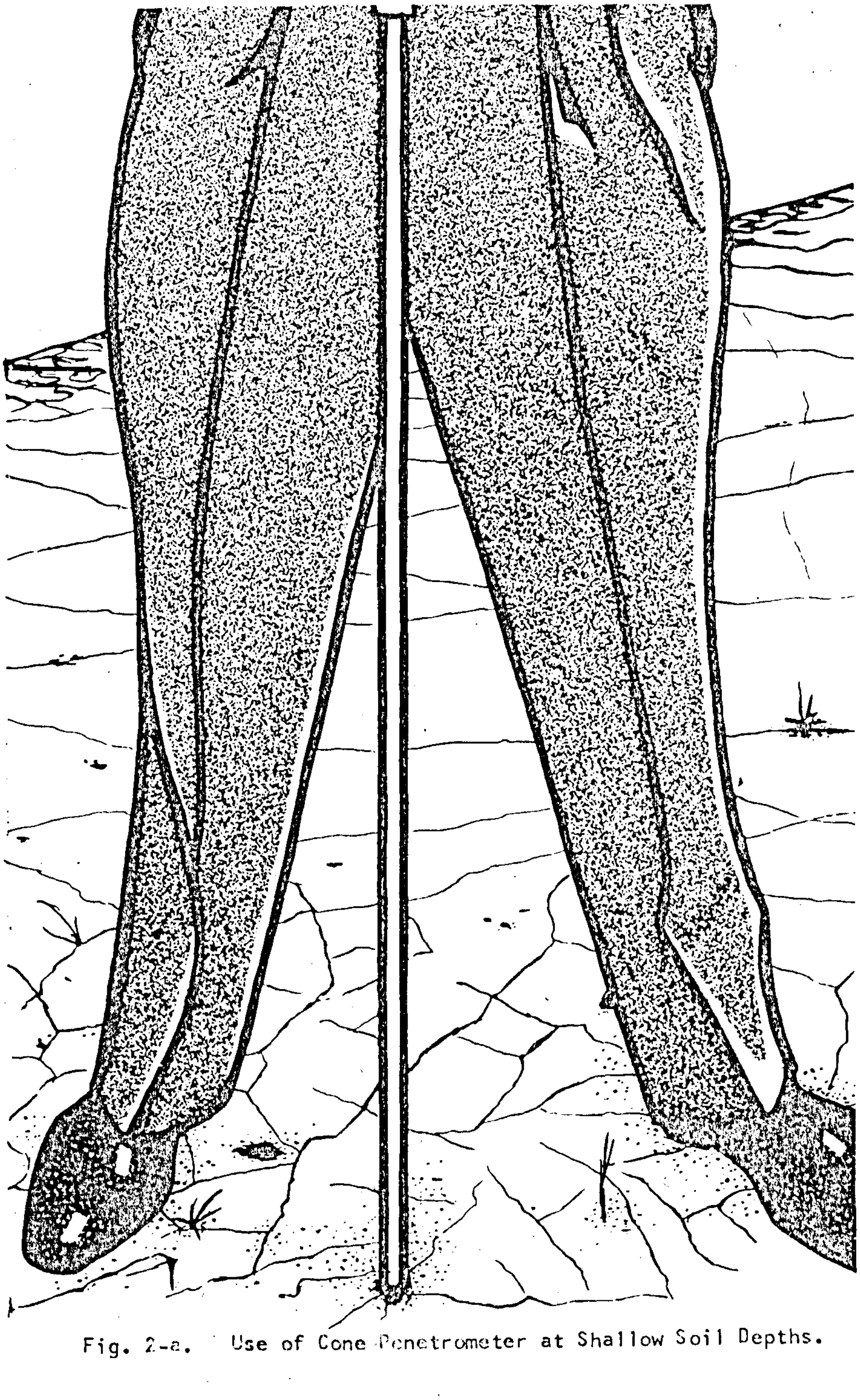


Fig. 2-a. Use of Cone Penetrometer at Shallow Soil Depths.

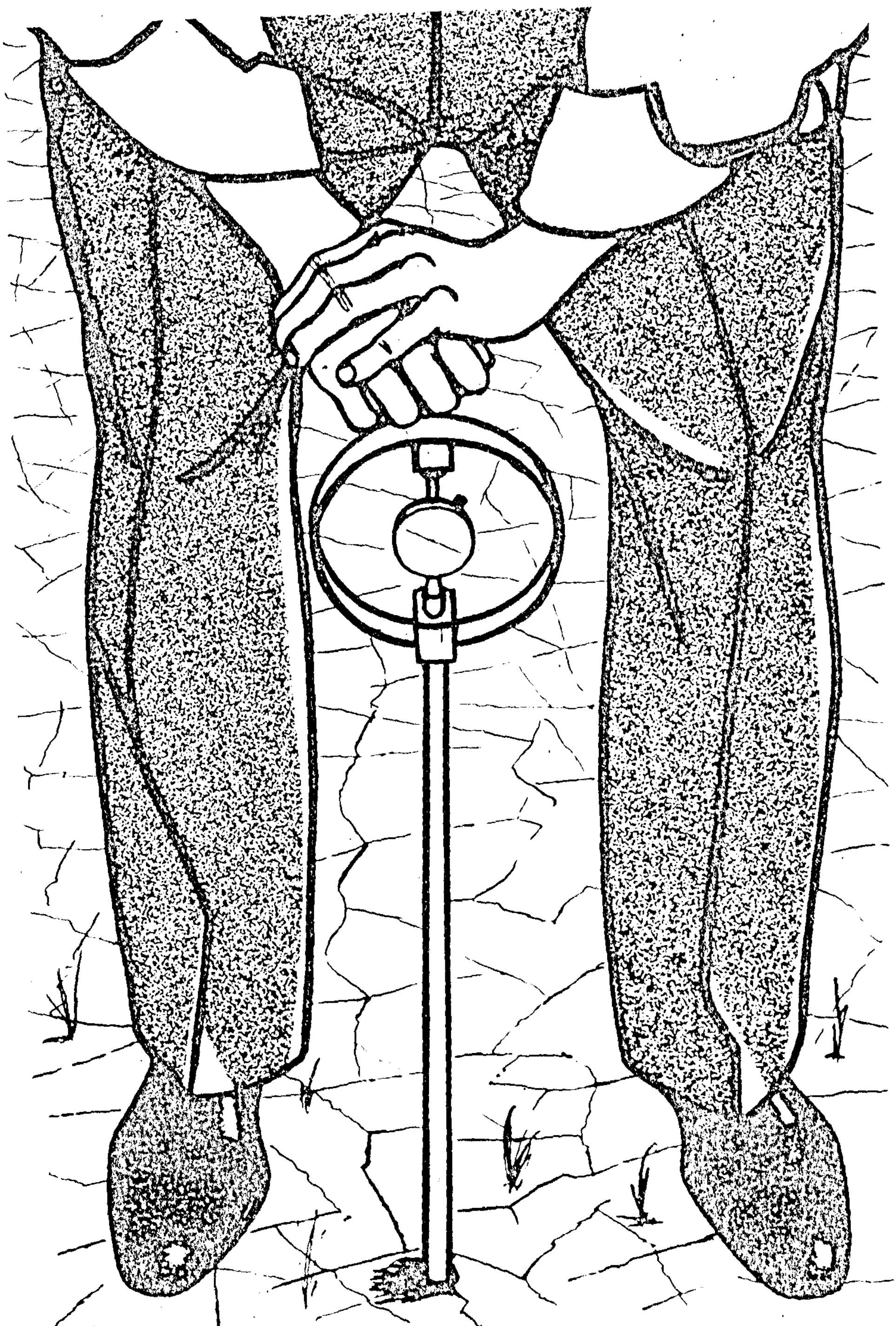


Fig. 9-2b. Use of Cone Penetrometer at Uepper Soil Depths.

TRAFFICABILITY PREDICTION DATA

CONE INDEX

STATION	SFC	3"	6"	9"	12"	18"	24"	30"	FIRM	AVERAGES	
										SFC	
										3"	
										6"	
										9"	
										12"	
										18"	
										24"	
										30"	
TOTAL										FIRM	

REMOLDING INDEX

STATION										
DEPTH SAMPLE										
DEPTH CYLINDER	0	100	0	100	0	100	0	100	0	100
SFC										
1										
2										
3										
4										
TOTAL										
REMOLD. INDEX										

Fig. 9-3: Example of Data Forms

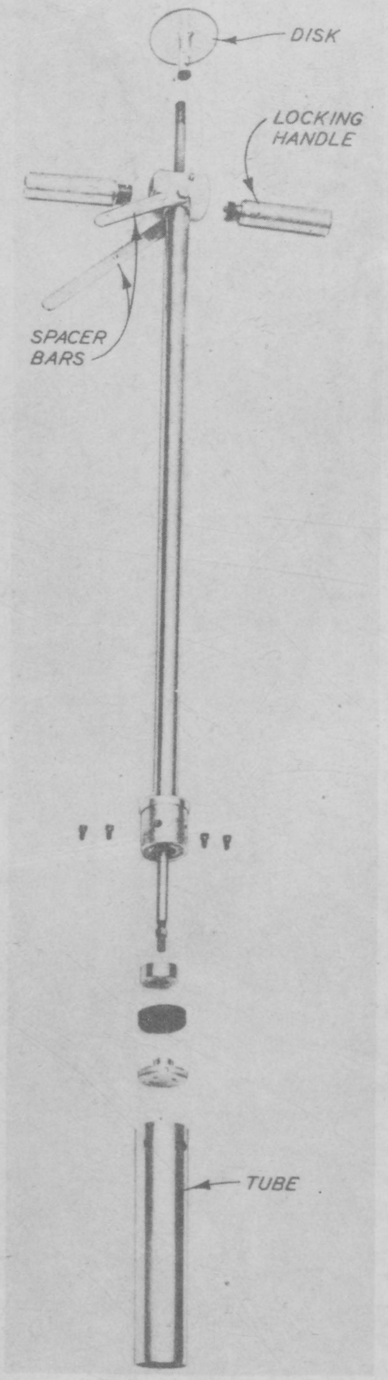


Fig. 9-4: Soil Sampler (Piston Type)

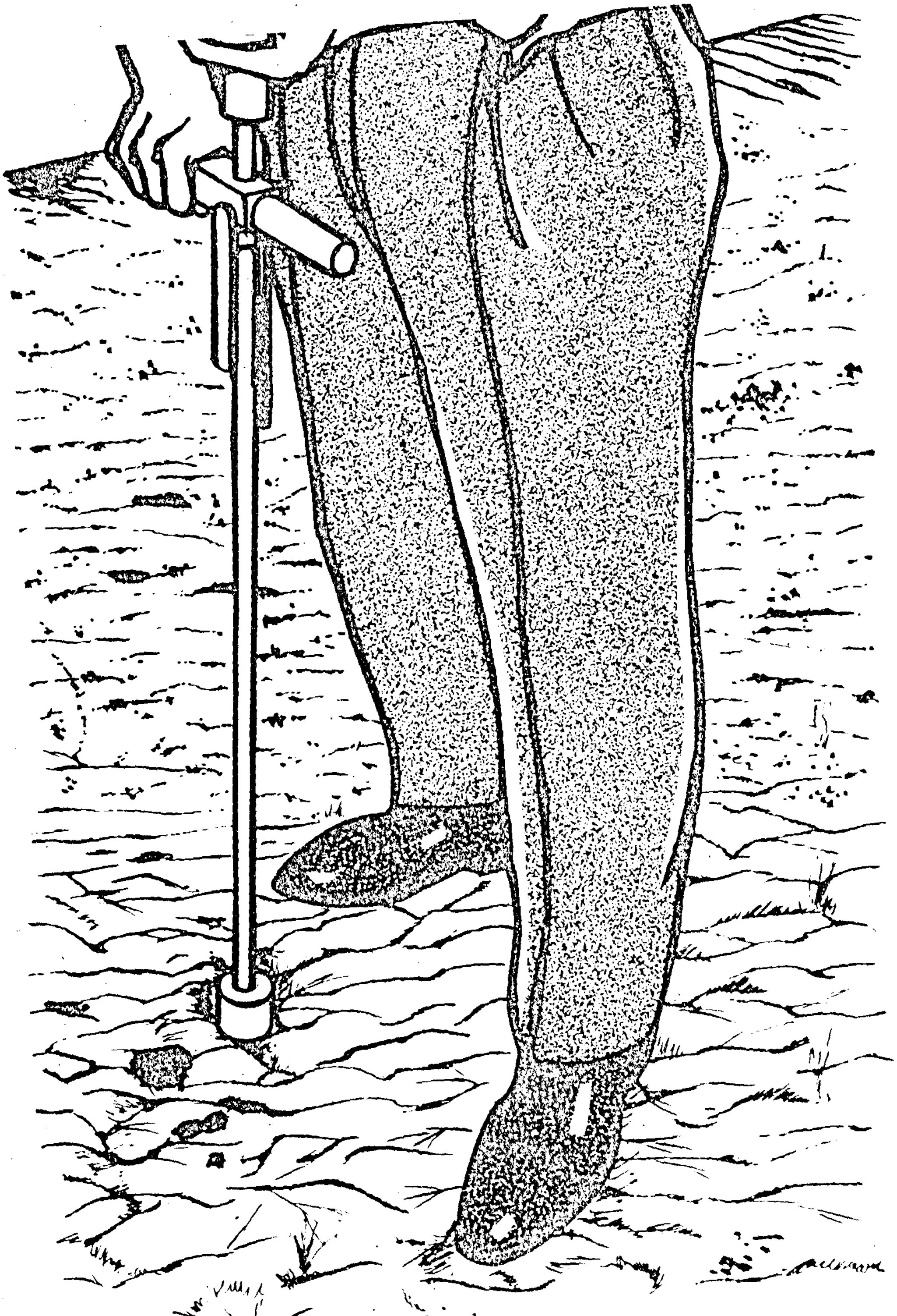


Fig. 9-5a. Taking Soil Sample.

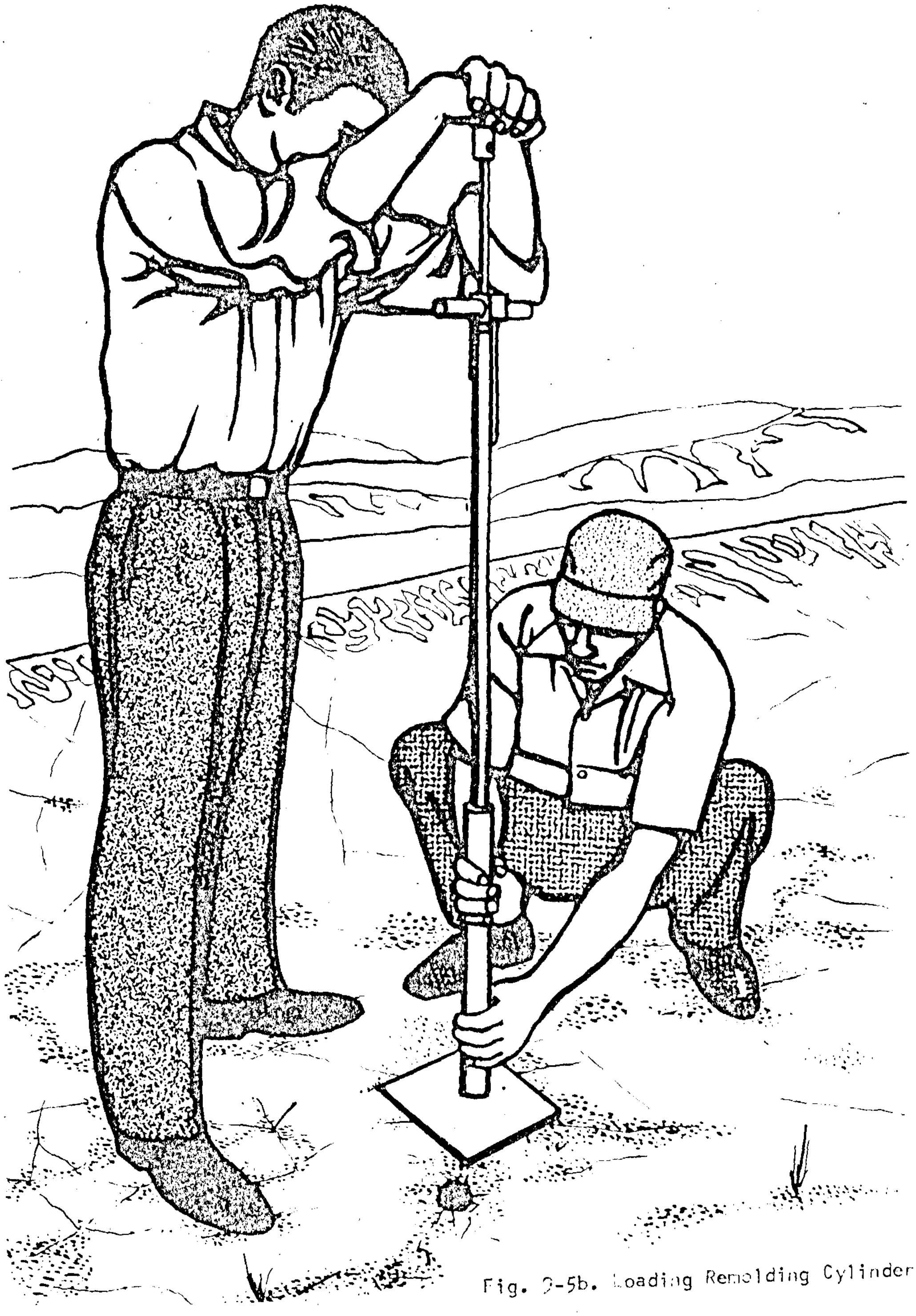


Fig. 9-5b. Loading Remolding Cylinder.

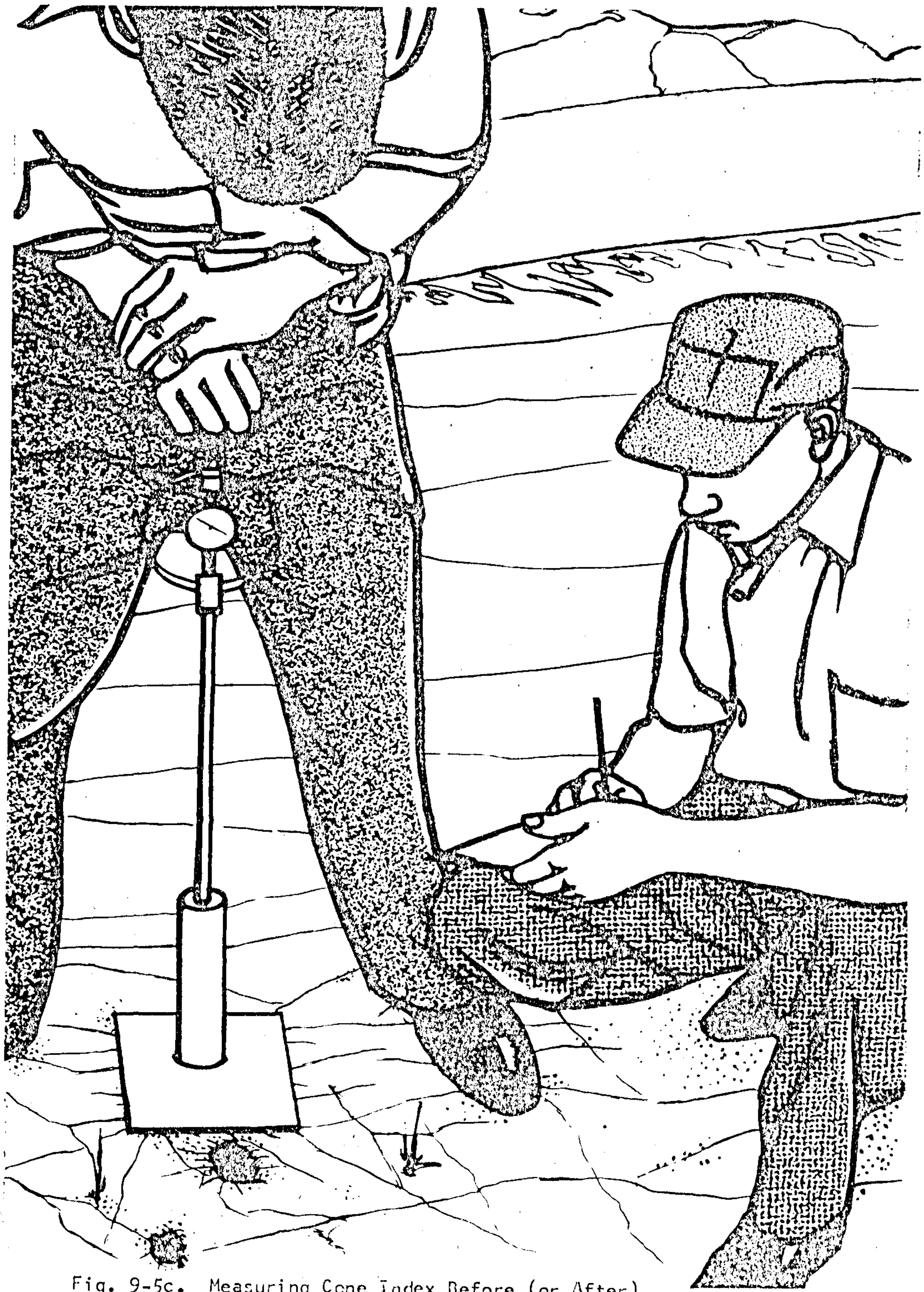


Fig. 9-5c. Measuring Cone Index Before (or After) Blows are Applied.

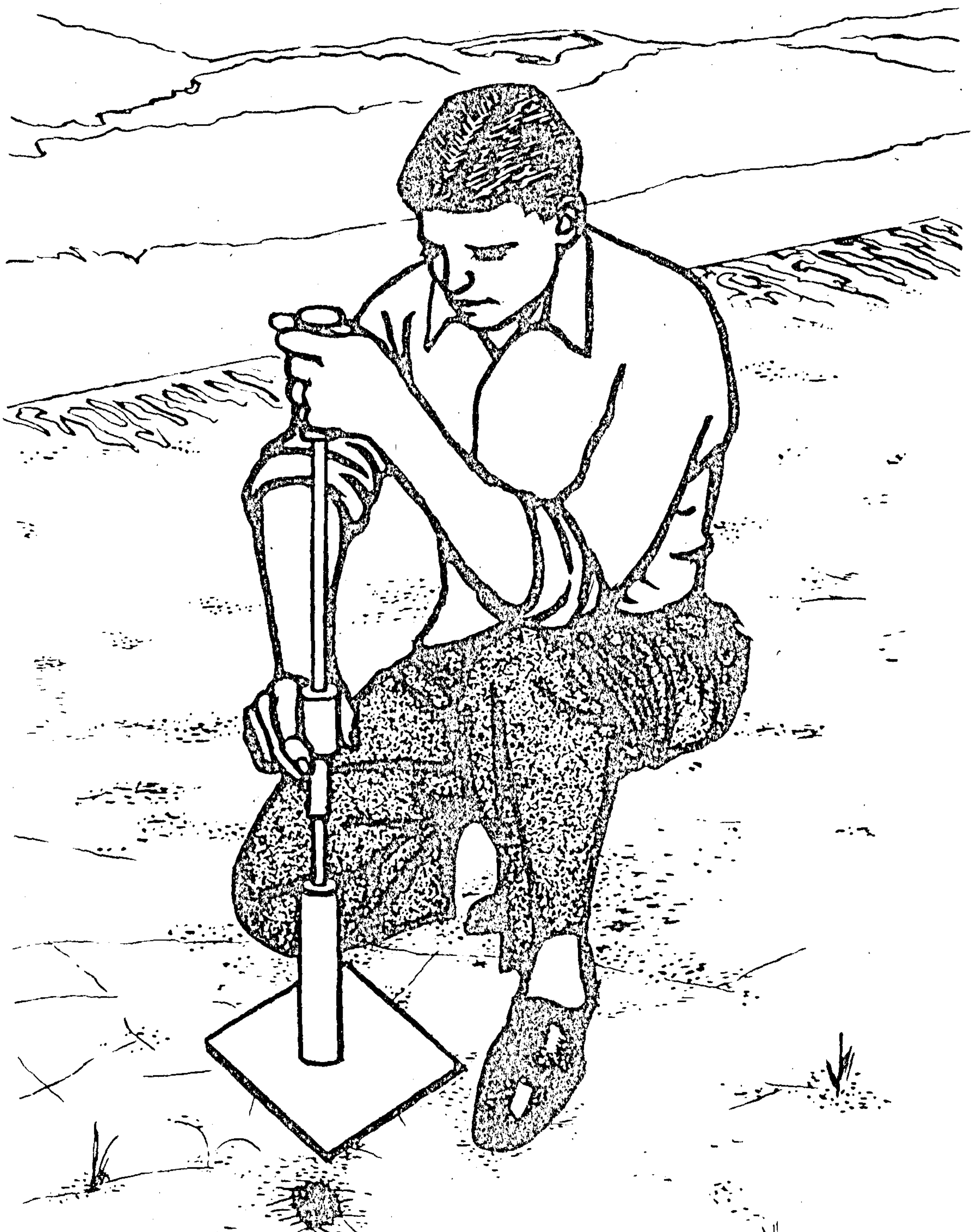


Fig. 9-5d. Applying Blows with Drop Hammer.

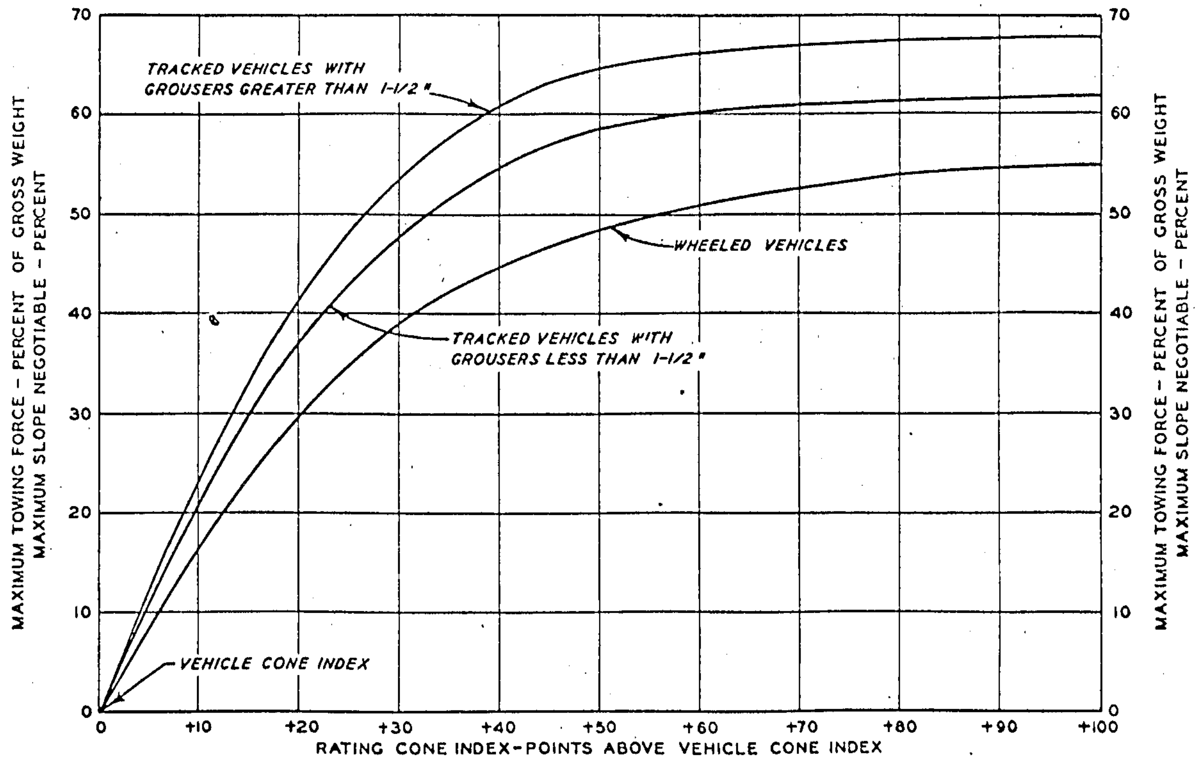
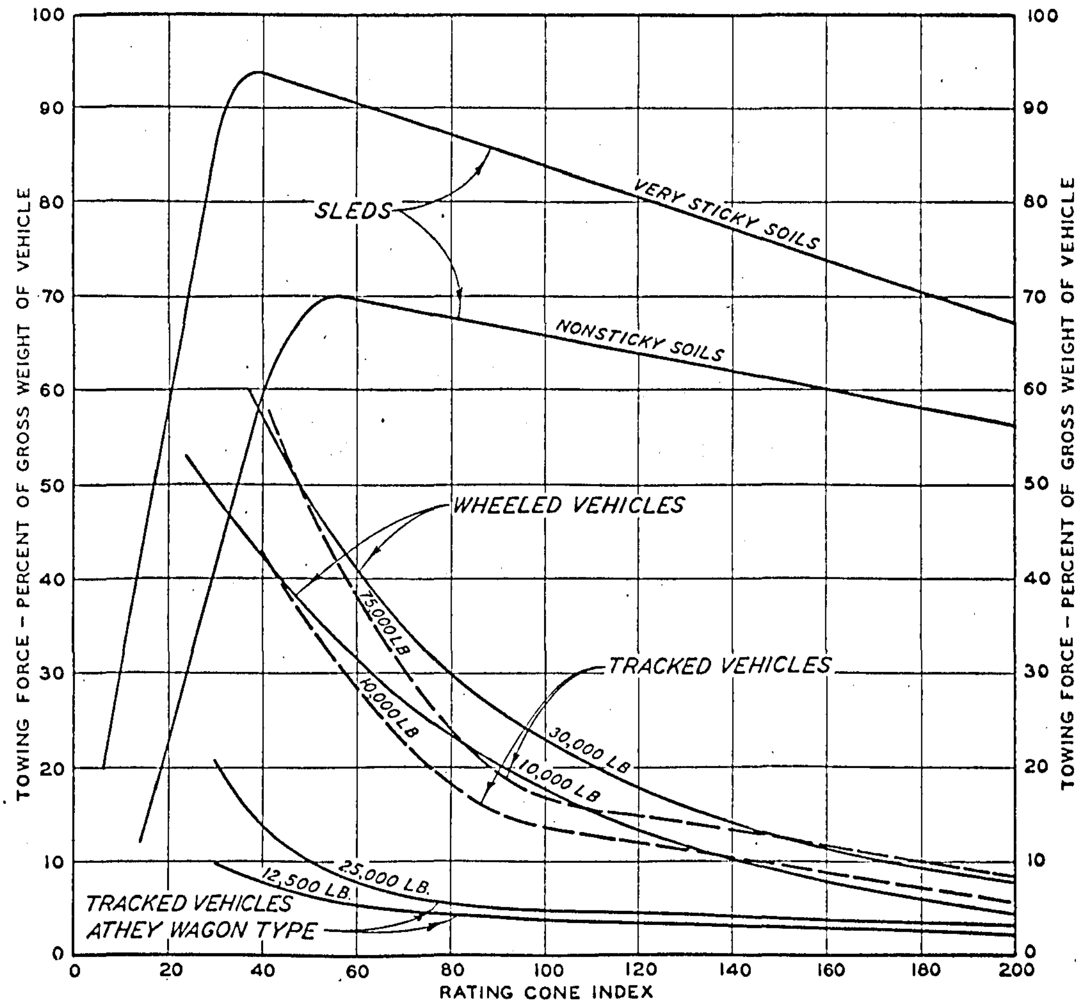


Fig. 9-6. Maximum continuous tractive effort on level ground; maximum slope and maximum towing force versus rating cone index expressed as points above vehicle cone index



NOTE: THE TOWING FORCE REQUIRED IN AN AREA WITH A CI 20 POINTS OR MORE BELOW THE VCI MAY EQUAL OR EXCEED THE WEIGHT OF THE VEHICLE.

Fig. 9-7. Towing force required on level ground

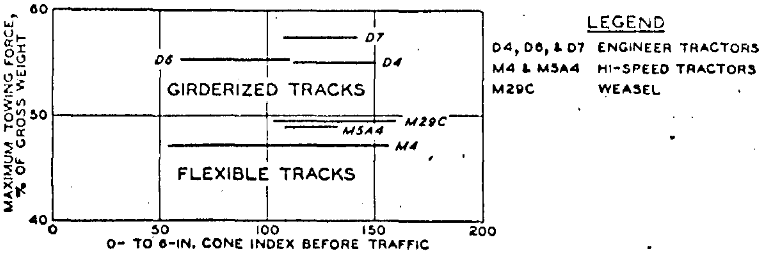


Fig. 9-8. Performance of tracked vehicles in dry-to-moist sand

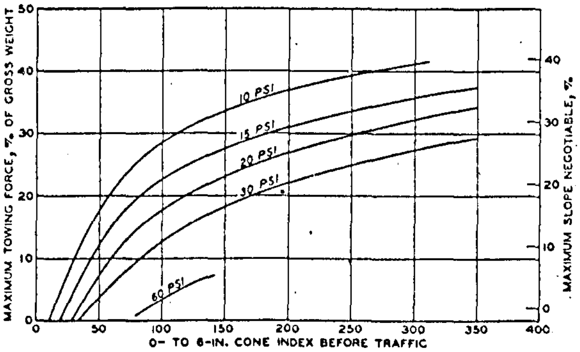


Fig. 9-9. Effect of tire pressure on vehicle performance on dry-to-moist sand. M34 and M135, 2-1/2-ton, 6x6 trucks; 11.00-20, 12-PR, NDCC tires

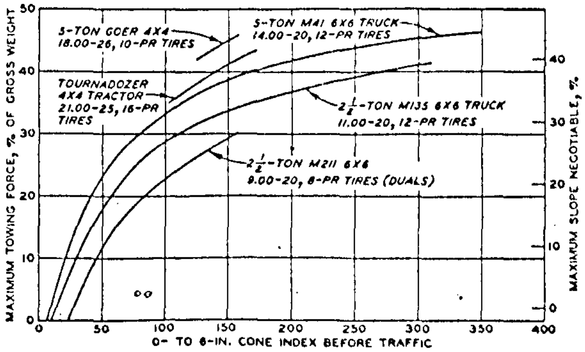


Fig. 9-10. Effect of tire size on vehicle performance on dry-to-moist sand. Vehicles operated at 10-psi tire pressure

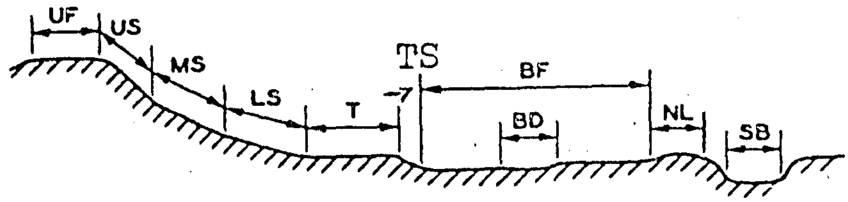


Fig. 9-11. Topographic classification

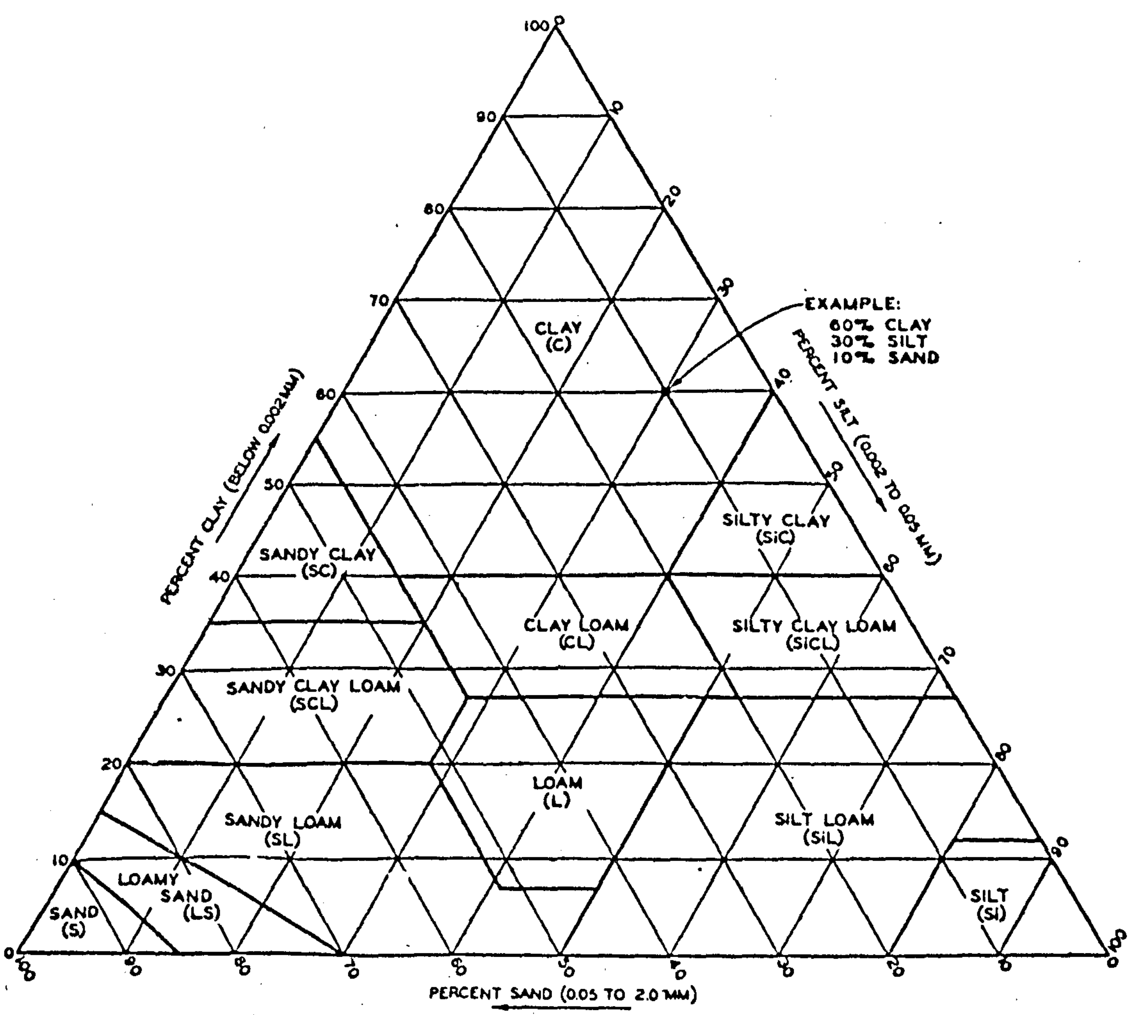


Fig. 9-12. USDA soil textural classification

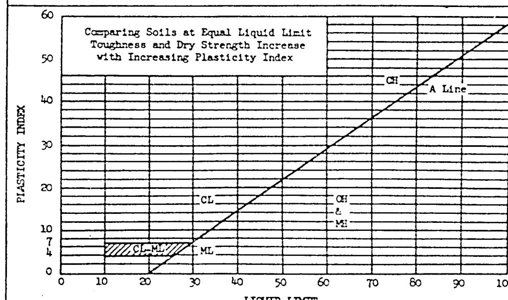
TABLE 9-1.

Unified Soil Classification System

UNIFIED SOIL CLASSIFICATION
(Including Identification and Description)

Major Divisions (1)	Major Divisions (2)		Group Symbols (3)	Typical Names (4)	Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights) (5)	Information Required for Describing Soils (6)	Laboratory Classification Criteria (7)	
Coarse-grained Soils More than half of material is <u>larger</u> than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye.	Gravels More than half of coarse fraction is larger than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size)	Clean Gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.	For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics. Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses. Example: <u>Silty sand,</u> gravelly; about 20% hard, angular gravel particles 1/2-in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).	Use grain-size curve in identifying the fractions as given under field identification. Determine percentages of gravel and sand from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse-grained soils are classified as follows: Less than 5% = GW, GP, SW, SP, More than 12% = GM, GC, SM, SC. 5% to 12% = <u>Borderline cases requiring use of dual symbols.</u>	$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			GP	Poorly graded gravels or gravel-sand mixtures, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			Not meeting all gradation requirements for GW
		Gravels with Fines (Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixture.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).			Atterberg limits below "A" line or PI less than 4 Above "A" line with PI between 4 and 7 are <u>borderline</u> cases requiring use of dual symbols.
			GC	Clayey gravels, gravel-sand-clay mixtures.	Plastic fines (for identification procedures see CL below).			Atterberg limits above "A" line with PI greater than 7
	Sands More than half of coarse fraction is smaller than No. 4 sieve size.	Clean Sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines.	Wide range in grain size and substantial amounts of all intermediate particle sizes.			$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			SP	Poorly graded sands or gravelly sands, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			Not meeting all gradation requirements for SW
		Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).			Atterberg limits below "A" line or PI less than 4 Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			SC	Clayey sands, sand-clay mixtures.	Plastic fines (for identification procedures see CL below).			Atterberg limits above "A" line with PI greater than 7

Major Divisions (1)	Major Divisions (2)	Group Symbols (3)	Typical Names (4)	Identification Procedures on Fraction Smaller than No. 40 Sieve Size (5): Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)	Information Required for Describing Soils (6)
Fine-grained Soils More than half of material is <u>smaller</u> than No. 200 sieve size.	Silts and Clays Liquid limit is less than 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	None to slight	Quick to slow	None	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions. Give typical name; indicate degree and character of plasticity; amount and maximum size of coarse grains; color in wet condition; odor, if any; local or geologic name and other pertinent descriptive information; and symbol in parentheses. Example: <u>Clayey silt,</u> brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML).
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Medium to high	None to very slow	Medium	
		OL	Organic silts and organic silty clays of low plasticity.	Slight to medium	Slow	Slight	
	Silts and Clays Liquid limit is greater than 50	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Slight to medium	Slow to none	Slight to medium	
		CH	Inorganic clays of high plasticity, fat clays.	High to very high	None	High	
		OH	Organic clays of medium to high plasticity, organic silts.	Medium to high	None to very slow	Slight to medium	
Highly Organic Soils		Pt	Peat and other highly organic soils.	Readily identified by color, odor, spongy feel and frequently by fibrous texture.			



PLASTICITY CHART

For laboratory classification of fine-grained soils

(1) Boundary classifications: Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well-graded gravel-sand mixture with clay binder. (2) All sieve sizes on this chart are U. S. standard.

FIELD IDENTIFICATION PROCEDURES FOR FINE-GRAINED SOILS OR FRACTIONS

These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 in. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (reaction to shaking)

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (crushing characteristics)

After removing particles larger than No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun, or air-drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (consistency near plastic limit)

After particles larger than the No. 40 sieve size are removed, a specimen of soil about one-half inch cube in size, is molded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eighth inch in diameter. The thread is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

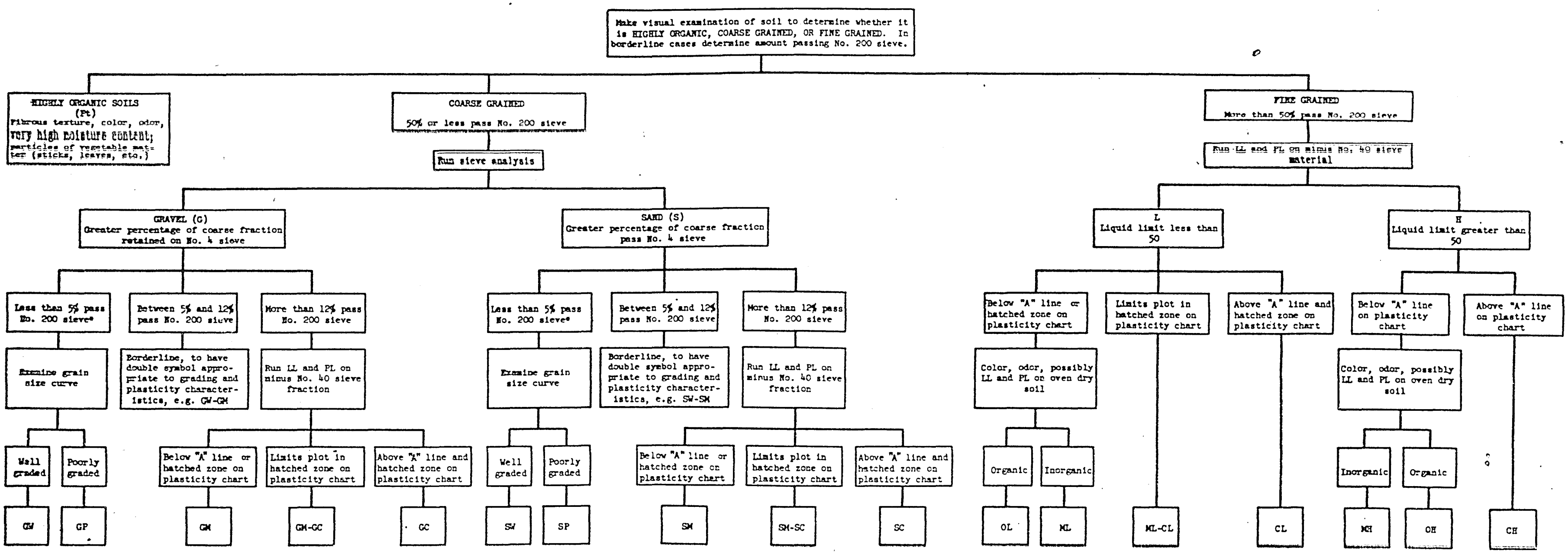
Highly organic clays have a very weak and spongy feel at the plastic limit.

Adopted by Corps of Engineers and Bureau of Reclamation, January 1952.

021260A

TABLE 9-2.

Auxiliary Laboratory Identification Procedure, Unified Soil Classification System



Note: Sieve sizes are U. S. Standard.

* If fines interfere with free draining properties use double symbol such as GW-GM, etc.

021260-B

List of References

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2. Association of Official Agricultural Chemists, Official and Tentative Methods of Analysis of the Association, 6th ed. Washington, D. C., 1945.

3. Department of Defense, Unified Soil Classification System for Roads, Airfields, Embankments and Foundations. MIL-STD-619A, Washington, D. C., 20 March 1962.

4. U. S. Army Engineer Waterways Experiment Station, CE, Trafficability of Soils; Soil Classification. Technical Memorandum No. 3-240, 16th Supplement, Vicksburg, Miss., August 1961.

5. U. S. Department of Agriculture, Soil Survey Manual. Agriculture Handbook No. 18, August 1951.

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13. ABSTRACT

Test procedures to be used for the evaluation of off-road vehicle mobility performance are presented. The development of a quantitative evaluation system represents an important step in the design of proper off-road vehicle tests. The procedures are presented as nine Annexes, entitled: (1) Drawbar-Pull; (2) Torque; (3) Vehicle Speed; (4) Vehicle Sinkage and Trim; (5) Resistance to Towing; (6) Fuel Consumption; (7) Load Distribution and Ground Pressure; (8) Determination of Land Locomotion Soil Values; and (9) Determination of WES Soil Parameters.

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