WHEEL BEVAMETER

Thesis for the Degree of M. S.
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Guillermo Carrera

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This is to certify that the

thesis entitled

Wheel Bevameter

presented by

Guillermo N. Carrera

has been accepted towards fulfillment
of the requirements for

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Wesley F. Buchele
Major professor

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WHEEL BEVAMETER

By

Guillermo Carrera

AN ABSTRACT

Submitted to the
College of Agriculture of Michigan State University
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ABSTRACT

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Many workers are now conducting research in which soil trafficability is being related to measurable psycho-geometrical parameters which pertain to both the soil and the vehicle. This investigation studied the feasibility of measuring soil values by means of a forced-slip test wheel, instrumented for determining the following: towing force, horizontal component of resistances to motion and sinkage at a pre-determined fixed-slip value.

An automotive tire was assembled in a carriage where it was free to move vertically under the action of a variable weight and the vertical reaction of the supporting soil. The amount of sinkage was measured with respect to the ground surface. The towing force and a horizontal opposing force were electronically recorded with a Brush direct writing oscillograph.

By recording the towing force and the opposing slip-force to various loads, it was possible to define the horizontal retarding force and relate it as the motion resistance of the test tire for different loads and soil conditions.

The results indicated that meaningful soil parameters can be obtained and with further modifications, an acceptable range of accuracy will be gained in which practical problems

involving the evaluation of soil trafficability can be studied without moving the prototype vehicle across the problem soil.

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INTRODUCTION

The mechanical properties of the soil, as far as agriculture is concerned, has been a neglected field of investigation due primarily to the lack of workable principles and fundamental knowledge upon which to build a systematic study. Only recently, and as a result of the investigations by Bekker (4) and others, it has been possible to establish a solid criterium for research.

Another reason for this apathy toward furthering the knowledge of the soil as a supporting medium of agricultural vehicles and implements is that, in the past, the trafficability of agricultural soils was not of major concern due to the limited power and weight of the farm tractor and the weight of the trailed implements. Because of the modern trend in farming, more powerful tractors and larger machines, the soil may no longer provide adequate support. As a result, the soil is often seriously disturbed, thus reducing the yielding potential of the soil and the performance of the machines.

The farm machinery manufacturing industry, soil scientists and farmers are well aware of the difficulties arising from the consequences of extensive agricultural soil traffic and have sought a reliable approach to the problem of relating the behavior of moving equipment to variable conditions imposed by different soil characteristics.

Using soil mechanics, they would like to predict the trafficability of the soil as well as the effects of the traffic upon tillage, subsequent operations, and plant growth.

As a result of this endeavor a new branch of scientific investigation has emerged. This new field, which has been called Land Locomotion, or even in a wider sense "Terramechanics," is the concern of many scientists in U.S.A. and abroad.

During the past several years intensive research work has been conducted by governmental as well as private institutions, each one in terms of their own objectives, but all of them using the same premises and theoretical values long used by civil engineers in foundation design.

The trafficability of a soil can be determined if certain values can be measured. These values, called parameters, are of paramount importance when evaluating the strength of the soil and its relation to sinkage and slippage of vehicles. Besides this purely mechanical problem, soil values may be related to even more complex problems of seedling impedance and plant growth, provided that a more extensive study of soil-plant interaction is undertaken.

To measure these values, different methods and procedures have been proposed. The shear-vane principle is used to determine the parameters in Coulomb's equation and a penetrometer is used to gather data used to calculate the parameters for Bernstein's equation. The Land Locomotion Laboratory of OTAC (Ordnance Tank-Automotive Command, U. S. Army) has developed a series of apparatus, most of them to be used under laboratory-controlled conditions, for this purpose.

The objective of this project is to develop a simple method of measuring the effects of a variable-weigh towed wheel upon the soil's strength parameters developed by Bekker (1).

The wheel bevameter discussed contains the geared forced-slip tester suggested by Reece (11).

It is hoped that with further refinements this device can be used to measure soil values rather quickly (within an acceptable range of accuracy) and thus be used where comparative study of mechanical properties of soils are desirable.

REVIEW OF LITERATURE

Terzaghi, in his book <u>Theoretical Soil Mechanics</u>, defines the scope of soil mechanics as the branch of applied mechanics which includes the study of the following:

1. Theories of behavior of soils under stress, based on radically simplifying assumptions.

2. The investigation of the physical properties of real soil.

3. The application of our theoretical and empirical knowledge of the subject to practical problems.

He emphatically excluded agricultural soils from his consideration. Nevertheless, his work served as a basic analytical tool from which other investigators derived fundamental knowledge applicable to various problems encountered in off-the-road locomotion.

Micklethwait (3) was the first to call the attention of automotive and agricultural engineers to the possibility of using Terzaghi's "stability problem" to study the relation between soil and tires in automotive vehicles. Nevertheless, the problem of cross-country locomotion has not been the subject of scientific investigation until recently when a series of studies has been undertaken by the U. S. Army, universities, automotive industry, and others.

Immediately after World War II, and as a result of the difficulties encountered by the fighting vehicles when crossing unusually rough terrains, a full scale research program was established by the Land Locomotion Research Branch, Ordnance Corp, U. S. Army.

This laboratory, in addition to other contributions, has developed an apparatus for measuring the vertical stress-strain function and a pneumatic tire test device (3).

The National Tillage Laboratory, in cooperation with the Alabama Polytechnic Institute, has conducted a series of research investigations in order to study the relationship of wheels and lugs to soils under various conditions, including rolling resistance and the distribution of forces from lugs throughout the soil (9).

Pavlics (10) reports the progress of a new test method using rigid wheels for measuring physical soil parameters instead of the sinkage plates and shear annulus ring plate proposed by Bekker (4). The approach was intended to provide a quick and continuous method for soil testing in the field. His conclusions show clearly that the wheel type measuring instruments are not only feasible, but practical for field tests. He reports that the soil parameters obtained by this method are in close agreement with the values obtained from conventional bevameter tests. The only objection that could be raised is that it required extensive instrumentation; this limits the usage to well equipped laboratories with highly specialized personnel for setting up the experiments.

Parallel to the U. S. Army, the Department of Tractor Research Center in Agricultural Engineering Center in Braunschweig (Germany) conducted a number of investigations on the relationship between vehicles and agricultural soils. A considerable number of measuring devices and methods were investigated; these instruments enabled them to correlate research data on the traction, performance of vehicles in relation to slippage and rolling resistance, as well as the determination of shearing resistance and vertical deformation under loaded plates and wheels. Sohne (12) developed a forced slip single-wheel tester and used it under field conditions.

Reece and Wills (11) reported the development of another similar apparatus which can measure the tractive effort, rolling resistance, and slippage of a wide range of rigid as well as resilient wheels and tracks. In the same way as Sohne's instrument, this device also works on the forced-slip principle, in which the test wheel mounted on a frame is obliged to rotate at a controlled slip by unwinding a wire rope from a drum which is geared to the wheel or track under test. The input torque and output thrust are simply measured by instruments hooked to the towing tractor and a cable.

The field of Land Locomotion is rapidly gaining popularity in American universities; several courses on this subject matter are actually offered within the Agricultural Engineering curricula, either as a distinctive type of studies or included in the content of courses in Power and Machinery. The interest of including this subject matter within the training framework of Agricultural Engineering students has been stimulated by the appearance of Bekker's book (4) and the publication of the research work done by the Land Locomotion Research Center of the Ordnance Tank-Automotive Command, U. S. Army.

At Michigan State University, an active and well oriented research program supported by a meaningful graduate course has already produced its first accomplishments shown by the research work carried on by Stong (13, 14), Trabbic (16), Dahir (5), VanderBerg (17), and Hovanesian (7).

DESIGN AND DEVELOPMENT OF THE TEST WHEEL

The Principle of the Forced-Slip Tester

The apparatus under consideration operates on what Reece and Wills (11) called a geared forced-slip principle. In short, the forced-slip tester consists of a towed free-floating test wheel of a rolling radius "r" (Figure 1). The angular velocity of the wheel was increased over a normally towed wheel by means of a gear-chain drive and a drum. Steel cable (wound around the drum) was led off and anchored behind the wheel, which is pulled forward by a tractor. The linear displacement of the wheel equalled the length of unwound cable from the drum. In order to obtain a constant slip of the test wheel, the peripheral speed of the drum was made proportionally less than the linear displacement of the wheel. Since the cable was unwound at no slip, the wheel was forced to slip in an amount proportional to the speed ratio. If "n" is the ratio of the number of teeth on the drum-shaft to the number of teeth on the wheel sprocket, then:

$$i = 1 - \frac{a}{nr} \qquad (1)$$

When:

i = Slippage in per cent
a = Drum effective radius
n = Speed ratio of sprocket
r = Test wheel effective radius

or:

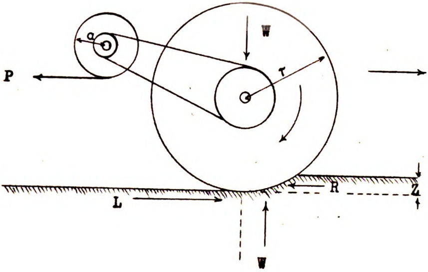

Fig. 1 Forced Slip Principle

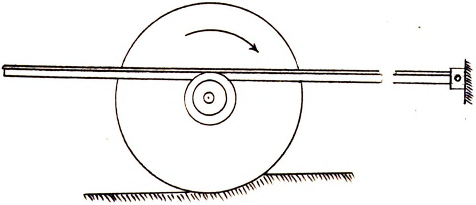

Fig. 2 Variable Weight Principle

$$i = 1 - \frac{A}{r} \qquad (2)$$

Where:

$A = \frac{a}{n}$ is the effective drum radius.

With the arrangement described, it was possible to obtain a constant slip at all times.

In order to obtain a variable sinkage "Z," which would enable us to determine the load sinkage function in the modified Bernstein equation, two rigid bars, mounted lengthwise at each side of the test wheel, provided a means of varying the vertical load upon the tire as it was towed forward with the variable force F against a horizontal component of the resistances P. The arrangement is shown in Figure 2.

Description of the Tester

Prior to the construction of the tester for measuring the above soil parameters, three different scale models were constructed using a FAC X-2 mechanical construction kit. The models (Figures 3 and 4) not only showed the best mechanical arrangement, but also gave an indication of the possible causes of unbalancing forces under dynamic condition.

Once the "best" arrangement was chosen a prototype was constructed.

The test wheel used, a 6.50 x 16 automotive tire, was assembled on a hub keyed to a 1-1/2 inch steel shaft, the tire was held in the middle of a rectangular angular frame with pillow block bearings.

The cable drum and its corresponding sprockets were mounted at the rear of the frame. Another sprocket was

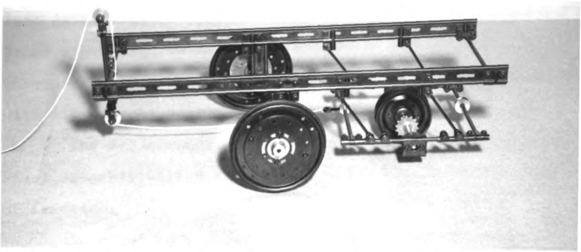

Fig. 3. Portable type wheel bevameter model.

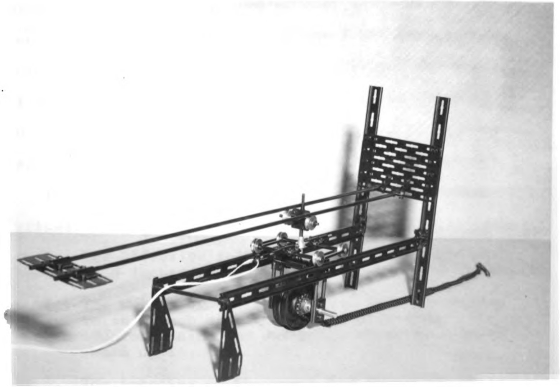

Fig. 4. Stationary frame wheel bevameter model.

located on the wheel-hub shaft and a chain transmitted the peripheral velocity of the cable drum to the wheel sprocket.

The assembly was then attached to the middle of two above-ground suspended tracks by placing the hangers' tips into guide sleeves protruding at each corner of the wheel frame assembly. To allow a free up-and-down movement of the wheel assembly, the connecting guide sleeves were provided with linear ball bearings.

The arrangement allows a linear displacement of the wheel assembly within the length of the tracks with a minimum of friction.

In order to provide a means of varying the vertical load upon the test tire, which, in turn, will cause a variable sinkage, two T-shaped 1/4-inch thick steel bars were mounted lengthwise and located on both sides of the wheel. One end of the bars was hinged to the frame structure and the other end was free. The bars rested upon the wheel shaft and the weight transmitted to the shaft depending on the distance from the hinge. Figures 10 and 11 show the overall view, as well as the details of the arrangement.

The dimensions and specifications of the device were as follows:

1. The effective rolling radius of the tire was 13.5 inches at an inflation pressure of 30 psi.
2. The motion of the towed wheel was transmitted to an 8-inch diameter forced-slip drum mounted behind and above the wheel by a gear-chain drive.
3. The sprocket of the wheel had 56 teeth, while the sprocket of the drum-shaft had 20 teeth; hence, the speed ratio was 0.34.

4. The cable wound around the drum was a 1/8-inch wire cable.

5. The tracks used were two tubular-type barn door tracks with matching rolling hangers mounted 36 inches apart to the structural assembly.

The dimensions of the components are substituted in Equation 1 and the constant slip value is calculated as follows:

Equation 1: $i = 1 - \frac{a}{nr}$

Where:

a = Drum radius 4.1 inches
n = 20/56 0.35
r = Effective radius of the wheel = 13.5 inches

$$i = 1 - \frac{4.1}{(0.35)\ (13.5)} = 15.6\%$$

Figure 12 shows the slip pattern imprinted on the rut created by the tire on the test soil.

Determination of Load-Sinkage Parameters

The relation between load and sinkage has been determined by Bekker and expressed by the equation:

$$p = (k_c/b + k_\phi)\ Z^n \qquad (3)$$

This equation has been applied to simple sinkage plates, tracks, and pneumatic tires, but it was further modified when applied to rigid towed wheels, and expressed as follows:

$$Z = \left[\frac{3W}{(3 - n)\ (k_c + bk_\phi)D^{1/2}}\right]^{\frac{1}{2n + 1}}$$

Where:

Z = Sinkage in inches
W = Normal load on the tire in pounds
D = Effective diameter of the wheel
b = Width of the ground contact area
n = Exponent of sinkage
K_c and K_ϕ = Cohesive and frictional modulus of deformation, respectively

If two successive measurements of sinkage Z_1 and Z_2 are taken corresponding to two different loads W_1 and W_2 under constant slip conditions, we have two equations:

$$Z_1 = \left[\frac{3W_1}{(3 - n)(k_c + b_1 k_\phi) D^{1/2}}\right]^{\frac{2}{2n + 1}}$$

$$Z_2 = \left[\frac{3W_2}{(3 - n)(k_c + b_2 k_\phi) D^{1/2}}\right]^{\frac{2}{2n + 1}}$$

Rearranging terms and taking logarithms of the above equations:

$$\log W_1 = \frac{2n + 1}{2} \log Z_1 + \log \frac{(3 - n)(k_c + b_1 k_\phi)}{3} D^{1/2}$$

$$\log W_1 = \frac{2n + 1}{2} \log Z_2 + \log \frac{(3 - n)(k_c + b_2 k_\phi)}{3} D^{1/2}$$

Now varying the load W and plotting log W vs. log Z we get two straight lines, the slope of which is:

$$\alpha = \frac{2n + 1}{2}$$

And the exponent of sinkage can be expressed as:

$$n = \tan \alpha - 1/2$$

The ordinates at $Z = 1$ are equal to:

$$a_1 = \frac{(3 - n)(k_c + b_1 k_\phi)}{3} D^{1/2}$$

$$a_2 = \frac{(3 - n)(k_c + b_2 k_\phi)}{3} D^{1/2}$$

Hence, the values of k_c and k_ϕ can be determined, being equal to:

$$k_c = \frac{3}{(3 - n)\ D^{0.5}} \left[\frac{a_1}{b_1} - \frac{a_2}{b_2} \right] \frac{b_1\ b_2}{b_2 - b_1}$$

and:

$$k_\phi = \frac{3}{(3 - n)\ D^{0.5}} \quad \frac{a - a}{b_2 - b_1}$$

Another analytical approach to the problem has been suggested by Bekker and Janosi (3). Using equation 3:

$$p = (k_c + bk_\phi)\ Z^n$$

Taking logarithms:

$$\log p = n \log Z + \log (k_c/b + k_\phi)$$

If the equation is plotted on a log-log paper for two different tires width, b_1 and b_2, corresponding to two different normal unit pressures, p_1 and p_2, we get two straight lines sloping to angle α . The tangent of α equals the unknown n value. The ordinates at Z = 1 are equal to:

$$a_1 = k_c/b_1 + k_\phi$$

$$a_2 = k_c/b_2 + k_\phi$$

Hence:

$$k_c = \frac{(a_2 - a_1)\ b_1\ b_2}{b_2 - b_1} \qquad (4)$$

and:

$$k_\phi = \frac{(a_2\ b_2 - a_1\ b_1)}{b_2 - b_1} \qquad (5)$$

Determination of Soil Strength Parameters

The evaluation of shear-slip parameters are much more involved and requires the computation of different slip values. Nevertheless, following Reece's analysis (11), it is possible to make a rough estimate of the soil's shear strength for different normal pressures of the test tire. In fact, from Figure 5 we can evaluate the condition of equilibrium of the forced slip system.

In order to simplify the analysis we rationalize that the geared-drum assembly has been hypothetically replaced for a drum having the same peripherical speed and has been directly attached to the tire's shaft (broken line). Then:

$$\sum F_x = 0 \overset{\rightarrow}{+} = L + F - P - R$$

$$L - R = P - F$$

But: Thrust = L - R

Therefore: Thrust = P - F

Bekker (4) defines the maximum soil thrust of a track or soft pneumatic tire in terms of Coulomb's equation:

$$H = Ac + W \tan \phi \qquad (6)$$

For our purpose we can say:

$$P - F = Ac + W \tan \phi$$

For our purpose we will consider that the above equation maximizes at the design dynamic slip value of 15.68 per cent (normally, maximum draw bar pull of pneumatic tires occurs at 15 to 18 per cent slip). Then:

$$\frac{P - F}{A} = c + p \tan \phi = S_s$$

Where S_s is the shearing strength of the soil. For two different normal pressure values, we have:

$$S_{s_1} = c + p_1 \tan \phi$$

$$S_{s_2} = c + p_2 \tan \phi$$

Thus:

$$\tan \phi = \frac{S_{s_1} - S_{s_2}}{p_1 - p_2}$$

Knowing tan ϕ, c is defined.

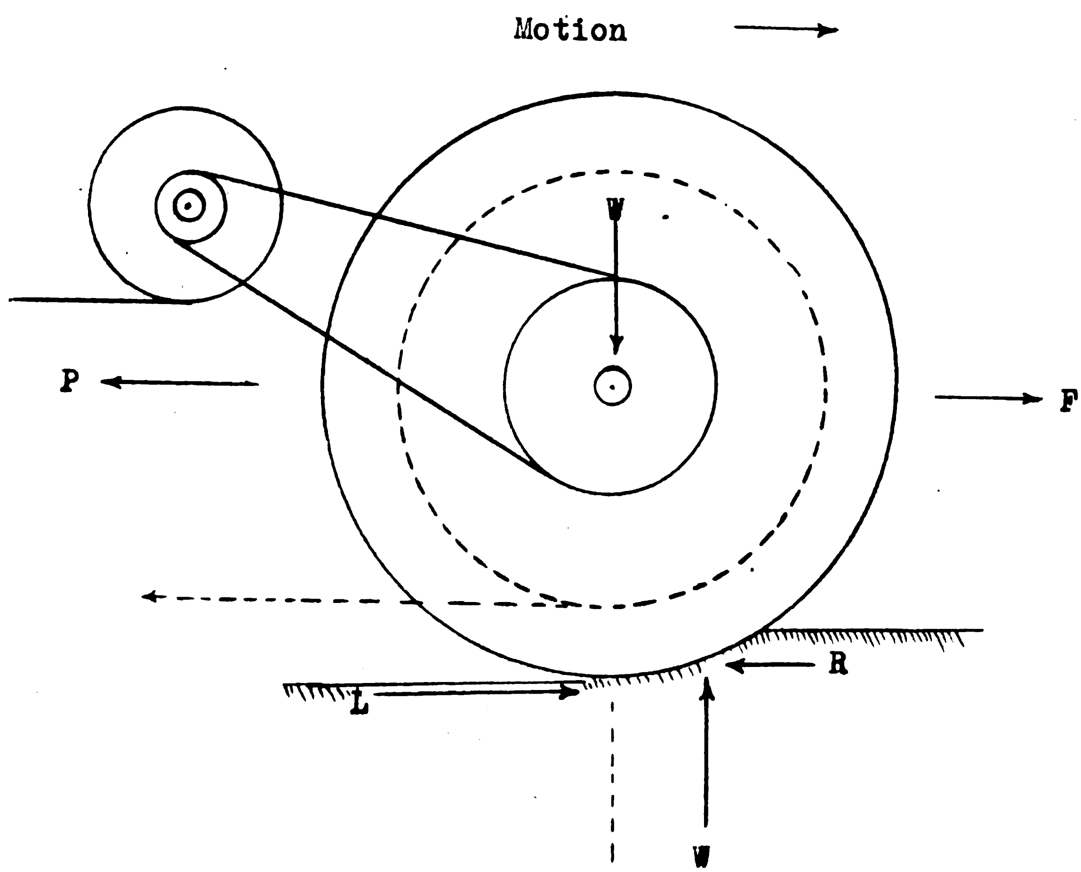

Fig. 5 Force distribution on Wheel Bevameter

INSTRUMENTATION

In order to provide the necessary information for evaluating the soil value system, the following measurements were required:

1. Sinkage values under variable loads.
2. Values of vertical loads upon the test tire.
3. Forward thrust and horizontal component of the resistant forces.

Sinkage Measurements

Figure 9 shows the device used to record sinkage under increasing load. It consists of a 10-inch circular plate keyed to one end of the tire's shaft and rigidly following the rotational and up-and-down movement of the tire. A marker held at a constant height by the barn door track and moving along with the wheel carriage draws a circular line which shows the vertical displacement as well as the angular displacement of the tire with reference to the stationary frame.

By marking the distance travel on the chart and referring to the actual weight on the wheel at various distance of travel, the operator can relate weight to sinkage of wheel.

At the end of each run and before returning the wheel carriage to the initial position, a set of sinkage measurements were taken directly from the rut of the tire (Figure 10).

Both measurements were then compared to secure representative values of sinkage corresponding to the loads imposed on the test tire.

Values of the Vertical Load

Once the loading bars were positioned on the track structure, the weight variation from the free ends were recorded at each two feet interval by a suspension method, using a conventional spring scale. Thus, the total weight imposed to the soil was the sum of the weight of the wheel assembly plus the weight of the bars at each particular interval.

Average values of the load on soil at various distances are as follows:

Distance feet from free end	2	4	6	8	10	12	14
Weight lb. total	320	356	376	406	452	506	636

Forward Thrust and Horizontal Component of Resistant Forces Measurement

Three different methods were studied for measuring the force variation of the forward pull and the horizontal component of the resistances:

1. Direct reading dynamometer scales.
2. Hydraulic dynamometers.
3. Strain gauges test rings.

Direct measurement of forces by means of spring scale dynamometers linked between the towing cable and tractor and between the anchor and drum cable were used during the early sta

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stages of development of the tester. It was soon discarded after a few trials because the vibration of the scales prevented accurate readings and the elongation of the spring of the scale prevented the maintenance of constant slip during the run.

The replacement of spring-scales by hydraulic dynamometers could minimize the vibration and elongation problem on the drum cable, but the recording of data appeared to be too involved.

Finally, it was decided to use proving rings and oscillagraph recording. Four SR-4 strain gauges were mounted on each ring to measure the imposed strain. Since the transmitted forces were within the elastic range of the test rings, a linear stress-strain relationship was assured. A Brush amplifier and a Brush Direct Writing oscillograph were used to record the data.

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TESTING PROCEDURE

A plot of ground was plowed to a depth of eight inches and thoroughly mixed with a rotary hoe to secure a uniform surface; all stones were removed before the surface was leveled.

The structural assembly was supported on two long boards placed on each side of the prepared plot and, once positioned in place, the height of the tracks were checked against the ground level to be sure that the tracks were parallel. At the end of each run the soil was renovated by spading and the surface was smoothed and releveled.

A series of comparative tests were performed using a bevameter with a shear annulus plate and circular sinkage plates.

Prior to each run, a hand wrench was used to place an initial tension in the drum cable, thus assuring that the tire would rotate at the designed slip from the start of the test. An ink pen mark, on the sinkage graph paper, showed the starting point. A tractor was used to tow the wheel at the lowest speed available, approximately 2 mph, in order to neglect the velocity factor as well as to insure proper reading and recording on the oscillograph.

The starting point of each run was set at two feet from the free ends of the loading bars and the final distance was twelve feet from the starting point when the bars

touched the ground surface.

Two kinds of tests were performed in order to secure two different values of sinkage:

1. The average width of the tire was 5.5 inches when the inflation pressure was 30 psi.

2. The average width of the tire was 6.5 inches when the inflation pressure was zero psi.

Besides these two tests a number of other tests were run without the slip-causing cable attached to the anchor.

RESULTS AND ANALYSIS OF DATA

More than fifty tests were performed in the same testing plot. Each set corresponding to a certain soil moisture content as determined on the testing days.

A group of tests with 12 per cent moisture content were selected for analysis as they were more uniform than tests at other moisture contents.

Prior to each run the test rings were calibrated at zero load and the drum cable was tightened.

To evaluate the force required to overcome the friction of moving parts of the wheel assembly, a number of runs were made without the tire touching the ground. It has been found that this, on the average, amounted to approximately 10 per cent of the total towing force. These values were taken into account when processing the data.

The values which appear in Tables I and II are average of all values recorded in each run under identical condition and corresponding to the set selected for analysis.

Table I. Load-sinkage values vs. width of tire.

Distance	Sinkage b = 5.5	Sinkage b = 6.5	Load
ft.	inches		lb.
3	1.118	0.400	329
5	1.253	1.000	349
7	1.331	1.050	366
9	1.331	1.100	389
11	1.440	1.200	426

Using the procedure outlined on pages 14 and 15, the above data were plotted on log-log paper to obtain the two parallel lines shown in Figure 6. The angle of inclination was equal to 47°. The tangent of that angle was 1.0724. Hence:

$$n = \tan 47^{\circ} - 1/2$$

$$n = .5724$$

$$a_1 = 290$$

$$a_2 = 349$$

$$k_c = \frac{3}{(3 - 0.5724)(5.1962)} \left[\frac{290}{5.5} - \frac{349}{6.5} \right] \frac{(6.5)(5.5)}{1}$$

$$k_c = -8.24$$

$$k_{\phi} = \frac{3}{(3 - 0.5724)(5.1962)} \quad \frac{349 - 290}{6.5 - 5.5}$$

$$k_{\phi} = 14.16$$

Using the second approach from pages 15 and 16, the values of unit normal pressure in pounds per square inch were calculated. The area of contact for width b = 5.5 inches was 33 in.^{2} and for b = 6.5 inches was 39 in.^{2}. The unit

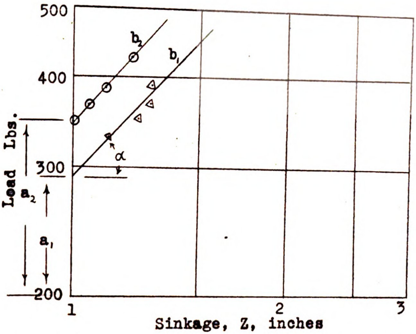

Fig. 6 Load vs. Sinkage Curves (1st. approach)

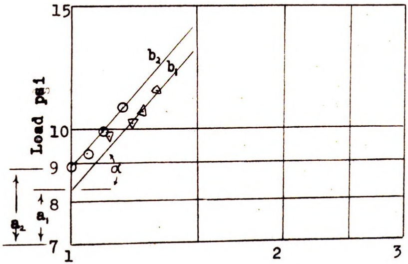

Fig. 7 Load vs. Sinkage Curves (2nd. approach)

pressure (psi) for different travel distances follows:

Distance Feet Width	3	5	7	9	11
		Pounds per square inch			
b = 5.5 in.	9.97	10.57	11.09	11.79	12.91
b = 6.5 in.	8.44	8.95	9.38	9.97	10.92

Plotting the logarithm form of the equation proposed by Bekker on log-log paper, two parallel straight lines were drawn through the points and are shown in Figure 7. The angle of inclination is $\alpha = 48.5^{o}$, the tangent of the angle is equal to the unknown parameter "n".

$n = 1.0176$

The ordinates at Z = 1, are:

$a_2 = 8.95$

$a_1 = 8.30$

Then:

$k_\phi = 12.52$

And:

$k_c = 23.95$

Table II. Average values of towing and resistant forces and calculated unit pressures and soil-tire contact area.

Distance	P	F	A Area	$\frac{P-F}{A}$	p
ft.	lbs.	lbs.	in.^{2}	psi	psi
3	174.57	77.80	39	2.48	8.44
5	188.38	83.43	39	2.69	8.95
7	190.40	80.61	39	2.81	9.38
9	197.35	78.75	39	3.04	9.97
11	216.22	88.65	39	3.27	10.92

We said that the dynamic soil strength can be calculated if $\frac{P - F}{A}$ is set equal to shearing stress, S_s. Then:

$$S_s = c + p \tan \phi$$

Plotting S_s values vs. the normal pressure per unit of area "p," we obtain the straight line shown in Figure 8.

The slope of which represent the angle of internal friction ϕ, and for that particular sample is equal to 18^o. Having defined this unknown parameter, the value of cohesion "c" is also determined.

In this form all the values of the soil parameters have been defined for that type of soil and for a specific moisture content. These values are in Table III.

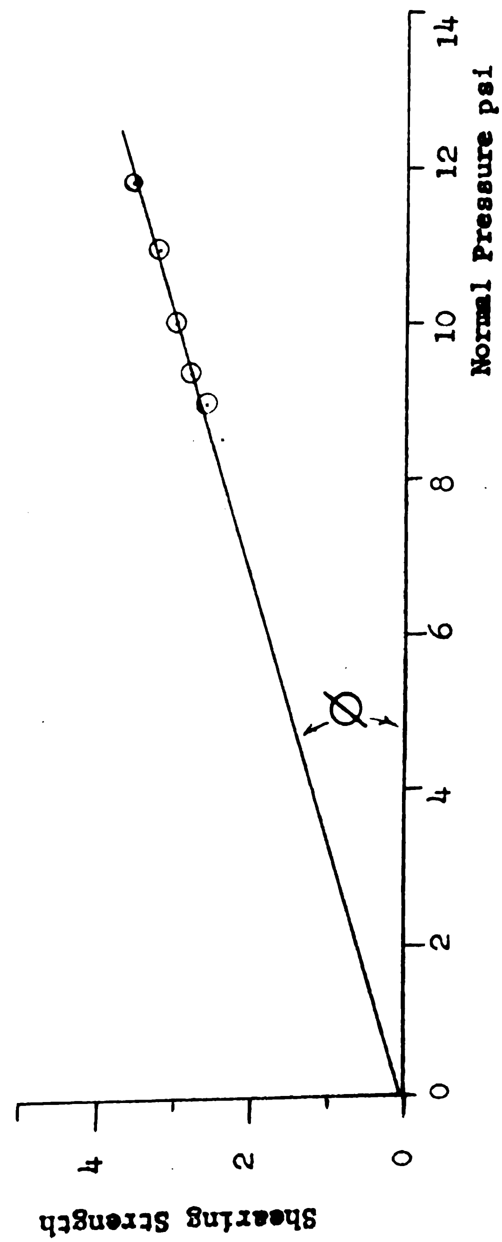

Fig. 8 Shearing Stress vs. Normal Pressure

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TABLE III. Experimental soil values.*

Parameter		Wheel Bevameter		Conventional Bevameter
		1st Approach	2nd Approach	
Cohesive modulus of deformation	k_c	-8.24	23.95	-7.5
Frictional modulus of deformation	k_ϕ	14.16	12.52	37.00
Exponent of sinkage	n	0.5724	1.0176	1.1184
Angle of internal friction	ϕ	18^o		36^o
Cohesion	c	0 psi		0.73 psi

*Moisture content: 12%, bulk density: 1.3 Gram/cc.

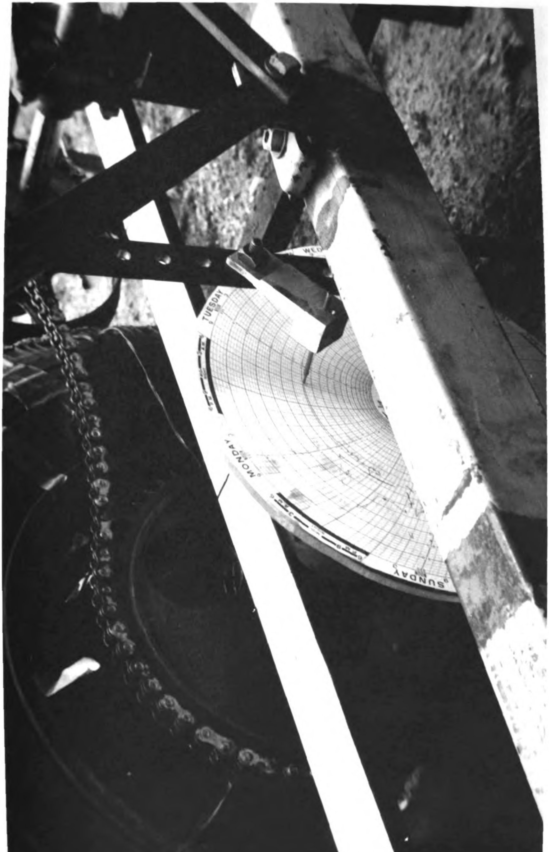

Fig. 9. Sinkage measuring device.

Fig. 10. Direct measurement of sinkage.

Fig. 11. Setting the ink marker on the sinkage plate.

SUMMARY AND CONCLUSIONS

Soil trafficability as it has been generally accepted can be assessed only if the physicogeometrical values pertaining to both the soil and the vehicle have been determined. This project dealt with only a fraction of the whole problem; that is, to prove the feasibility of measuring soil values by means of a forced-slip test wheel, instrumented for determining: towing force, horizontal component of resistances to motion and sinkage under a predetermined fixed-slip value.

The wheel used, an automotive tire, was assembled in a carriage where it was free to move vertically under the action of a variable weight and vertical reaction of the soil. The amount of sinkage was measured with respect to the ground surface. The towing force and a horizontal opposing force was electronically recorded with a Brush analyzer.

At the present stage of development it was only possible to get approximate values of the parameters in the modified Bernestein equation, i.e., k_c: cohesive modulus of deformation, k_ϕ: frictional modulus of deformation, and: n, the exponent of sinkage reflecting the rate of strain change with load.

Relating the towing force (F) and the opposing slip-force (P) to various loads (W), it was possible to define the horizontal retarding force and relate it as the motion re

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resistance of the test tire for different loads and soil conditions.

A complete evaluation of soil trafficability factors required the determination of additional soil values, expressed in Coulomb's equation, that is: cohesion "c" and the angle of internal shear ϕ. To accomplish this, certain modifications will have to be introduced to the basic design of the tester which will allow not only the measurements of the thrust but the maximum thrust attainable at certain slip values.

Some of the causes of unbalancing forces of the free-floating wheel assembly will have to be overcome in order to have net force readings. The effect of inflation pressure and carcass stiffness have to be taken into account.

Fig. 12. Slip pattern when operating at 10 per cent slip.

RECOMMENDATIONS FOR FURTHER STUDIES

The wheel bevameter has proved to be a fairly reliable instrument for measuring load-sinkage parameters under controlled field conditions. To make it a more worthy instrument, the following features should be considered:

1. A precise sinkage reading may be obtained by replacing the sinkage-recording-plate with linear potentiometers.
2. It has been found that the use of linear bearings intended to allow a free floating action of the wheel assembly introduced serious problems of dirt inclusion and friction. Test tires free to rotate around crankshaft-like shafts would eliminate this problem.
3. As all the tests were performed without moving the tester from the same plot, no transportation wheels were provided. But, if the apparatus is going to be used extensively for practical field measurements, some kind of retractable wheels should be provided.
4. To get accurate sinkage readings and to eliminate the terrain uneveness factor, it is advisable to have some sort of built-in tilling and leveling device.

5. In order to determine the sinkage parameters, according to standard procedures, it is necessary to record the load sinkage values for two different contact patch widths. Therefore, the addition of another test tire of same rolling radius and different width may provide the required information without recurring to the artificial procedure followed during the tests.
6. It has been already mentioned that the evaluation of the shear-strength parameters require the determination of maximum soil thrust attainable at optimum slippage. If the resistance to motion and power demand were the only objective, the fixed-slip arrangement is satisfactory, but if the parameters in Coulomb's equation are to be defined, it is necessary to incorporate some method of varying the slippage within a wide range of values; some kind of electromagnetic friction brakes might do the job.

REFERENCES

1. Bekker, M. G. (1950) Relationship between soil and a vehicle. SAE Transactions No. 3.

2. Bekker, M. G. (1957) Terrain evaluation in automotive off-the-road operations. Research Report No. 13. Department of the Army, Ordnance Tank-Automotive Command, Research and Development Division. Land Locomotion Research Branch.

3. Bekker, M. G. and Janoski, Z. (1958) Terrain evaluation of pneumatic tires in soft soils. Report No. 5. Department of the Army, Ordnance Tank-Automotive Command, Research and Development Division. Land Locomotion Research Branch.

4. Bekker, M. G. (1960) Off-the-road locomotion. The University of Michigan Press. Ann Arbor. 220 pp.

5. Dahir Abdallah George (1961) The effect of liquid and dry ballast on the stability of pneumatic tired tractors. Unpublished M.S. thesis. M.S.U.

6. Harris, W. Lamar (1961) Dynamic stress transducers and the use of continuum mechanics in the study of various soil stress-strain relationship. Ph.D. thesis. M.S.U.

7. Hovanesian, Joseph der. (1958) Development and use of a volumetric transducer for studies of parameters upon soil compactation. Ph.D. thesis. M.S.U.

8. Janosi, Z. (1961) An analysis of pneumatic tire performance on deformable soils. Paper No. 45. Proceedings of the 1st International Conference on the Mechanics of Soil-Vehicle Systems. Mechanics of Soil Vehicle Systems Edizione Minerva Tecnica. Torino, Italy.

9. Nichols, M. L. (1958) Purpose and history of the National Tillage Laboratory. Proceedings of seminar on tillage and traction equipment. ARS 42-16. Agricultural Research Service. USDA.

10. Pavlics, Ferenec. (1961) Bevameter-100. A new type of field apparatus for measuring locomotive stress-strain relationships in soils. Paper No. 22. Proceedings of 1st International Conference on the Mechanics of Soil-Vehicle Systems. Mechanics of Soil Vehicle Systems. Edizione Minerva Tecnica. Italy.

11. Reece, A. R. and Wills, B. M. D. (1961) Forced-slip wheel and track tester. Paper No. 25. Proceedings of the list International Conference on the Mechanics of Soil-Vehicle Systems. Mechanics of Soil Vehicle Systems. Edizione Minerva Tecnica. Torino, Italy.

12. Sohne, Walther. (1960-1962) Personal correspondence.

13. Stong, J. V. (1961) The effect of liquid and dry ballast on the stability of pneumatic tired tractors. M.S. thesis. M.S.U.

14. Stong, J. V. and Buchele, W. F. (1962) Effect of soil parameters on strength of tillable tools. ASAE Paper No. 62-132.

15. Terzaghi, Karl. (1959) Theoretical Soil Mechanics. 9th Ed. John Wiley and Sons, Inc., New York.

16. Trabbic, W. G. (1959) The effect of drawbar load and tire inflation on soil-tire interface pressure. M.S. thesis. M.S.U.

17. VandenBerg, G. E. (1958) Application of continuum mechanics to compaction in tillable soils. Ph.D. thesis. M.S.U.