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Project NY 440-008
Technical Memorandum M-084

STUDY OF THE MOBILITY OF VEHICLES AS RELATED TO TRAFFICABILITY OF TRACTION MEDIA

15 January 1954

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port hueneme,
california

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S.J. Weiss

SUMMARY

This report is a summary of the work conducted by the U.S. Naval Civil Engineering Research and Evaluation Laboratory in relating the external performance of off-the-road vehicles to measurable characteristics of the terrain. The importance of the shear strength of the soil to its ability both to support vehicle loadings and to allow the creation of tractive effort for the propulsion of the vehicle has motivated consideration of a portable, direct shear apparatus as a trafficability instrument. Presented herein is a possible form of such an apparatus and an approach to performance prediction made possible by its utilization. Over-all success in achieving the ultimate objective of reliably estimating the soft ground performance of vehicles by these methods and techniques will depend upon continued theoretical development of the fundamental relationships between soil and vehicles.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

Historical Background

The necessity of transporting personnel and supplies while carrying out its assigned mission of creating and maintaining the shore establishments in support of the Fleet has dictated the interest of the Bureau of Yards and Docks in the problems of off-the-road vehicle mobility and soil trafficability. Vital interest in this problem has not been confined to the Navy department for intensive application to these problems has been the concern of both the Ordnance Department and the Corps of Engineers of the U.S. Army. Pertinent work has also been accomplished by the British and Canadian Governments.

In the program being conducted by the Army Engineers, begun prior to 1945, emphasis has been placed upon the utilization of the Cone Penetrometer, a trafficability instrument that is essentially a modification of the Proctor Needle. An extensive experimental program of correlation of the penetrometer readings and remolding characteristics of soils with actual vehicle passage has been aimed at predicting the ability of the soil to allow divisional movements of fifty vehicles. The work of the Corps of Engineers is reported in Reference 1 and in a series of supplements bearing the same technical memorandum number published later.

The work in vehicle-mobility research of the Aberdeen Proving Ground and of the Canadian Directorate of Vehicle Development[2] as well as British efforts[3,4] has had a more theoretical basis but, although significant contributions have been made in this approach to the study, there does not exist as yet a full theoretical understanding of vehicle mobility. Most of the theoretical development has been confined to soil strength or to what has been called the stability problem in soil mechanics. This theoretical development has allowed an adequate analysis of the creation of tractive effort under the running gear of a tracked vehicle. However, the problems of elasticity and plasticity, leading eventually to the determination of the relationship between sinkage, slippage, and motion resistance, have not been as thoroughly investigated.

Project Assignment

Owing to the need for determining the trafficability of soils encountered in the field, Project NY 440 007, Estimating Soil Trafficability, was assigned to the U.S. Naval Civil Engineering Research and Evaluation Laboratory in August 1949. This assignment, in July 1952, became a sub-task of the more general Project NY 440 008, Soil Stabilization. The purpose of the sub-task assignment is:

> "to develop instruments and techniques suitable for field use which will reliably estimate the volume and magnitude of vehicular loads that can be carried on various types of unstable soils."

Work on this project is closely related to an additional assignment to the Laboratory under Project NY 112 004, Low Pressure Tracks and Wheels, dated December 1949, which authorized:

> "soil studies and the relation of vehicle design to soil characteristics."

METHODS

Theoretical Studies

PERFORMANCE ANALYSIS. The generalized performance equation indicating incipient immobilization of a vehicle operating in soil can be expressed as:

$$H = R + F \qquad (1)$$

where

H = tractive effort developed by the running gear in the soil.

R = resistance to motion caused by sinkage, soil displacement, slippage, compaction, and other effects.

F = external loads such as towbar forces.

A quantitative index of performance of a prime mover would be the amount of drawbar pull, F, it can exert in addition to propelling itself over the terrain. A self-propelled vehicle not required to pull an additional towed load need develop only sufficient tractive effort to overcome its own resistance to motion. A towed vehicle can be quantitatively rated by the load a prime mover would have to exert as drawbar pull in order to move the vehicle. This load is the sum of the external resistance to motion, R, and the internal resistance caused by friction in the moving parts.

The ability to rationally estimate the performance of these vehicles is therefore dependent upon the success achieved in relating H and R to the pertinent soil parameters and then developing suitable reconnaissance instruments for quickly determining these soil values in the field. The internal resistance of a towed vehicle, being independent of the terrain, would be a constant value predetermined for each vehicle.

TRACTIVE EFFORT. Previous research has shown that maximum tractive effort is dependent upon two soil characteristics. These may be represented as the slope and intercept of the empirically-obtained straight line (Figure 1) that represents shearing stress at failure when plotted against normal stress. The slope of this line is expressed as $\tan\phi$ and the intercept is expressed as c. The units of c are the same as that for stress.

Thus, the relationship between normal load, σ, and shearing stress, s, is represented by the equation:

$$s = \sigma \tan\phi + c \qquad (2)$$

When considering the action of a rigid track in soil,

s = the tractive effort per unit area of track contact,

σ = the vehicle load per unit area of track contact.

Although the c, ϕ soil properties cannot be considered as unchanging characteristics of terrain for they will reflect changes in void ratio, pore-water pressure, climatic changes, and the effects of repeated vehicle passage, this simple relationship for tractive effort already allows some estimate of the performance of a vehicle in relation to parameters of the soil providing that it is possible to gage the vehicle's motion resistance. In Figure 2 the slope-climbing ability of a conventionally-tracked vehicle is represented in chart form as a function of the c, ϕ soil parameters and the nominal ground pressure of the vehicle. In this case the effective vehicle load per unit of track-contact area is equal to the product of the nominal ground bearing pressure of the vehicle and the cosine of the angle of the slope. The product of the nominal ground bearing pressure and the sine of the angle of slope is the equivalent of a towbar force to be overcome. The external motion resistance encountered is assumed such as to reduce the computed limiting percentage slope to 70 per cent of its value. This simplified representation of the problem does not take into consideration the non-uniform distribution of contact pressure caused by such effects as the driving torque and the location of the center of gravity.

That the conventional closed-link track creates soil shear along its sides to the depth of the grousers as well as along the bottom surface created by the plane of the grouser tips requires a modification of equation 2 to take into account the lateral flow effects of the soil beneath the track.

The work of the Canadian Directorate of Vehicle Development and the Aberdeen Proving Ground[5] has resulted in the devising of the following modified equation for the predicting of tractive effort of a conventional-grousered closed-link track:

$$H = V\left[(1+F_h)\tan\phi + F_h F_s \tan^2\phi\right] + 2cL(w+2h) \quad (3)$$

where

V = vehicle weight, lb

$F_h = .64 \frac{h}{w} \cot^{-1}\frac{h}{w}$

$F_s = .64 \frac{s}{w} \cot^{-1}\frac{s}{w}$

h = grouser height, in.

s = grouser spacing, in.

L = length of tract contact, in.

w = track width, in.

and all other symbols are as previously defined.

This equation has been closely corroborated by experiment. The point of interest in the development of a performance-prediction technique is that the tractive effort is dependent upon the soil characteristics of c and Ø and all else are vehicle constants. This is graphically demonstrated in Figure 3 which shows coincident values of H, Ø and c computed for the D-4 Caterpillar tractor on the assumption that the change in length of track contact in different c,Ø soil conditions may be neglected.

DEVELOPMENT OF THE SOIL TRUSS. The soil characteristics of c and Ø are closely related to the mechanical soil properties of apparent cohesion and apparent angle of internal friction of the soil that form the basis for the development of theoretical soil mechanics. The determination of these properties in the laboratory has been the subject of considerable research and numerous laboratory methods have been devised for this purpose. Among these are the direct shear box, the ring shear machine and the triaxial compression apparatus. The similarity between the action of a vehicle track in creating tractive effort in the soil and the simple, direct shear laboratory apparatus led to the development by the Laboratory of a portable direct shear apparatus called the Soil Truss for the field determination of the required soil characteristics / (Figures 4 and 5).

The action of this instrument is such that a small sample of the soil is trapped and caused to shear along a horizontal plane. The force required to shear the soil is produced as a vertical effort by the operator. This vertical effort produces both normal and shearing stresses upon the entrapped soil as shown in Figure 6. The ratio of these two stresses is dependent upon the leg angle to which the truss initially is set.

Plotting the data is facilitated by the use of a special chart, Figure 7, whereby vertical force and protractor readings are plotted directly without the necessity of converting the data to normal and shearing stresses. Operation of the Soil Truss at various leg angles enables the determination of the strength envelope from which the shearing strength of the soil at zero normal loading and the rate of increase of shearing strength with normal loading may be determined. In Figure 7 these properties are shown as c and Ø respectively.

Although the present Soil Truss embodies the simplest form of the instrument principle with a minimum of possible refinements, the lack of any other field instrument for the determination of these mechanical soil properties led to its adoption by the member agencies of Working Group E, Panel on Vehicles, Committee on Ordnance, RDB, as a tentative standard.[6] Soil Truss kits were made available to numerous military and educational agencies engaged in allied research in order to aid its rapid evaluation and development. More formal study of the usefulness of this instrument for other than trafficability research has also been undertaken under government contract.[7,8] These studies have consisted of comparisons of the Soil Truss determination of c and Ø with the values of apparent cohesion and angle of internal friction determined by standard laboratory tests. Once the precise relationship between these properties can be ascertained, there is the likelihood that the Soil Truss in its present or a modified form would be valuable in providing a rapid field approximation of the soil properties needed for the computing of foundation- and retaining-wall requirements. The investigations conducted by the University of Pennsylvania indicate that the Soil Truss and the laboratory direct shear tests provide identical quick-unconsolidated shearing-strength characteristics of c and Ø provided the tests are conducted at comparable rates of shear. The work at the California Institute of Technology indicates that there is also reasonably good agreement with triaxial compression tests when total rather than intergranular pressures are utilized in constructing the Mohr circles.

MOTION RESISTANCE. If there were no vehicle sinkage accompanying its motion, the determination of the tractive effort alone would enable accurate estimation of its cross country performance. Vehicle immobilization in adverse terrain, however, most often results when the tractive effort developed in the soil by the running gear is not sufficient to overcome the resistance to motion attendant upon the sinkage of the vehicle. Under such a situation a slip-stall condition is created wherein the vehicle's tracks or wheels spin freely and no forward motion is accomplished. Thus any adequate technique for assessing the soft ground performance of vehicles will require some formulation of the relationship between motion resistance and vehicle sinkage.

Analytical work on this problem initially attempted for rigid wheels shows promise of later extension to track configurations and pneumatic tires.[9,10] At the present time, it is possible to present only a conservative approximation to the true relationship. Such a relationship is:

$$R = V\sqrt{\frac{z}{D-z}} = V \tan\frac{\theta}{2} \qquad (4)$$

where

z = wheel sinkage, in.

θ = arc of wheel contact in the soil, degrees

and all other terms are as previously defined.

Equation 4 is derived by assuming that the arc of contact of the wheel in the soil is bounded by the bottom of the wheel and the soil surface and that the resultants of the vertical and horizontal soil reactions are located at the center of these respective projections of the contact surface.

An interesting feature brought out by equation 4 is that if the further assumption of uniform vertical and horizontal loading is made, such that

$$\frac{V}{b\sqrt{Dz - z^2}} = \text{unit vertical loading} \tag{5}$$

and

$$\frac{R}{bz} = \text{unit horizontal loading} \tag{6}$$

where

b = wheel width, in.,

equation 4 when reduced to

$$\frac{V}{b\sqrt{Dz - z^2}} = \frac{R}{bz} \tag{7}$$

shows that the vertical and horizontal unit loads are equal.

This allows an estimate of the external motion resistance of a tracked vehicle on the basis that the resistance per unit frontal area of the track in the soil will approximate the nominal ground pressure of the vehicle.

VEHICLE SINKAGE. The postulating of an adequate theory enabling the determination of vehicle sinkage is perhaps the most challenging of the unsolved problems in the development of a full theoretical understanding of vehicle mobility. At the present stage of development, no rigorous treatment of the problem has been attempted owing to the complexity of the stress-strain patterns and the transition from zones of elastic settlement to those of non-elastic (plastic) settlement under the loaded areas. The problem is further complicated by the lateral and upward displacement of the soil in the vicinity of the mass undergoing compression. It has been suggested that the relaxation methods that have been so brilliantly applied to problems of theoretical physics, intractable by orthodox methods, may be profitably applied to the problem of vehicle settlement.[11]

A semi-empirical relationship, at best a crude approximation that has been developed by the Laboratory to relate soil and vehicle properties with vehicle sinkage, is as follows:

$$\frac{mV}{b\left[L+\sqrt{Dz-z^2}\right]} = \frac{\gamma z N_\phi + 2c\sqrt{N_\phi} + \frac{2c}{1+\tan\phi}}{\tan(45-\phi)} \tag{8}$$

where

b = track or wheel width, in.

γ = specific weight of soil, lb per cu in.

$N_\phi = \tan^2\left(45+\frac{\phi}{2}\right)$

L = distance from the center of the drive sprocket to the center of the front idler for a tracked vehicle, in.; for a wheel, L = 0.

m = influence factor, varies between 0.25 and 1.0, depending upon whether the load can be considered rigid or flexible.

Experimental Studies

SCALE-MODEL TESTING. The experimental studies conducted by the Laboratory in relating soil and vehicle characteristics have been greatly influenced by the program of soil vehicle scale-model testing initiated in 1946 by the Experimental Towing Tank of Stevens Institute of Technology under Army contract. This agency has demonstrated that the use of scale models and the associated dimensional theory are powerful research tools enabling the economical and orderly investigation of the many parameters of cross country vehicle performance.

Techniques for the conducting of soil-vehicle model tests, including methods of soil handling and control have been developed and have been found to provide greater economy, precision in measurement and control of conditions, speed in developing data, adaptability and flexibility of test facilities, than in full-scale testing.[12,13]

When a study of the available reports of previous vehicle-mobility research had disclosed no adequate formulation of the tractive effort developed by a spudded wheel, an expedient laboratory traction-test device (Figure 8) was improvised to allow experimentation in this field. Limited tests in sand and sandy loam indicated that an estimate of this quantity can be made in accordance with the following relationship:

$$H = (V + R) \tan \phi + \frac{cbD\theta}{2} \qquad (9)$$

This equation, like equation 8, is also acceptable only as an empirical approximation with some theoretical basis and limited experimental verification.

The traction-test apparatus also allowed investigation of the conformance with test results of the expressions for motion resistance and sinkage embodied in equations 4 and 8. It was determined that a fair agreement of the actual and computed sinkages of the 9-in.-diameter grousered wheel used in the tests is obtained when the value of m in equation 8 is taken as 0.25.

The experience gained with this expedient test apparatus along with study of the operation of the Stevens Institute soil tank led to the consideration of expansion of the Laboratory's activities along this line and the design of a more suitable scale-model test facility was initiated. The design of this equipment has been essentially completed but its fabrication and installation have not been accomplished. Figure 9 shows a general arrangement of the design of the dynamometer carriage of this proposed facility.

FULL-SCALE TESTING IN NATURAL SOILS AND SNOW. During 1952 the Laboratory undertook an experimental program of terrain and vehicle-performance measurements on six California beaches under Project NY 140 002. Soil Truss classification of the terrain was included in this investigation of the range of variation of natural sand properties occurring on sand beaches of varying oceanographic and topographic character. The data obtained from these beach surveys are currently being analyzed and correlations between various measurements are being sought. Representatives from Waterways Experiment Station, Corps of Engineers, U.S. Army, participated in the investigation of the Del Mar Beach at Camp Pendleton, California, by collecting cone-index and remolding-index data at the stations where the Laboratory took soil samples and determined moisture content, density, and Soil Truss classification of c and Ø.

In September 1951, a Laboratory representative participated in the Army Ordnance Climatic Test Program at Yuma, Arizona, by determining the c,Ø classification of the desert test terrain enabling the verification of agreement of the computed and experimental tractive performance of the M29C Weasel.

The ability of the Soil Truss to provide a classification of the strength of a snow cover was the purpose of a separate study during the winter of 1951-1952.[14, 15] Data obtained during this period indicated that in all but freshly fallen snow, the Soil Truss is capable of determining c,Ø characterizations of the initial shearing strength of the snow cover but that the collapse in snow structure and strength subsequent to its initial loading precluded the direct evaluation of tractive performance applied in the case of soils. Representatives of Aberdeen Proving Ground participated with the Laboratory in conducting these tests in snow in which the vehicles under study were the Tucker Sno-Cat No. 443 and the Weasel M29C.

RESULTS

Vehicle-Performance Charts

The expressions for tractive effort, motion resistance, and sinkage previously presented make possible the preparation of pre-computed performance charts of individual vehicles based upon c,Ø classification of the soil. It must be borne in mind that these performance ratings will reflect the degree of approximation of all the component expressions that go into its preparation. At this time such charts are proposed only as an approach to performance prediction, to be further refined as new information becomes available through continued research.

Such a performance chart for a typical prime mover, the D-4 Caterpillar tractor, is shown in Figure 10. For simplification of computation, a constant soil weight of 0.7 lb per cu in. has been assumed. Each point on the chart represents a solution of equation 1. The area of immobilization represents the condition where the computed motion resistance exceeds the computed tractive effort. On those soils that allow the development of the full power of the tractor engine, the maximum drawbar pull will be limited by the capacity of the engine rather than the strength of the soil.

A motion resistance chart for a tracked trailer is shown in Figure 11. Reference to these two charts provides an indication of the suitability of coupling of the two vehicles in any c,Ø soil condition.

Performance charts of this type can also be computed for wheeled vehicles. Figures 12 and 13 have been computed with the assistance of the IBM Computing Section of the Naval Ordnance Test Station at Inyokern, California, on the untested assumption that the expressions developed for a rigid grousered wheel may be applied to a pneumatic tire and the further assumption that all wheels may be considered operating in undisturbed soil. The division between the mobile and immobile areas of the chart are those c,Ø soil conditions where either the computed tractive effort developed by the wheels equals the computed motion resistance or where the computed sinkage exceeds the ground clearance of the vehicle. In the computation procedure for these charts, the variation in effective tire width and diameter caused by changes in inflation pressure has not been considered.

Evaluation of the Soil Truss

Soil Truss kits upon the request of the receiving agency have been distributed on extended loan to the following agencies:

Experimental Towing Tank, Stevens Institute of Technology, Hoboken, New Jersey
Tillage Machinery Laboratory, Auburn, Alabama
Marine Corps Equipment Board, Washington, D.C.
Aberdeen Proving Ground, Aberdeen, Maryland
Waterways Experiment Station, Vicksburg, Mississippi
Higgins, Inc., New Orleans, Louisiana
Office of Naval Research, c/o Louisiana State University, Baton Rouge, Louisiana
Central Sierra Snow Laboratory (SIPRE), Soda Springs, California
Directorate of Vehicle Development, Ottawa, Canada
U.S. Naval Photographic Interpretation Center, Washington, D.C.
Transportation Research and Development Station, Fort Eustis, Virginia

British Joint Services Mission, Washington, D.C.
University of Pennsylvania, Philadelphia, Pennsylvania
California Institute of Technology, Pasadena, California.

Apart from the contracted investigations of extending the usefulness of this instrument to other than trafficability studies,[7,8] no formal reports on the evaluation of the instrument have been received by the Laboratory. Information from the Corps of Engineers indicates that a study of the correlation of Soil Truss and Cone Penetrometer readings is planned as part of a program of extending its trafficability research to those soils characteristic of beach areas.

Comments[16] by representatives of the participating agencies of Working Group E, Panel on Vehicles, Committee on Ordnance, RDB, to whom copies of the instrument have been loaned indicate that its present stage of development is not entirely satisfactory for precise field work for the following reasons:

a. The instrument appears to give higher values of apparent cohesion than that apparently experienced by a tracked vehicle in the same soil.

b. The quick shear value obtained by the instrument does not reflect any remolding characteristic of the soil.

c. Use of the instrument when sampling soil strata below the surface is laborious.

CONCLUSIONS

The approach to the trafficability problem as set forth in this report has followed the assumption that the ability to reliably estimate vehicle performance would follow a theoretical understanding of the soil dynamics involved. Emphasis in the development of a trafficability instrument has been placed upon empirical determination of soil shear strength in situ through use of a direct shear apparatus because of the conviction that this theoretical understanding would necessarily be built upon knowledge of the same mechanical soil properties used in the development of the soil mechanics theories applied to earthwork and foundation studies.

Although the theoretical investigations conducted in recent years have established the problems, methods, and specific character of the required research, there is still insufficient knowledge of the fundamental interaction between the vehicle and the soil. A complete vehicle-mobility analysis cannot be evolved without additional investigation of the so-called plasticity and elasticity problems of soil mechanics as applied to vehicle movement over soil.

RECOMMENDATIONS

It is recommended that, in recognition of the basic character of the required research and as an attempt to evoke the interest of those soil engineers and physicists who are perhaps best qualified to undertake the work, research under this project be continued under contract by a university with a recognized soil engineering department; this work to consist of the application of those soil mechanics principles previously applied to the study of the essentially static loading of footings to the dynamic loading under vehicular loads. In the foundation engineering work which has absorbed much effort to the present time, the emphasis was placed upon allowable settlement over a period of years. This must now be directed to the almost instantaneous sinkage experienced under a vehicle.

It is further recommended that favorable consideration be given the establishment at the Laboratory of a scale-model test facility that will allow the development of data under closely controlled test conditions for the experimental verification of theoretical solutions and for their intelligent formulation.

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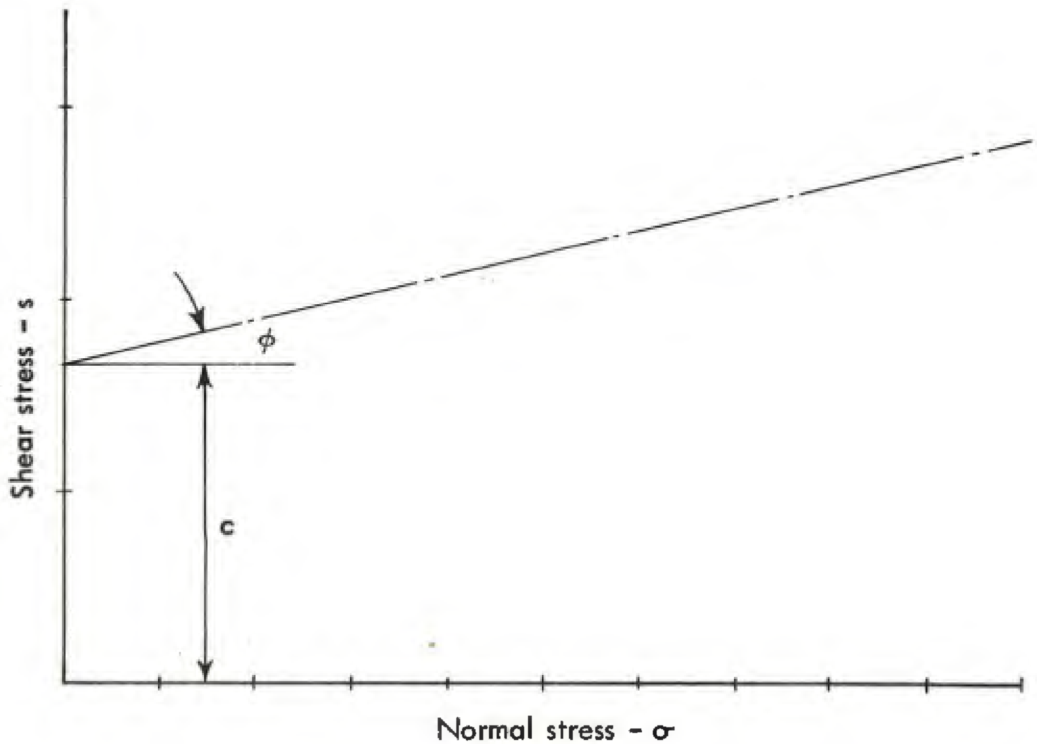
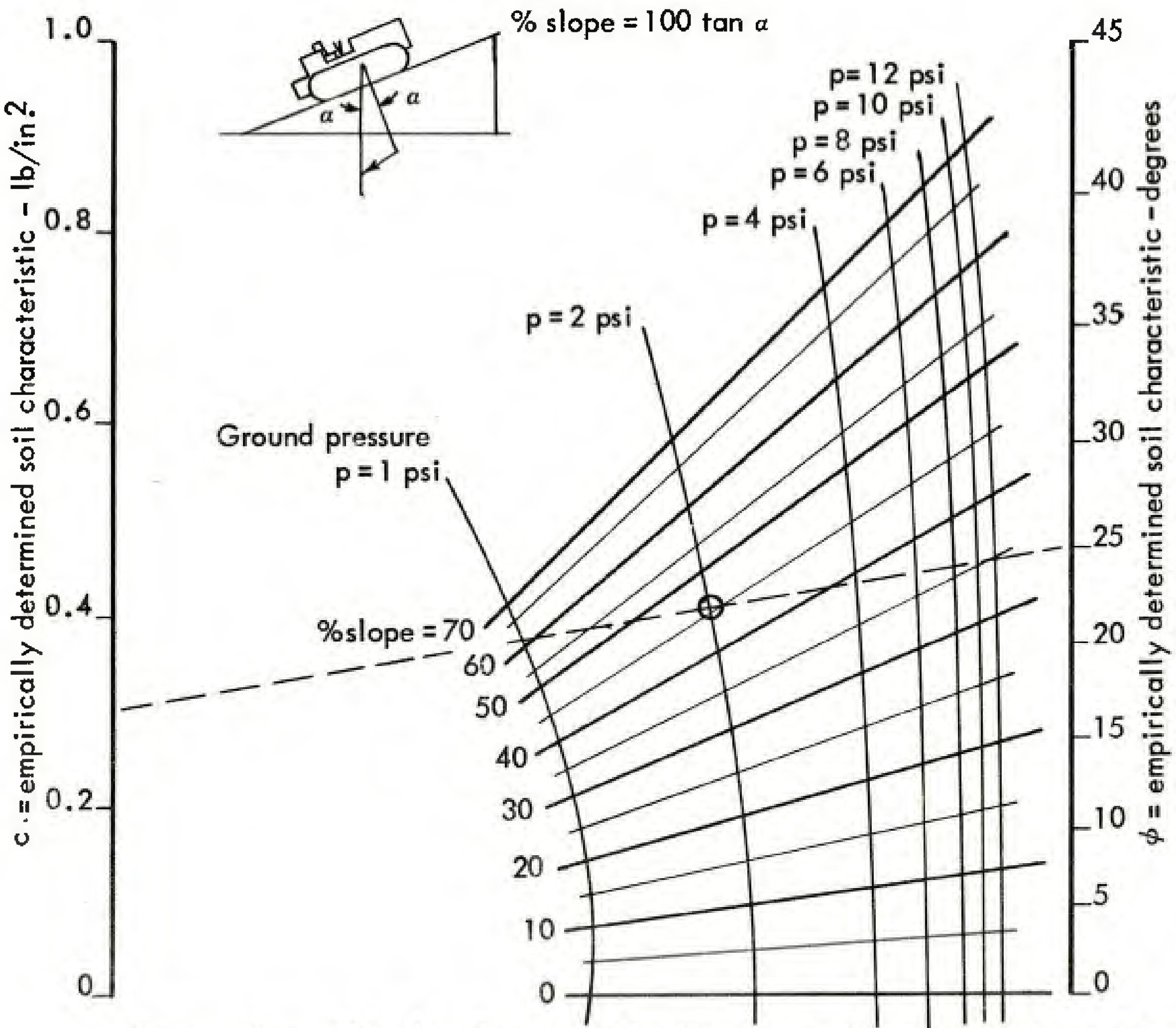


Figure 1. Relationship of shearing stress at failure vs normal loading on the soil.



Illustrative example:
given p = 2 psi
$\phi = 25°$
c = 0.3 psi

From chart:
negotiable slope 45%

φ and c are soil characteristics obtained by means of Navcerelab Soil Truss Mk II

p = nominal ground pressure, psi

$$p = \frac{\text{vehicle weight}}{\text{area of track contact}}$$

The equations utilized to develop this chart assume that the additional motion resistance arising through vehicle sinkage will reduce the limiting slope, computed by neglecting sinkage, to 70 % of its value.

Figure 2. Approximate slope-climbing ability of conventional-tracked vehicles.

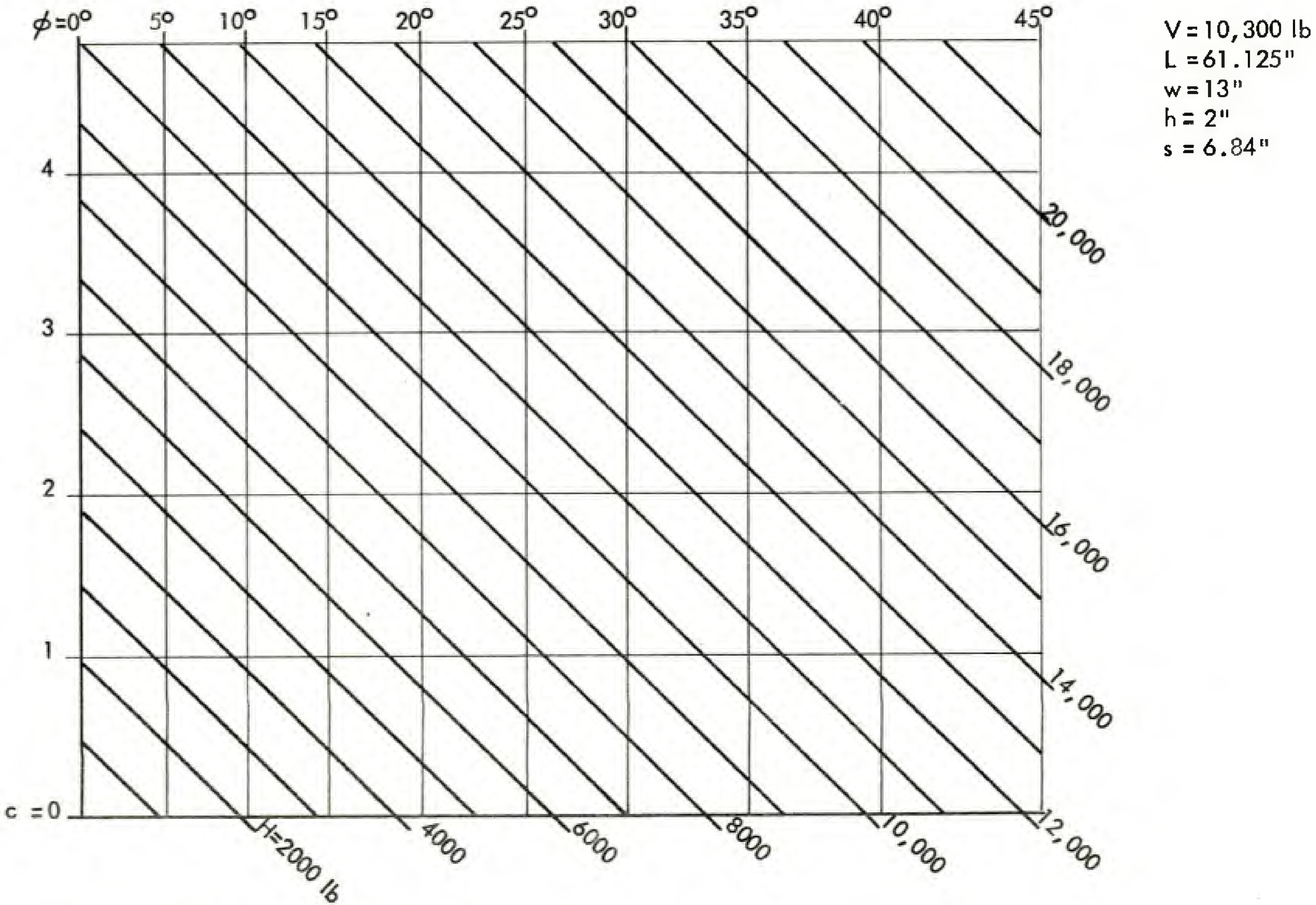


Figure 3. D-4 Caterpillar Tractor tractive-effort chart.

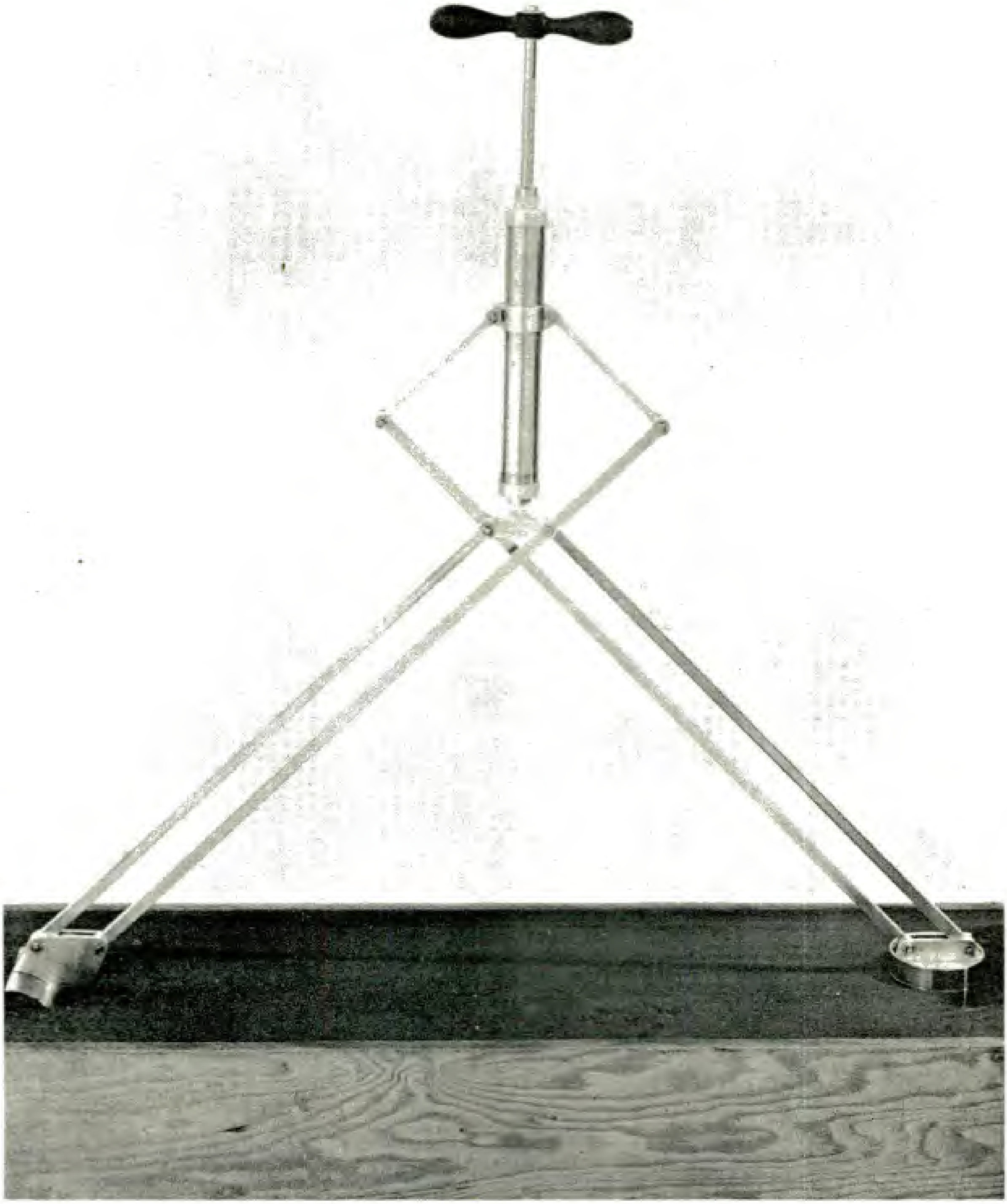


Figure 4. Soil Truss Mark II

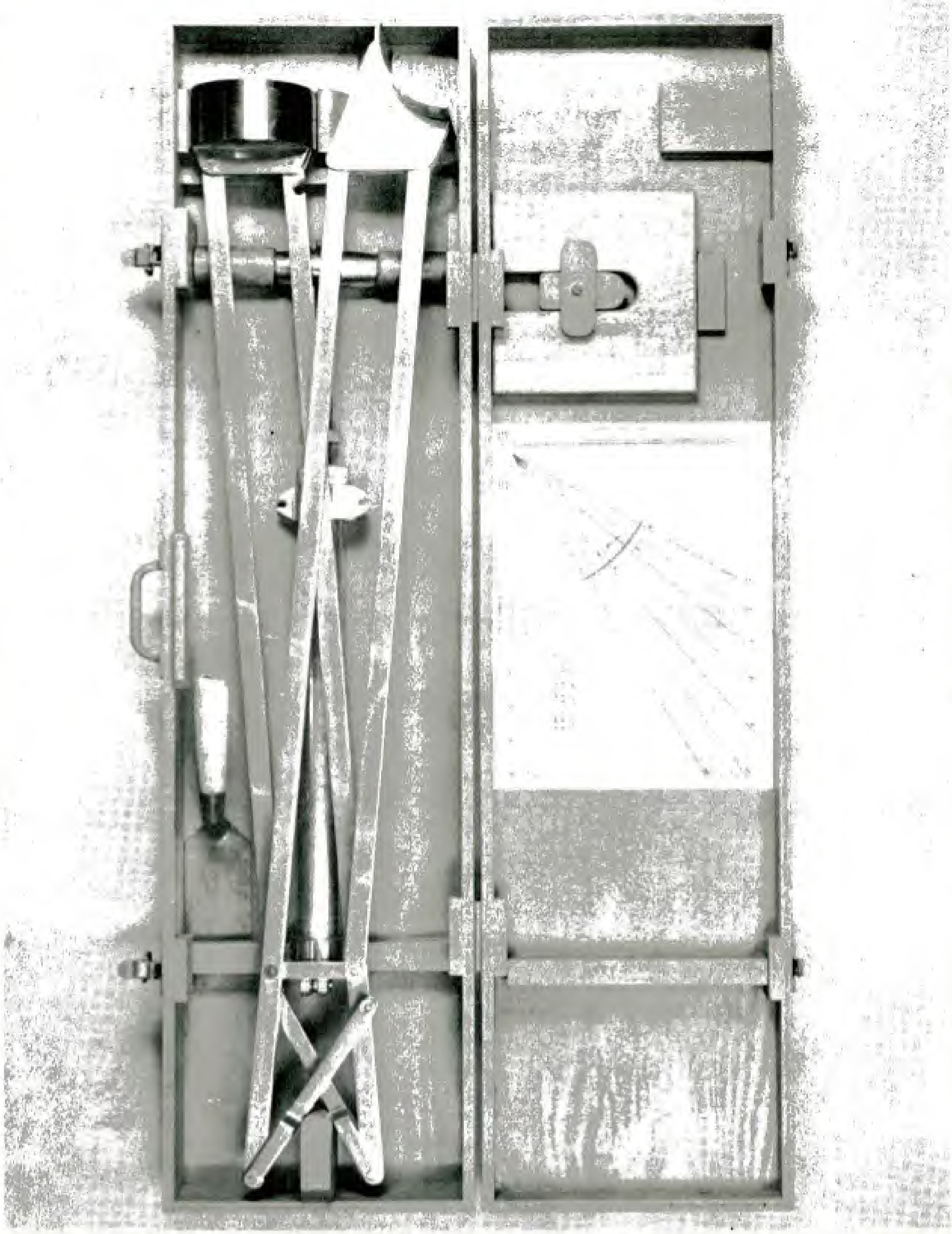


Figure 5. Soil Truss Mark II kit

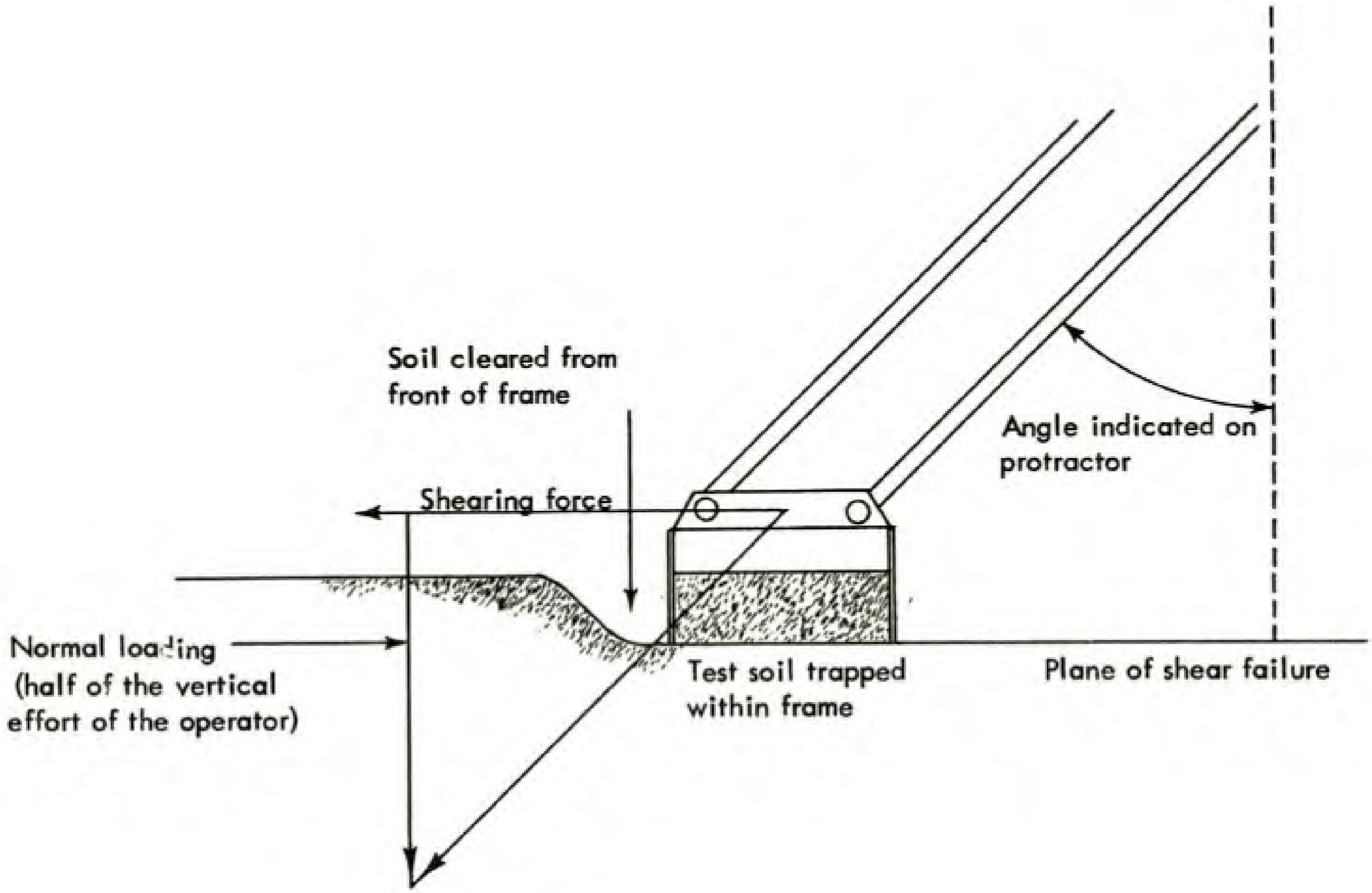


Figure 6. Forces exerted on the soil by Soil Truss, Mark II.

Illustrative Problem	
Protractor	Load reading
35°	70.5
45°	41.5
55°	24.5

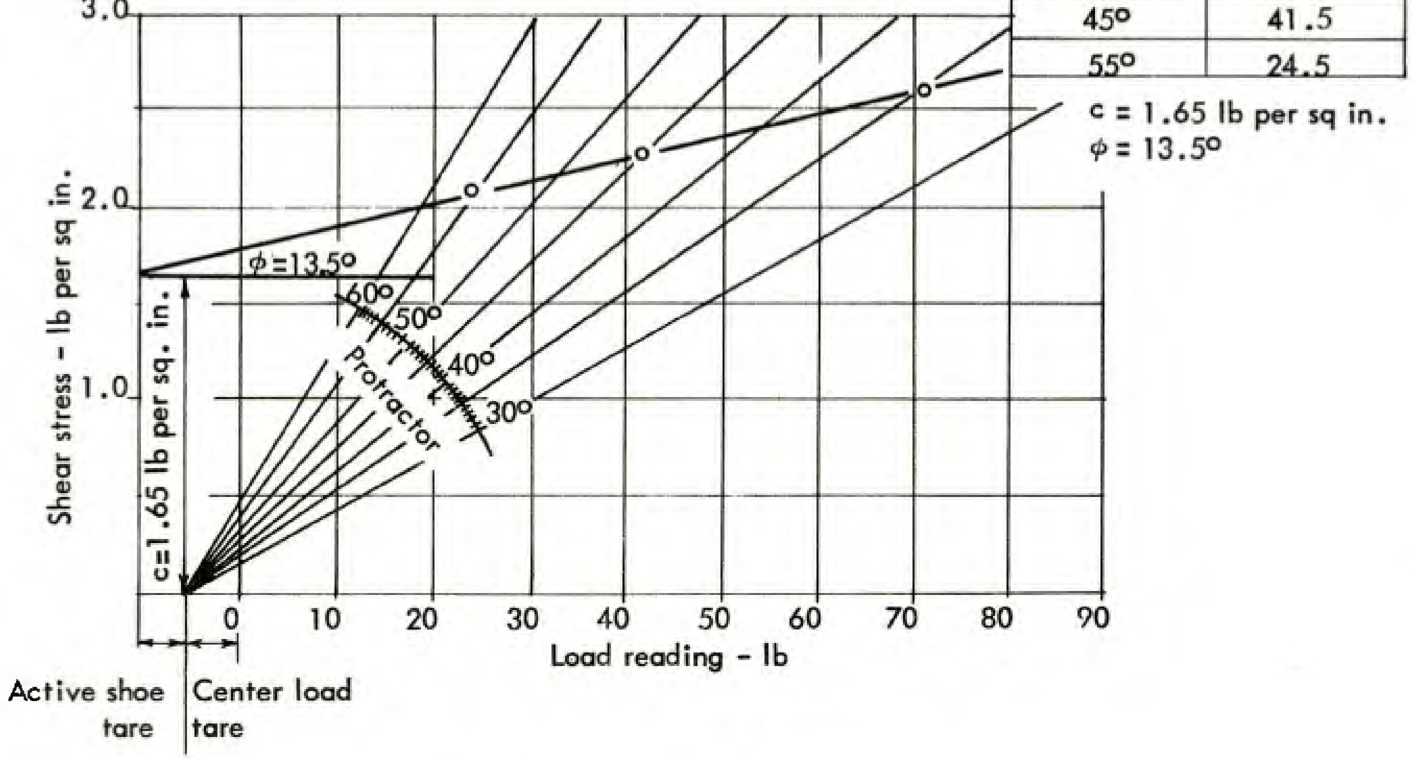


Figure 7. Soil Truss Mark II field chart.

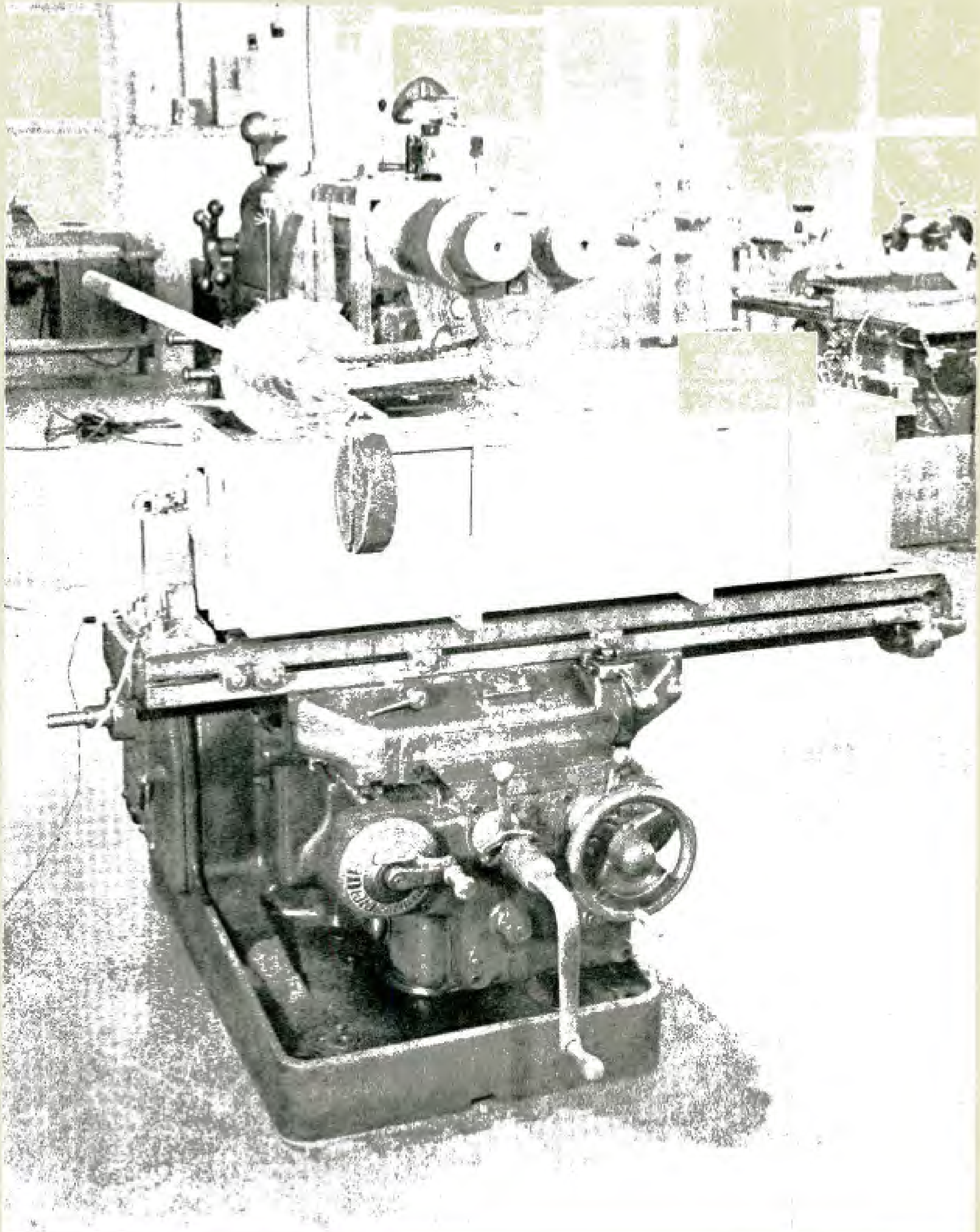


Figure 8. Expedient laboratory traction-test device

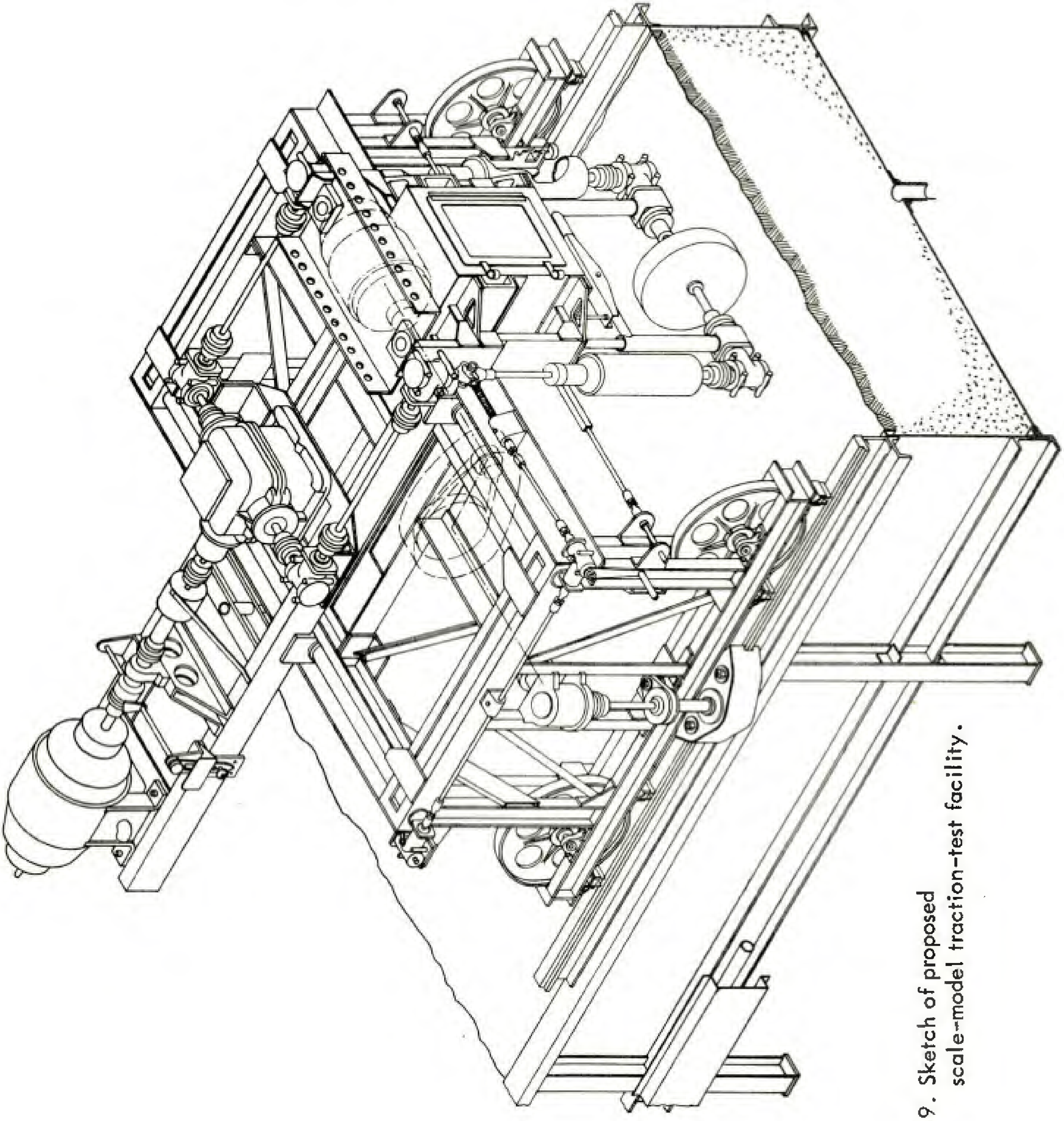


Figure 9. Sketch of proposed scale-model traction-test facility.

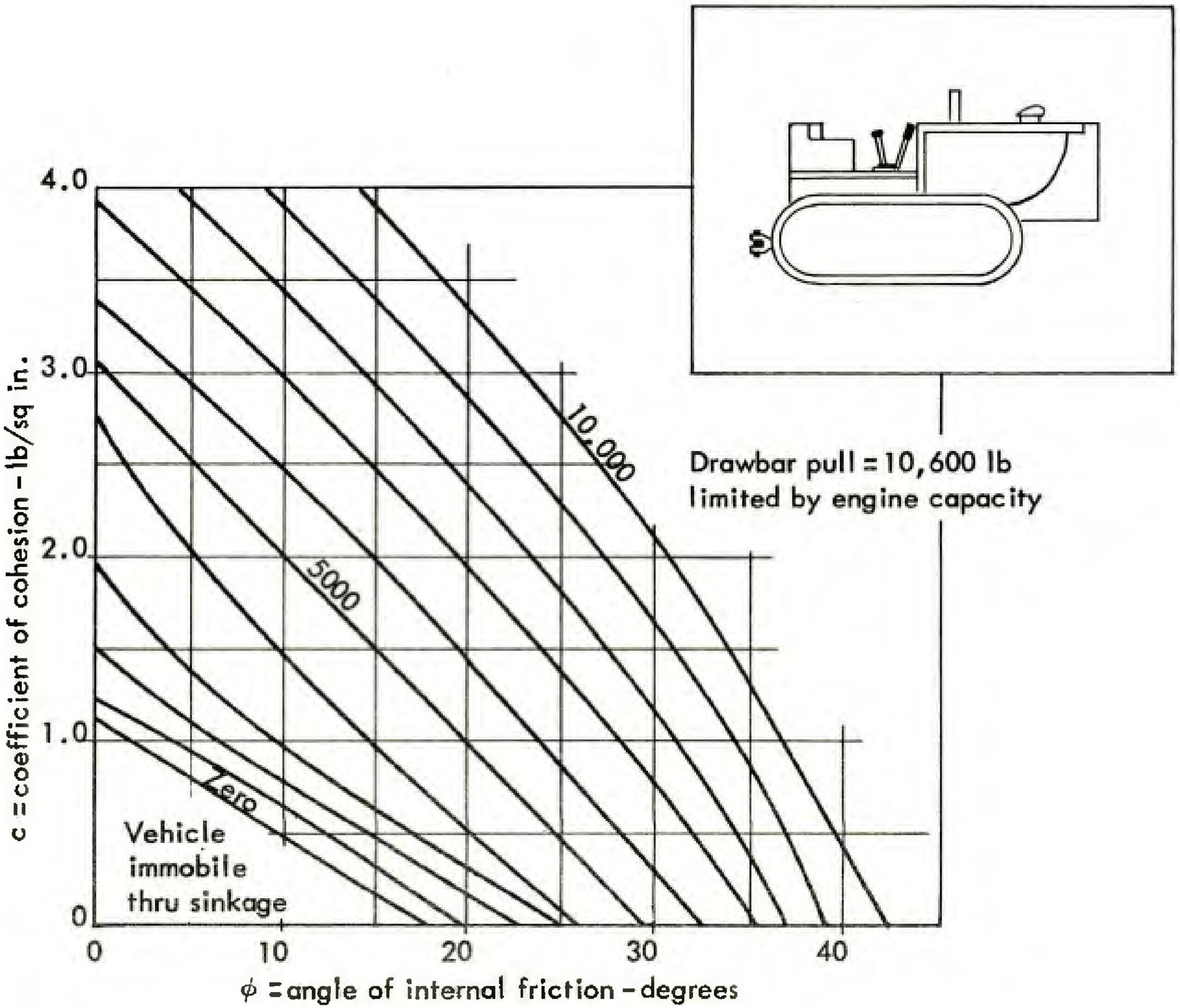


Figure 10. D-4 Caterpillar Tractor maximum drawbar-pull chart.

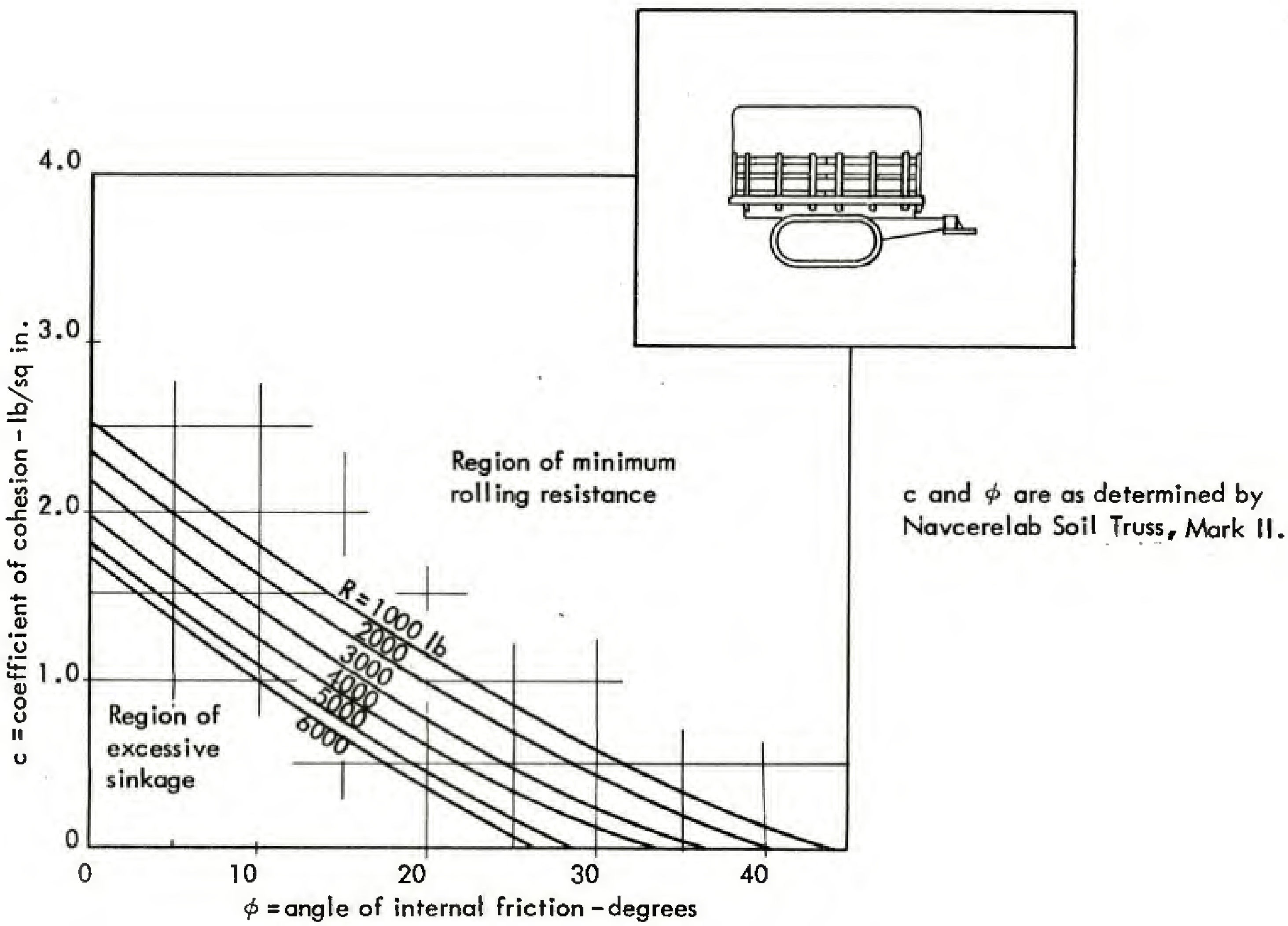


Figure 11. Athey Trailer BT 898-4 rolling resistance.

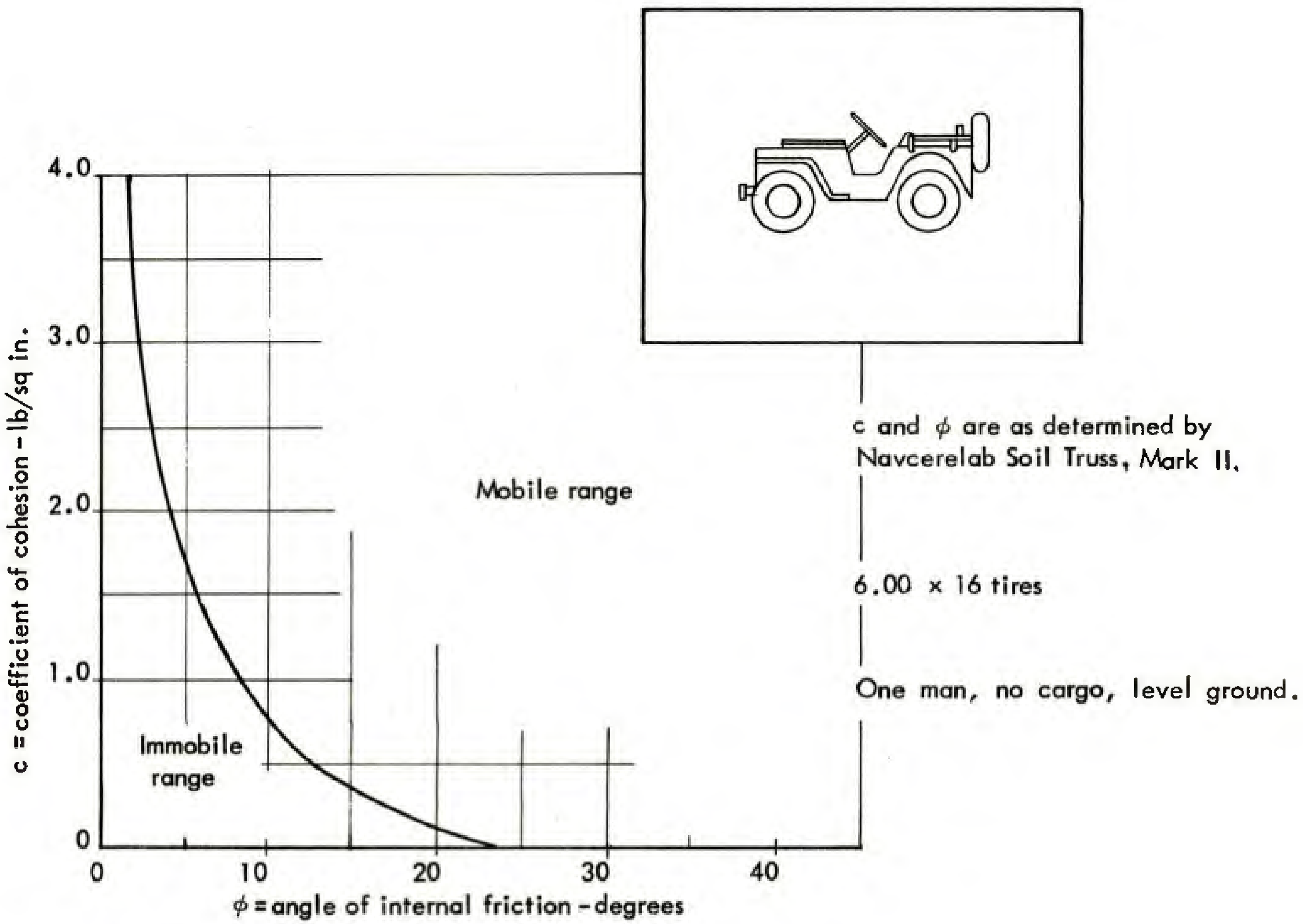
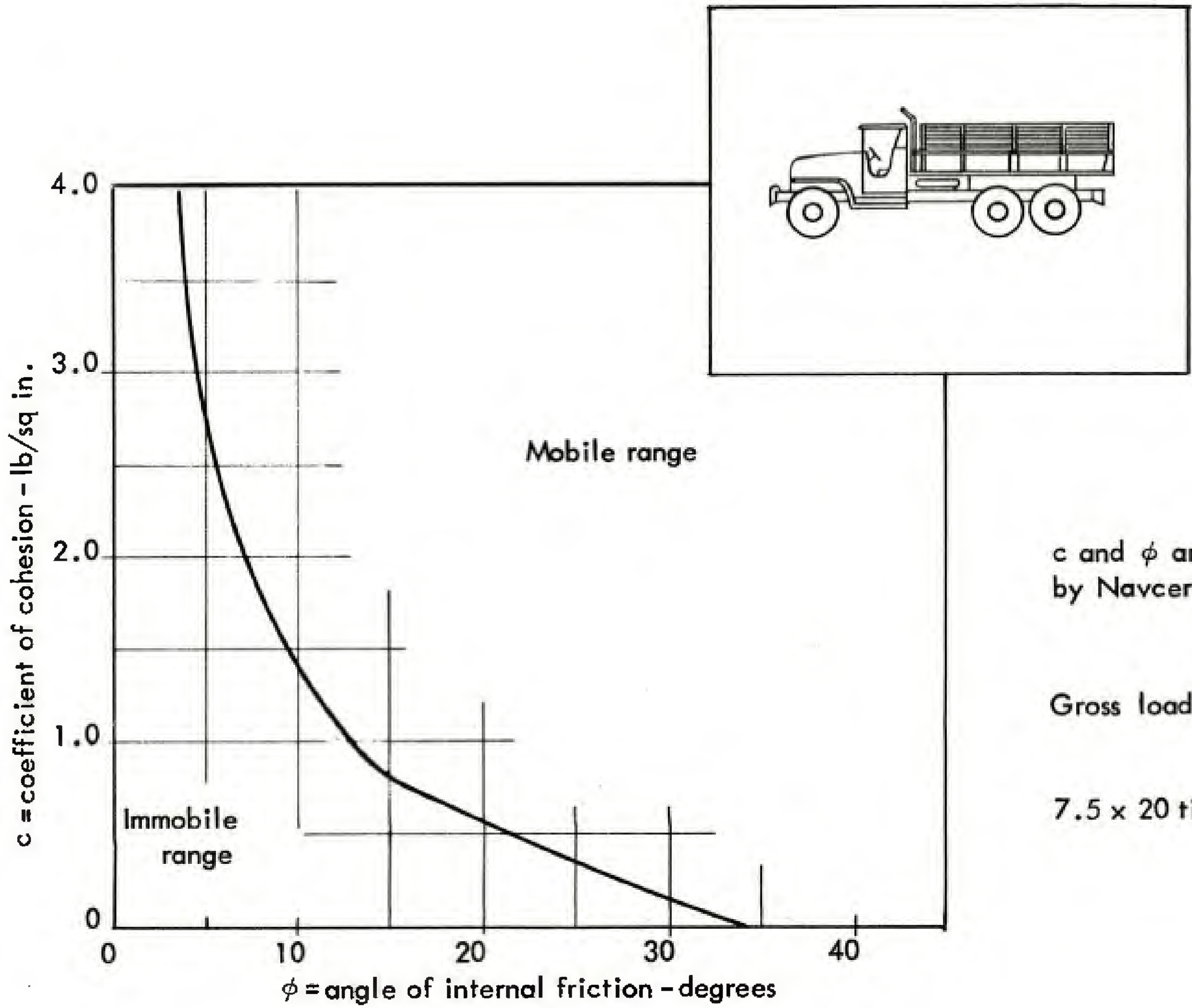


Figure 12. 1/4-ton truck, 4 × 4 Command Reconnaissance (Jeep).



c and ϕ are as determined by Navcerelab Soil Truss, Mark II.

Gross load 17,300-level ground

7.5 x 20 tires, single front - dual rear

Figure 13. 2 1/2-ton truck, 6 x 6 Cargo Dump.