TECHNICAL REPORT NO. 3-666

PERFORMANCE OF SOILS UNDER TIRE LOADS

Report I

TEST FACILITIES AND TECHNIQUES

by

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January 1965

Sponsored by

U. S. Army Materiel Command
Project No. 1-T-0-21701-A-046
Task 03

Conducted by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi
The test facilities and techniques described herein are being used in studies conducted at the U. S. Army Engineer Waterways Experiment Station under DA Project 1-T-0-21701-A-046, "Trafficability and Mobility Research," Task 1-T-0-21701-A-046-03, "Mobility Fundamentals and Model Studies," under the sponsorship and guidance of the Directorate of Research and Development, U. S. Army Materiel Command.

Acknowledgement is made to Lt. Gen. A. G. Trudeau, former Chief of Research and Development, Department of the Army, who directed the initiation of the study of the performance of soils under pneumatic tires; to Mr. R. C. Kerr, chairman, and Dr. Lester Goldsmith, Dr. L. C. Stuart, Dr. Robert S. Rowe, and Mr. C. J. Nuttall, members of the ad hoc committee that recommended the research program; and to Messrs. R. R. Philippe and R. F. Jackson, U. S. Army Materiel Command, and Mr. M. V. Kreipke, Office, Chief of Research and Development, who visited the Waterways Experiment Station and advised in the formulation of the research procedures. Personnel of the Land Locomotion Laboratory, U. S. Army Tank-Automotive Center, and of the U. S. Army Transportation Research Command, both of which are under the U. S. Army Materiel Command, maintained liaison and made valuable comments and suggestions. Messrs. C. J. Nuttall and C. W. Wilson of Wilson, Nuttall, Raimond, Engineers, Inc., served as consultants and aided in the formulation of the test program, design of the test equipment, and analysis of data.

Testing to determine the performance of soil under pneumatic tires has been and is being conducted by personnel of the Army Mobility Research Branch, Mobility and Environmental Division, Waterways Experiment Station,
under the general supervision of Messrs. W. J. Turnbull, W. G. Shockley, and S. J. Knight, and the direct supervision of Mr. D. R. Freitag.

Mr. J. L. McRae directly supervised this project during a 12-month absence of Mr. Freitag, who was studying under a Research and Study Fellowship grant. Other personnel who have been actively engaged in the study are Messrs. C. J. Powell, A. B. Thompson, J. L. Smith, G. T. Easley, R. D. Wismer, G. W. Turnage, and SP-4 J. R. Wood, engineers, and Miss M. E. Smith, mathematician. This report was written by Messrs. McRae, Powell, and Wismer. Material assistance in the prosecution of the work was given by 1st Lt. L. J. Lanz, Transportation Corps Liaison Officer.

Col. Edmund H. Lang, CE, and Col. Alex G. Sutton, Jr., CE, served as Directors of the Waterways Experiment Station during the preparation of this report, and Mr. J. B. Tiffany was Technical Director.
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SUMMARY

This report presents introductory and background information on research being conducted on performance of soils under tire loads, and describes in detail the test facilities and techniques used by the Army Mobility Research Branch, Mobility and Environmental Division, U. S. Army Engineer Waterways Experiment Station. It also includes a complete list of definitions of mobility terms with particular reference to those concerning pneumatic tires.
PART I: INTRODUCTION

Background

1. The vehicle mobility research program discussed herein began in March 1959, when an ad hoc committee appointed by the Chief of Research and Development, Department of the Army, with Mr. R. C. Kerr as chairman, held its first meeting. This committee was created to study the status of ground vehicle mobility research in the Department of the Army and to make recommendations as to how the research could be accelerated. Among the several recommendations of this committee were the following:

a. Institute a "crash" research program at the Army Mobility Research Branch (AMRB)* test facility to evaluate the relative soft soil performance of currently available sizes of pneumatic tires. This study would produce data that would aid in the proper selection of tire sizes for a new family of Army vehicles scheduled for procurement within the next few years and would take precedence over the normal pursuit of the long-range objectives of the AMRB research program.

b. Establish a permanent working committee that would encourage coordination of mobility research efforts by Ordnance Corps, Transportation Corps, and Corps of Engineers. The committee would also make periodic reviews of progress and report to the Chief of Research and Development.

2. The Chief of Research and Development concurred with the findings of the ad hoc committee and implemented them in a disposition form dated 27 May 1959 to the Chiefs of the three Technical Services involved

* At the time of the committee's action this organization was designated the Army Mobility Research Center, Soils Division, U. S. Army Engineer Waterways Experiment Station. It is now known as the Army Mobility Research Branch, Mobility and Environmental Division, U. S. Army Engineer Waterways Experiment Station.
(Ordnance, Transportation, and Engineers). Specifically, the U. S. Army Engineer Waterways Experiment Station (WES) was to complete the main test facility and activate the research program. The recommended review committee also was formed, with Mr. R. C. Kerr again acting as chairman. This committee met in September 1959 and recommended that additional necessary funds be provided. Representatives of the three Technical Services met in February 1960 to agree upon a definite plan of tests for the research program. A copy of this plan is included as Appendix A. Briefly, it provided for testing with a range of tire sizes, under varying conditions of load and inflation pressure, on three representative types of soil. The tire sizes were chosen to provide variations of both width and diameter; loads and inflation pressures were chosen to cover the useful working ranges of the tires and the test equipment. The three soils chosen for testing were sand, heavy clay, and clayey silt, since these would be representative of a wide range of inorganic soils. All testing was to be done with treadless tires so that geometry effects could be evaluated independently of tread effects. Study of effects of tire treads and track configurations was to be deferred until a later date. The WES was directed to proceed with the research program in a letter dated 7 March 1960 from the Chief of Engineers, subject, "Plan of Tests, Performance of Soils Under Tire Loads" (see Appendix A). Steps were taken immediately to procure test tires and to develop operating techniques. Testing with sand was started on 6 June 1960, and full operating efficiency was attained by 1 August 1960. Testing with clay was started on 13 September 1961. No tests have yet been conducted with clayey silt.

Purpose of This Report

3. The purpose of this report is to describe the test apparatus, equipment, and techniques being employed in the main testing facility of the AMRB in the study of the performance of soils under moving pneumatic tires, and to present definitions of frequently used words peculiar to this study to provide a reference for use in future reports of this series.
Previous Investigations

4. The present research program was preceded by and now is being performed in conjunction with other related mobility research studies. The results of these studies have been or are being published. The studies include investigations of the deflection of moving tires, tests with rigid wheels, determinations of stresses in the soil mass under moving vehicles and stresses at the tire-soil interface, and laboratory studies of the relations among various soil parameters used in vehicle mobility research. The published reports dealing with these subjects are listed on the inside of the back cover of this report.

Definitions

5. Many of the terms used in this report and in several already-published reports have not been rigidly defined heretofore. The following list defines these terms as they are now used at the WES and in this report:

a. Tire geometry* (refer to fig. 1):
   Carcass diameter (d): Outside diameter, exclusive of tread, of the inflated but unloaded tire. Equals the rim diameter plus twice the carcass section height.
   Tire diameter: Outside diameter, including tread, of the inflated but unloaded tire. Equals the carcass diameter (d) plus twice the tread height at the center line of the cross section. In fig. 1, one-half of the tire diameter, i.e. the tire radius, is shown.
   Section width (b): Maximum outside width of the cross section of the inflated but unloaded tire.

* These definitions are in general agreement with established terminology of the tire industry, but include some additional terms adapted specifically to the WES mobility program.
Fig. 1. Dimensional terminology for tire and rim

NOTE: PERCENT DEFLECTION = \[
\frac{\text{DEFLECTION}}{\text{CARCASS SECTION HEIGHT}} \times 100,\]

CARCASS SECTION HEIGHT
Loaded section width: Maximum outside width of the cross section of the loaded tire when the tire is resting on an unyielding, horizontal, plane surface.

Tire section height: Distance from the shoulder of the rim to the periphery of the tire, including tread, measured along the vertical center line of the cross section of the inflated but unloaded tire.

Carcass section height: Distance from the lip of the rim flange to the periphery of the tire, exclusive of tread, measured along the vertical center line of the cross section of the inflated but unloaded tire.

Loaded carcass section height: Minimum distance from the lowest point of the lip of the rim flange to the unyielding level surface on which the loaded tire is resting, less the tread height.

Tire deflection: Any displacement of a point on the tire surface from its position on the inflated but unloaded tire.

Maximum hard-surface deflection ($\delta_{\text{MH}}$)*: Difference between carcass section height and loaded carcass section height.

Maximum in-soil deflection ($\delta_{\text{MS}}$): Maximum deflection measured on the center line of the cross section of the tire as it moves in the soil. Its magnitude depends upon load, inflation pressure, and soil strength.

Contact area: The portion of the tire in contact with the supporting surface. Interruptions of the contact area due to tread patterns are considered part of the contact area.

* $\delta$ is often expressed in percent by dividing the deflection by the carcass section height and multiplying by 100.
Tire print: Contact area on an unyielding surface.
Contact pressure: Load on the tire divided by the contact area.
Contact length: Maximum length of the contact area, measured parallel to the plane of rotation of the tire.
Contact width: Maximum width of the contact area, measured perpendicular to the contact length.
Hard-surface rolling circumference: Forward advance per revolution of the loaded tire when towed on a flat, level, unyielding surface.
Nominal rim diameter: Wheel diameter at the shoulder of the rim. This is the rim diameter figure which appears in the designation of the tire size (e.g. the "16" in "6.00-16").
Rim diameter: Wheel diameter at the lip of the rim flange.

b. Soil strength:
Cone index: An index of soil strength obtained with the cone penetrometer. It is the unit load required to maintain movement of the cone-shaped probe normal to the surface of the soil. It has the dimensions pounds per square inch, and is usually given as an average value for a specified layer of soil several inches thick.

$k_c$ and $k_\phi$ and $n^*$: Constants of the equation $p = \left(\frac{k_c}{b^c} + k_\phi\right) z^n$, where $p$ is pressure, $z$ is sinkage, and $b$ is the width of the penetrating plate. The equation is intended to approximate the plate-penetration test results.

\( c_t, c_d, c_a, \phi_t, \phi_d, \) and \( \phi_a \): Constants of the equation \( s = c + p \tan \phi \), which expresses the linear relation of shear strength \( s \) to normal pressure \( p \) for a given soil. The subscripts \( t, d, \) and \( a \) denote the device (triaxial shear, direct shear, in-situ ring shear, respectively) with which the data were obtained.

c. Wheel performance:

Torque \((M)\): Torque input at the axle.

Travel ratio: Ratio of the actual wheel advance per revolution to the theoretical advance per revolution.

Slip: Unity minus the travel ratio where the theoretical wheel advance per revolution is taken as the hard-surface rolling circumference. Slip is usually expressed as percentage.

Pull \((P)\): The component, acting parallel to the direction of travel, of the resultant of all soil forces acting on the wheel. It is considered positive when the wheel is performing useful work, and negative when an additional force must be applied to maintain motion. Pull at any particular level of slip is denoted by use of the letter \( P \) with a subscript specifying the percentage of slip. For instance, \( P_{20} \) is the pull at 20 percent slip.

Maximum pull point \((P_M)\) (fig. 2): The point in a programmed-slip test where the pull is a maximum (in the mathematical sense) on the pull-slip curve.

Self-propelled condition: The condition in which the pull is zero and the torque input is just

* See U. S. Army Engineer Waterways Experiment Station Technical Report No. 3-639, Strength-Moisture-Density Relations of Fine-Grained Soils In Vehicle Mobility Research, January 1964.
sufficient for the wheel to propel itself.

Self-propelled point (figs. 2 and 3): The point in a programmed-slip test where the wheel attains the self-propelled condition.

Fig. 2. Sample pull-slip and torque-slip curves for Yuma sand

Towed condition: The condition in which torque input to the wheel is zero and the pull is negative.

Towed point (figs. 2 and 3): The point in a programmed-slip test where the wheel attains the towed condition.

Towed force ($P_T$): Pull at the towed condition.

Hard-surface rolling resistance: Horizontal force required to tow the wheel, under load and with transmission out of gear, on a flat, level, unyielding surface. This force includes wheel bearing friction and partial transmission losses.
Fig. 3. Sample pull-slip and torque-slip curves for clay

**Load (W):** The vertical force applied to the wheel.

**Hub movement:** Vertical movement of the wheel hub relative to the original soil surface.

**Sinkage (z):** Maximum depth to which the wheel penetrates the soil relative to the original soil surface.

**Rut depth:** Depth of rut, relative to the original surface, after passage of the wheel. (May differ from sinkage because of soil rebound or fill-in.)
PART II: PREPARATION OF SOILS FOR TESTS WITH PNEUMATIC TIRES

General Layout of Soil Preparation Facilities

6. A general view of the operational area of the main AMRB test facility, showing the soil-processing plant, a straddle truck on which are mounted soil-processing tools, and soil cars, is shown in photograph 1. The soil cars are constructed of steel plate to the cross-section shape and dimensions shown in photograph 2; they are 27 ft long, and fitted with removable endgates. Two cars, joined end to end, make up a test unit which is formed before soil placement is started. Holes are provided in the sides of the cars for mounting pressure cells or inserting electrical leads for test purposes. A gridwork of steel tracks on the floor of the test facility is used to move the soil cars about the facility as required.

Procedure for Preparing Test Cars of Dry Sand

7. Preparation of test cars of sand presents relatively few problems, primarily because all the tests are performed with air-dried material. Actual moisture content is usually about 0.5 percent of dry weight. Different degrees of soil strength are achieved by varying the density of the sand. Depending upon strength conditions desired, the sand is placed in the cars either in uniform layers and then finally screeded and vibrated on the surface, or in individual layers which are screeded and vibrated as the filling progresses. Uniform deposition of each layer is achieved by placing a large 1/4-in.-mesh screen on top of the car and depositing the sand uniformly over the screen with a tractor-mounted shovel, commonly called a front-end loader. This procedure is illustrated in photograph 3. Use of the screen assures a uniform distance of fall for each individual layer of sand; but, of course, the height of fall becomes progressively less with the addition of each new layer. Thus, in the initial condition the sand density is somewhat greater in the first layers placed than in the last. Compaction is accomplished by a vibrating skid unit consisting of an electric vibrator mounted on a steel baseplate that is long enough to span the
width of the soil car. This vibrator, which delivers blows of 1800-lb magnitude at the rate of 3600 per minute, is pulled back and forth over the length of the car at a constant speed by an electrical towing unit built especially for this purpose (photograph 4).

8. After placement of the sand, appropriate measurements are made to determine if the desired strength level and strength profile have been achieved. If not, further treatment, including scarifying or vibrating as required, may be given. Then the test cars are moved over the track system to their proper position in the test lane, which usually consists of two approach cars and the two test cars; occasionally one or two additional cars may be included to accommodate an overrun of the test wheel. When the test cars have been positioned in the test lane, the endgates are removed and the cars are fastened to the other cars in the test lane to provide a continuous soil surface. During removal of the endgates, a certain amount of soil is spilled. Therefore, after the test cars have been fastened to the other cars the joints are refilled, tamped, and brought to grade by hand.

9. Normally, two tests are run side by side in each pair of test cars. When these two tests have been completed, the test cars are rolled out of the line and the top 18 in. of the sand is removed by means of a special bulldozer attachment mounted on a modified lumberyard straddle truck (see photograph 5). Then the sand is either put into a storage bin or used to reconstruct the test car.

Procedure for Preparing Test Cars of Cohesive Soil

10. The processing of cohesive soils is inherently difficult because both density and moisture content must be controlled. Different degrees of soil strength are achieved by preparing the soil at different moisture contents. Load-independent soil conditions at each level of moisture content are approximated by compacting the soil-water mixture to a density such that nearly all the voids are filled with water.

11. The initial preparation of material for use in the construction of a typical test car of clay begins on an outdoor, asphalt-paved, processing area where the natural clay is turned and worked until it has been
air-dried to about 10 percent moisture content. It is then transported to soil storage bins in a building attached to the main test facility. Horizontal augers sweep across the floors of the storage bins and feed the soil into a main auger which carries it to a bucket elevator. The bucket elevator raises the soil into an even-flow measuring hopper (photograph 6). At this point, the soil is metered onto a belt conveyor which raises it to the hopper of a disintegrator where the lumps of soil are broken to smaller sizes and dropped into a roller crusher. The crusher breaks the clods down to a maximum diameter of 1/4 in. and feeds them into a pug mill below. Water is metered into the pug mill at a predetermined flow rate and blended into the soil to provide both a uniform texture and the desired moisture content. The prepared soil issues continuously from the end of the pug mill into the soil cars, while they are propelled slowly back and forth by a forklift truck. This procedure allows the soil to be deposited fairly uniformly along the length of the test cars, as shown in photograph 7.

12. The modified lumberyard straddle truck supports several soil-working tools that can be mounted at either end of the truck. The tools include a set of pneumatic tires for compaction by rolling (photograph 8), a section of grader blade for leveling the clay surface (photograph 9), a drop-hammer compactor (photograph 10), and a special bulldozer-type blade for scraping soil out of the cars in the unloading operation (photograph 5). Since the pneumatic-tired roller does an effective job of compacting clay at the moisture contents normally used in this testing program, it is the compaction device generally used. First, enough soil is placed in the cars to produce a layer of approximately 6-in. thickness (after compaction). A tough membrane is placed over the surface of the uncompacted soil; the membrane is necessary to prevent the wet clay from adhering to and accumulating on the compactor wheels. The straddle truck then propels the pneumatic-tired roller over the membrane-covered layer while pressure is applied on the roller by means of a cable-and-winch arrangement, continuing until a density corresponding to that obtaining when about 95 percent of the void space is water-filled has been produced. The next layer is placed and compacted in the same manner, as is each succeeding layer. This procedure is repeated each time a test car is filled with soil.

13. After construction is completed, measurements are made to
determine whether the desired soil conditions have been achieved. From undisturbed samples taken at selected locations in the soil car by means of a thin-wall piston trafficability sampler (photograph 11), the soil moisture content, dry density, and degree of saturation are determined. Cone indexes are obtained to evaluate the soil strength profile. If the measurements reveal unacceptable variations in density and/or cone index but not in moisture content, the soil is assumed to have been mixed properly with water but to have received inadequate compaction. Therefore, it is removed from the cars but is immediately replaced and subjected to a compaction effort greater than that previously used. Occasionally, moisture content measurements reveal unacceptable variation (horizontally or vertically), indicating improper mixing of soil and water. In such cases the soil is removed from the cars and discarded.

14. The principal criteria used to judge acceptability involve:
   a. The range of dispersion of the strength at the soil surface in the horizontal direction and in relation to the underlying soil.
   b. The dispersion of the average strength values in the top 6 in. of the soil as measured at different points in the test car.
   c. The magnitude of the average rate of change of strength with depth in the top 1 ft of soil.

The actual numerical values allowed for these criteria and their development as testing experience was gained will be described in a future report of this series that will present the results of the initial tests in clay.

15. As previously described for the sand tests, two complete tests, each consisting of five passes of the wheel in the same rut, usually are run side by side at the transverse quarter points of a set of test cars. A waterproof cover, kept in place on the surface of the clay except when a test pass actually is being run, prevents excessive loss of moisture. It has been found that if the soil is sprinkled lightly every other day the original moisture content of the soil, both in the mass and at the surface of the test bed, can be maintained and the density and strength of the soil are not altered by the traffic loads. This makes it possible to reconstitute the test car for the next pair of tests by filling the ruts, rolling
the surface, and trimming it to a smooth, uniform surface. After each such reprocessing, all soil strength tests are repeated to define precisely the soil condition for the next wheel tests. Test cars of clay can be reprocessed in this manner only about four times because some soil is lost in the leveling process and the surface elevation becomes lower with each reprocessing until the sinkage range of the test carriage is exceeded.
PART III: SOIL STRENGTH MEASUREMENTS

16. One of the important decisions that had to be made in the early stages of the research program concerned the types of soil strength measurements to be made. Since there is wide difference of opinion as to what constitutes a valid measurement of dynamic soil strength for mobility, it was necessary to adopt some kind of index that would quantify the soil strength accurately enough for correlation of experimental data. Experience has shown that cone penetrometer data have correlated well with vehicle performance in field tests of actual military vehicles. This fact, coupled with the inherent advantages of the penetrometer's simplicity and light weight, and the large amount of worldwide data that has been obtained with it, led to its adoption as the primary strength-control device for the research program. In addition, it was decided that as many measurements as possible would be made with flat plate penetrometers and rotary-shear devices, so that analysis methods proposed by other researchers, in this country and abroad, could be applied. Triaxial- and direct-shear determinations also were to be made on representative samples, so that cohesion and friction values could be calculated.

Cone Penetrometer Tests

17. The cone penetrometer was developed at the Waterways Experiment Station for use in trafficability studies. The field instrument consists of a right-circular cone with an apex angle of 30 deg, mounted on the end of a rod that is, in turn, mounted on a proving ring and dial-gage assembly. As the cone is forced into the soil at a constant rate (6 ft per min), the depth of penetration is noted visually with the aid of markings on the shaft, and the force is read on the dial gage. The usual index of force is cone index, which is in units of pounds per square inch and is obtained by dividing load applied to the penetrometer by the projected base area of the cone. Cone index is recognized as an empirical number, and the units of pounds per square inch, while indicative of the dimensional nature of the index, are not to be regarded as shear strength or bearing capacity per se. The data obtained from a penetration test may
be plotted as cone index versus depth of penetration. Zero penetration is taken as the point where the base of the cone is flush with the surface of the soil.

18. The projected area of the base of the cone used in the sand tests is 1/2 sq in., and the diameter of the shaft is 5/8 in. When this combination of cone and shaft was used in soft clay, the penetration hole collapsed against the penetrometer shaft, resulting in sufficient drag to cause erroneous readings. To correct this error, a 1-sq-in. cone on a 5/8-in.-diameter shaft was used in the first 117 clay tests. Later in the testing program, it was discovered that a 1/2-sq-in. cone on a 3/8-in.-diameter shaft also eliminated all adverse effects of shaft drag and was stiff enough not to bend under load; therefore, this combination was adopted for use in the remainder of the test program. Although these two cone sizes did not yield identical measurements of the soil strength, the difference was so small that a correction factor was not considered necessary. The details of the study on results of cone penetrometer shaft-drag tests will be presented in a future report of this series.

19. A mechanized cone penetrometer was developed for laboratory use in mobility tests (photograph 12). A load cell was substituted for the proving ring and dial-gage assembly, and a gear-driven circular potentiometer for the depth markings on the shaft, so that a continuous record of cone index versus depth of penetration could be obtained on an X-Y recorder. The load cell is mounted on a vertical shaft, and load is applied by an electric motor through a system of gears and threaded shafts that drives the cell, mount, and penetrometer vertically downward at a rate of penetration of 6 ft per min. The penetrations are made along the center line of the wheel path before the tests and also during the tests to detect any changes that might occur.

**Plate-Penetration Tests**

20. Plate-penetration tests are made with flat, circular plates of different diameters (1.4, 2.8, and 4.2 in.). The purpose of these tests is to determine size-scale effects on the pressure-sinkage relation in the sand and in the clay. The plates are forced into the soil by mechanical
means at a rate of 6 in. per min. (Note: As mentioned previously, the cones are forced in at the faster rate of 6 ft per min.) The plate penetrations are made on the center lines of the test cars rather than in the wheel paths to avoid excessive disturbance of the soil in critical areas.

**Vane-Shear Tests**

21. Vane-shear tests are conducted with the torque machine shown in photograph 13. This device is used to apply and measure the torque required to rotate the vane at various depths with no normal loading. The rate of rotation is about 7 deg per sec. The cylinder of rotation produced by the vane is 1.75 in. in diameter and 2.25 in. high. The applied torque is divided by the product of the area of the cylinder and its effective moment arm to provide an estimate of the average shearing resistance of the soil. The tests are run on the test car center line.

**Ring-Shear Tests**

22. Ring-shear tests are conducted with the same torque machine. The shear ring has an outside radius of 7 in. and an inside radius of 5-1/2 in. Grousers 3/16 in. high are mounted at angular intervals of 20 deg on the base of the ring. The annular shear head is mounted on a ball-spline shaft that is essentially frictionless, so that vertical motion can take place while torque is being applied. The grousers on the annular ring are pressed into the soil, and a predetermined normal load is applied by means of deadweights. The ring is rotated (at a rate of about 7 deg per sec) and a continuous record of torque versus angle of rotation is produced. Different normal loadings can be used to produce a family of curves. Tests are run on the soil car center line.

**Triaxial Compression Tests**

23. Triaxial compression tests are conducted on undisturbed samples extracted from representative cohesive-soil cars to determine the parameters $c_t$ and $\phi_t$ of the different soil strength levels used in the
program. Triaxial tests also are conducted on the cohesionless sand, but the sand test specimens have to be formed in the laboratory. The sand specimens are tested at several density levels within the range of densities used in the test cars.

**Moisture-Density Determinations**

24. Moisture-density determinations are made at three selected points in each test lane for at least the top two 6-in. layers (i.e. 0- to 6-in. and 6- to 12-in. layers). A trafficability sampler, shown in photograph 11, is used to extract the moisture-density samples of cohesive soil. This sampler excludes the top and bottom 1-in. segments of the sample from the density determination because of possible disturbance during sampling. However, the top 1-in. segment of the 0- to 6-in. sample is used for the 0- to 1-in. moisture determination in the clay tests. Determination of sand density is accomplished with a steel box of a known volume that is carefully forced into the surface layer, after which the sand is removed from the box by hand and weighed. The weight per unit of volume can then be computed.
Test Carriage

25. The primary research instrument used in determining the performance of soils under tire loads is the test carriage of the main facility, built especially for testing under a variety of loading conditions. The test carriage is supported by solid rubber-tired rollers on a pair of accurately aligned and graded overhead rails that are, in turn, suspended from cantilever columns and crossarms (photograph 14). The carriage is towed by an endless steel cable that is fastened fore and aft to the carriage, passes up over pulleys at the ends of the track system, and is driven by sheaves mounted on a platform above the overhead rails. Photograph 15 shows a section of the test lane with soil cars in place and the carriage positioned directly under the towing cable drive mechanism. The speed of the towing cable can be varied continuously from zero to about 30 fps, and the cable and pulleys can be shifted transversely across the width of the soil cars, along with the test carriage, so that the traffic lane can be established at any transverse position in the cars.

26. The test wheel is mounted in the lower frame assembly, which consists of an inner and an outer frame (see photograph 16). The entire assembly is fastened to the upper frame by columns and roller assemblies so that free vertical movement of the wheel is possible. Both the wheel and the transmission are suspended from the inner frame. The inner frame is fastened to the outer frame at all four corners by specially built load cells, mounted vertically, which also serve as hinges and allow relative movement of the two frames longitudinally. These four load cells measure the vertical load on the wheel and are connected in a bridge circuit so that torque effects will be canceled. The relative longitudinal movement is opposed by a load cell mounted horizontally between the two frames so that the reading from this cell is a measure of the pull, which may be positive or negative (see definition on page 15).

27. Load can be applied to the wheel by the addition of deadweights or by Bellofram pneumatic cylinders mounted between the upper and lower frames. The Bellofram assembly consists of an outer cylinder and
loose-fitting piston joined together and sealed against air leakage. As the piston moves through the length of the cylinder, the Bellofram or membrane turns inside out, thus eliminating wall friction as experienced in an ordinary piston-and-cylinder arrangement. The travel of the piston is fairly long, but the system is single-acting so that two cylinders are required, one for upward force and one for downward. The test carriage utilizes one pair of cylinders at the front and another pair at the rear. The air storage tanks, which are visible on both sides of the upper frame in photograph 16, provide a reserve air supply to compensate for movement of the loading cylinders caused by increasing sinkage of the wheel as it progresses down the test lane.

Test Carriage Instrumentation

28. The carriage is instrumented to measure torque input to the wheel hub, vertical movement of the axle, dynamic tire deflection, wheel revolutions, and carriage position, in addition to the horizontal and vertical forces described in paragraph 26. A sample recording of these measurements is presented in fig. 4. Provision also is made for recording the profile of the soil surface before traffic is applied. Torque input for most of the tests is provided through a mechanical transmission mounted on the axle of the wheel and a hydraulic motor. Most of this equipment is visible in photograph 16. A transmission driven directly by an electric motor has also been used, and for special applications a chain-driven auxiliary reduction gear can be mounted. The transmission is restrained from rotating about the axle by a lever arm of known length attached to a load cell that is anchored to the inner frame; consequently, the load cell output signal can be calibrated to indicate the reactive torque directly. Axle movement is measured by circular potentiometers mounted on the outer frame and geared to rack gears mounted on supports from the upper carriage. There is an assembly for this purpose at both front and rear of the lower carriage; the front assembly is visible in the lower left corner of photograph 17. Tire deflection is measured by two linear potentiometers that are mounted through the rim and spaced 180 deg apart radially around the wheel (photograph 18). The signals are transmitted through a slip ring
Fig. 4. Typical oscillograph trace
mounted on the axle (see photograph 19). Wheel revolutions are recorded by a stationary photoelectric cell and a perforated circular disk that rotates with the axle, and carriage position is indicated by a photoelectric cell on the upper frame, which is actuated by tabs spaced 1 ft apart on the overhead rails.

29. All the measurements made with the soil-test instruments and the test carriage originate as electrical signals. These impulses are relayed through cables to the temperature- and humidity-controlled instrumentation room (photograph 20) and into the recorders. Several different types of recorders are employed with the selection determined by the nature of the data and the manner in which they are handled. Soil strength data usually are recorded on X-Y recorders. This provides a plot of the dependent variable versus the independent variable, e.g. pressure versus depth or torque versus angle of rotation. The data from the test carriage are recorded as a function of time by a direct-writing light-beam oscillograph (see photograph 20). Where desired, selected items of information gained from the test carriage can be recorded simultaneously on a magnetic-tape recorder. These data can then be played back to be recorded on the direct-writing oscillograph at a slower speed or to plot one value against another on an X-Y recorder.

30. The operation of the test carriage during a test run is controlled by a specially constructed programer which causes the forward speed of the carriage to conform to a preselected value or to vary through a predetermined pattern. Another programer has been constructed to sense the actual speeds of the carriage and the wheel and to convert these values into the slip ratio.

Test Tires

Variables

31. Tire geometry. A primary tire variable is tire geometry. Tires with various overall diameters and widths are included in the program. Tests are being conducted with tires of the same diameter but different widths to determine the effect of tire width on performance. The effect of tire diameter on performance is being investigated in a similar manner.
by using tires of the same width but different diameters. Other tires have extremely large or extremely small diameter/width ratios. The various dimensions used to quantify tire geometry are shown in fig. 1, page 12, and are discussed briefly in Part I under "Definitions."

32. **Tire flexibility.** Tire flexibility is a complex variable that incorporates the effect of other variables such as load, inflation pressure, and ply rating. For a given tire geometry, different combinations of load, inflation pressure, and ply rating can yield the same value of radial deflection of the tire. This deflection is usually quoted as a percentage of the carcass section height; thus, percent deflection, as it is called, becomes a primary variable for defining tire flexibility.

33. **Tread.** The last tire variable considered is tread. Tires without tread are used almost exclusively because they eliminate the nonuniform pressure distribution caused by tread lugs, problems of cleaning in clay soil, etc. A few tests have been run with a treaded tire, however, to gain some information on the possible effect of lugs.

**Tires used**

34. The tires used exclusively in the test program until June 1963 were as follows:

1.75-26 bicycle tire, buffed smooth
4.00-18, 2-PR,* buffed smooth (originally motorcycle-tire tread)
4.50-18, 4-PR, buffed smooth (originally motorcycle-tire tread)
6.00-16, 2-PR, buffed smooth (originally automobile-tire highway tread)
6.00-16, radial ply, buffed smooth (originally directional bar tread)
6.00-16, radial ply, with directional bar tread
6.00-16, solid rubber tire, buffed smooth (originally non-directional bar tread)
9.00-14, 2-PR, molded smooth
9.00-14, 4-PR, buffed smooth (originally automobile-tire highway tread)
9.00-14, 8-PR, molded smooth

* PR indicates the ply rating specified by the manufacturer.
5.00-12, 2-PR, buffed smooth (originally directional bar tread)
4.50-7, 2-PR, buffed smooth (originally industrial studded tread)
4.50-18, 4-PR, buffed smooth, mounted in dual configuration
16x15-6R, 2-PR Terra-Tire, molded smooth

35. In addition to the tires listed above, which are predominantly commercially available tires with the treads ground off, a special series of tires has been constructed to certain geometric specifications so that for a single diameter several widths are available and for a single width two diameters are available, etc. All these tires were molded without tread. Tests were begun with these tires in June 1963. They are denoted by the suffix "G." A list of the available tire sizes and ply ratings in this special series follows:

<table>
<thead>
<tr>
<th>Size</th>
<th>Ply Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00-7G, 2-PR</td>
<td>9.00-14G, 4-PR</td>
</tr>
<tr>
<td>4.00-20G, 2-PR</td>
<td>9.00-14G, 8-PR</td>
</tr>
<tr>
<td>6.00-16G, 2-PR</td>
<td>12.00-8G, 2-PR</td>
</tr>
<tr>
<td>9.00-14G, 2-PR</td>
<td>12.00-14G, 2-PR</td>
</tr>
</tbody>
</table>

Testing Technique

36. The tests performed in this program may be classified in one of two main categories: constant slip or programed slip. A constant-slip test is one in which a preselected slip value is introduced and maintained mechanically, or it may be a towed test in which the slip value, although not mechanically controlled, varies so slightly that it may be considered constant for practical purposes. The vast majority of the tests conducted to date have been of the programed-slip type and usually involved a uniform increase in slip throughout a pass of the wheel. Fig. 5 is a schematic diagram illustrating how this is accomplished. Power is applied to the axle of the wheel at the beginning of the approach cars; the desired rotary speed of the wheel is attained almost instantaneously and is held essentially constant throughout the pass. At the same time, power is applied to the towing cable so that the carriage is accelerated through the length of the approach cars and enters the test cars traveling faster than the wheel is propelling itself. This results in negative slip or skidding. At the beginning of the test cars a photoelectric cell engages the carriage-speed
program unit, and the speed of the towing cable is reduced linearly with time until the carriage is brought to a standstill near the end of the test cars. This produces slip that varies linearly with time and ranges from some negative value at the beginning of the test cars to a large positive slip near the end of the cars. It is necessary to adjust the automatic programer by experimentation so as to obtain sufficient negative slip at the beginning of the test cars to cause the towed point (figs. 2 and 3, pages 16-17) to occur well within the test cars.

37. It has been recognized that the programed-slip technique is a departure from the usual method of developing the pull-slip relation and that in the programed-slip test each pull-slip state exists only transiently. These considerations have made it mandatory that the technique be verified in terms of the test results obtained. Therefore, special tests were conducted to develop comparisons between data from programed-slip tests and data from constant-slip tests. Furthermore, comparisons were made between the data from programed-slip tests with the single-wheel test carriage and data from constant-slip tests with an actual multiwheel vehicle. The results of these tests indicate the programed-slip tests to be valid. They will be discussed in subsequent reports as appropriate.

38. In either type of test, the first step in the testing procedure is to establish zero positions for all the recording traces and to record
them at the beginning of the oscillogram for each pass. The transducer signal representing each important variable is then calibrated to ensure that the instrumentation is working properly and the calibrations are recorded on the chart. Next, a zero profile of the soil surface and the dynamic unyielding-surface readings of the tire-deflection gages are recorded. All these calibration procedures are performed with the aid of a "launching" platform placed just ahead of the first approach car. This platform has a plane, level, sheet steel surface, can be raised and lowered electrically, and has provisions for applying calibration loads to the wheel.

39. Before traffic and after each pass of the wheel through the soil, cone index measurements and point gage profiles are made in the traffic lane. Additional measurements, such as moisture-density determinations, vane shear, and in-situ ring shear, are made as required. Checklists for instrumentation procedures and carriage operations are kept to ensure that all the routine operations are accomplished.
40. Because of the tremendous volume of data involved, their efficient processing requires extensive use of the latest electronic devices and techniques for each step in the operations from recording to final calculation and tabulation. The various operations are discussed briefly in the following paragraphs.

Marking Oscillograph Charts

41. Interpreting the traces on the oscillograms is a highly important operation. This step takes place immediately after the test. The operation is primarily one of identifying the towed, self-propelled, maximum pull, and other points pertinent to test analysis. Several factors make this task an exacting one. First, the oscillogram must be scrutinized for any irregularities, such as abnormal speed variation, abrupt changes in vertical wheel movement, or fading in the load or torque levels. Also, it sometimes happens that the test does not run exactly as planned, e.g. the towed point may occur too near the beginning of the test lane. Such occurrences may invalidate all or part of the test. Finally, in every case, the inherent unevenness of the individual oscillograph traces must be smoothed for the data readers.

Reading Data

42. Reading test data from the analog traces of the oscillograms and X-Y recorder plots and translating them into accurately scaled digital quantities are important and time-consuming operations. Major effort has been made to automate this procedure and to develop efficient techniques. The physical reading of the charts is performed on two data reducers that are capable of reading actual distances on the charts and of converting these distances to the proper units of measurement through the medium of infinitely variable scale ranges. The output of the readers is normally typewritten numbers, but it can be punched cards or tape. Equipment in the reader room is shown in photograph 21.
43. It has been found advisable to read each chart twice in order to reduce the incidence of reading errors to tolerable levels. When the two readouts have been completed, the engineer who marked the charts compares the two versions and resolves any differences by a manual check of the doubtful readings. He then transfers the data tabulations to special format sheets from which the information can be entered on punched cards for further processing. Two carbon copies are made of the format sheet; one is used for day-to-day preliminary analysis work and the other is stored in a remote area to guard against complete loss of data in case of fire.

Retrieval of Data

44. When the test program was initiated, it was specified that summaries of all the test data would be forwarded to the Land Locomotion Laboratory, U. S. Army Tank-Automotive Center, and to the U. S. Army Transportation Research Command for analysis and evaluation. The data also are sent to Wilson, Nuttall, Raimond, Engineers, Inc., consultants. This requirement for transmitting a large volume of data was a significant factor in determining how the data would be handled after being read from the charts. A system has been developed which involves punching all pertinent test data onto cards and assembling a permanent master retrieval deck. It is possible to extract any desired items of information for listing in tabular form or to perform computer operations with them. The data-transmittal sheets are printed directly by the computer, utilizing information which is extracted from the retrieval deck. This system of storing data has proved to be very effective and has made it possible to do a great deal more analysis work with the time and people available than would have been possible without it.
Photograph 1. Operational area of main test facility. Soil-processing plant is at right rear and tire test facility is along left wall.
Photograph 2. End view of soil car with endgate removed, showing dimensions of car
Photograph 3. Front-end loader spreading Yuma sand on screen during filling of soil cars
Photograph 4. Surface vibrator and propelling unit used for compacting sand.
Photograph 5. Bulldozer attachment for removing soil from cars, shown mounted on modified straddle truck
Photograph 6. Fine-grained soil processing plant
Photograph 7. Clay soil being discharged from pug mill into soil car
Photograph 8. Pneumatic-tired compactor
Photograph 9. Leveling blade
Photograph 10. Drop-hammer compactor
Photograph 11. Trafficability sampler
Photograph 12. Mechanized cone penetrometer
Photograph 13. Torque machine with vane-shear head
Photograph 14. Overhead rail system for test carriage showing cantilever supports
Photograph 15. Test carriage in position on soil cars
Photograph 16. Left side view of test carriage with wheel resting on launching platform
Photograph 17. Hydraulic-drive system for wheel on test carriage
Photograph 18. Linear potentiometer adapted for tire-deflection measurements
Photograph 19. Slip-ring connector mounted on axle
Photograph 20. Instrumentation room with multichannel oscillographs, analyzers, and magnetic tape recorder
Photograph 21. Data-processing equipment including data typewriter, 099 data reducer, teleducers and program unit, and 10-channel calibration unit.
APPENDIX A

PLAN OF TESTS

PERFORMANCE OF SOILS UNDER TIRE LOADS

FEBRUARY 1960
PLAN OF TESTS

PERFORMANCE OF SOILS UNDER TIRE LOADS

FEBRUARY 1960

Introduction

1. The proposed plan of tests described herein modifies and supersedes the plan of tests on performance of soils under tire loads submitted by OCE to Chief, R&D, in DF dated 10 July 1959, subject, "Acceleration of Research in Off-Road Ground Mobility." The modifications are the result of discussions held by representatives of Ordnance Corps, Transportation Corps, and Corps of Engineers at a meeting in OCE on 10 February 1960. The plan as submitted has the approval of all participants at the meeting regarding the objectives and general methods for accomplishing them. It is recognized that exact details regarding many specific phases of the experiments could not be spelled out at the meeting, but must be governed by results of the program in its early stages. The plan is thus considered to be flexible and may be changed from time to time. While this plan admittedly does not cover the subject of soil behavior under tire traffic in a general comprehensive sense, it is nevertheless considered that the data forthcoming will be of considerable value in the development of basic relations between conventional-type tires and the soils on which they move.

Facilities

2. The major portion of the proposed experiments will be conducted in the small-bin testing facility at the Army Mobility Research Center. A photograph of this facility is shown as inclosure 1. The facility is adequate for testing single wheels up to 32-in. diameter at loads to 2000 lb and speeds to 20 mph. Instrumentation is installed that permits measurement of the forces, speeds, and sinkages involved in the motion of a wheel through a soil.

3. A special apparatus also is available for tests on large single tires up to 50-in. outside diameter, with loads to 6000 lb and speeds to about 5 mph. A photograph of this apparatus is shown as inclosure 2. The apparatus shown is making a test using a rigid wheel 6 in. wide and 48 in. in diameter. This apparatus also is instrumented for forces, speeds, and sinkages. Minor modifications will be made that will permit tests using tires of 60-in. diameter at loads up to about 10,000 lb.
4. The objective of this research program is to determine the behavior of three soil types when subjected to traffic of a limited number of tires. In moving toward this objective, several tires will be used to introduce variations in size, proportions, and inflation pressure. These variations will be examined under a range of vertical loads and traffic speeds. The interrelations between behavior of soils and tire traffic will be sought in terms which will permit an extrapolation of results to soil conditions and tire traffic other than those observed. Performance of the tires will be expressed in terms of motion resistance, torque input, drawbar output, sinkage, and slippage. Soil strength will be measured with the cone penetrometer, bevameter, conventional shear apparatus, the British shear vane, and bearing plates similar to those used by TRECOM. Soil moisture and density also will be measured. The principal data will be collected for single tires not greater than 28-in. outside diameter.

Details of Plan

5. Details of the plan of tests are described in the following paragraphs. Other details, such as exact number of specified tests to be conducted, may vary after the program has been started.

Tires

6. The tires selected for use in this soils investigation constitute a rational series of currently producible tires. They can be obtained readily at modest cost. Tire rims recommended by the Tire and Rim Association will be used. The tires and their pertinent characteristics are shown in the following tabulation.

<table>
<thead>
<tr>
<th>Section Width</th>
<th>Rim Diameter</th>
<th>Approximate Over-all Diameter, in.</th>
<th>Ply Rating</th>
<th>Cross-section Shape</th>
<th>Tread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire</td>
<td>in.</td>
<td>in.</td>
<td>in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>4.50</td>
<td>7</td>
<td>14</td>
<td>2</td>
<td>Circular</td>
</tr>
<tr>
<td>B</td>
<td>4.50</td>
<td>18</td>
<td>28</td>
<td>2</td>
<td>Circular</td>
</tr>
<tr>
<td>C</td>
<td>6.00</td>
<td>16</td>
<td>28</td>
<td>2</td>
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</tr>
<tr>
<td>D</td>
<td>9.00</td>
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<td>28</td>
<td>2</td>
<td>Circular</td>
</tr>
<tr>
<td>E</td>
<td>12.00</td>
<td>10</td>
<td>28</td>
<td>2</td>
<td>Circular</td>
</tr>
<tr>
<td>F</td>
<td>*</td>
<td>--</td>
<td>28</td>
<td>2</td>
<td>Low-profile</td>
</tr>
<tr>
<td>G</td>
<td>18.00</td>
<td>26</td>
<td>56</td>
<td>8</td>
<td>Circular</td>
</tr>
</tbody>
</table>

* Section width of tire F will be widest procurable in 28 in. O. D. size.

Loads

7. Three loads will be used for each tire—a light load, an intermediate load, and a heavy load. The selection of loads will be guided generally by Tire and Rim Association recommendations modified as required to compensate for differences in tire behavior under various soil conditions. The same absolute loading will be used on several different tires were feasible. Insofar as feasible, the maximum load for a given test condition (soil strength, deflection rates (tire pressure), speed) will be determined. For example, the heavy load for the 4.50-18 tire might be equivalent to the intermediate load for the 6.00-16 tire and the light load for the 9.00-14 tire. A load schedule will be prepared, with assistance from consultants, before initiation of the program.

Deflections

8. Deflection ratio has been selected as a variable in this program, rather than tire or contact pressure per se. Tire pressures will be used as needed to achieve desired deflection ratios. Tire inflation and contact pressures will be recorded. Deflection ratio, or percent deflection, is defined as

\[
\text{Deflection ratio} = \frac{100 \times (\text{height of unloaded tire section} - \text{height of loaded tire section})}{\text{height of unloaded tire section}}
\]

At least three deflection ratios—high, intermediate, and low—will be used. Exact ratios will be determined following an opportunity to develop a static tire pressure-deflection curve for each tire at each load. Deflection ratios will be selected to represent inflation pressures below and above "critical" pressures as defined by Land Locomotion Research Laboratory. More than three deflection ratios will be employed if needed to develop fully deflection (tire pressure) effects. For each tire, the same ratios will be used for all three load conditions. Several tires will be tested at the same ratios.

Speeds

9. Tests will be conducted at a low speed, selected at 3 fps (about 2 mph) to correspond to the normal speed of military vehicles in very difficult terrain, and a high speed which will be the highest speed feasible in the AMRC facility for the largest tire and heaviest load, estimated at 20 fps (about 15 mph). In addition, a few tests designed to develop more fully the speed effects will be conducted at an intermediate speed (about 10 mph) under heavy loads.
Soils

10. Three soils will be tested, a clayey silt, a heavy clay, and a sand. The clayey silt is a loess found locally at Vicksburg and is typical of large areas throughout the world. When very wet in its natural position, this near-silt soil is known to lose a considerable proportion of its in-situ strength under the action of a moving vehicle. The heavy clay is a typical alluvial clay. In nature, its characteristics do not change radically under the action of a test load. The sand is a desert dune sand from near Yuma, Arizona, and is typical of many desert sands of the world. Handling and preparation of the sand to consistent, desired strengths in the test bins are not expected to be difficult. Fine-grained soils, on the other hand, are expected to be difficult to handle and prepare to consistent, desired strengths. Upon completion of the sand tests, however, an ability to handle fine-grained soils is expected to have been achieved. Inclosure 3 shows grain-size distribution curves for the three soils.

a. Fine-grained soils conditions. At least two conditions of each fine-grained soil will be examined with all tires. At least two additional conditions will be examined under at least two tires. Additional conditions will be examined for other tires if results indicate the need therefor.

b. Sand conditions. All tests on sand will employ air-dried sand. At least two conditions of strength or density will be tested. At least two additional conditions will be examined under at least two tires. Additional conditions will be examined for other tires if results indicate the need therefor.

Propulsion

11. Testing will be accomplished by towing the wheels and by driving them.

a. Towed-wheel tests. Each towed-wheel test will consist of a minimum of ten passes in the same path. Data will be measured for each pass.

b. Driven-wheel tests. Driven-wheel tests will consist of developing the pull-slip relation from the self-propulsion point from low to 100 percent slip. Driven-wheel tests in sand will consist of a minimum of ten passes in the same path, and data will be measured for each pass. In fine-grained soil tests, a sufficient number of passes will be run until the sinkage is stabilized or reaches a depth limited by the equipment.

Miscellaneous Observations

12. A few of the sand tests will be selected for the addition of color strata in the sand for visual observation of displacements induced by the loads. Photographic coverage of all tests will be done by means of motion pictures and still pictures. Visual observations will include behavior of the soil and buckling point of the tires.

Number of Tests

13. It is estimated that approximately 800 tests will be required to accomplish the objective of the program. (The number of possible permutations is in the order of 1500.) The tests themselves can be made comparatively rapidly, once the soil has been prepared. Preparation of the soil is expected to be the major time-requiring phase of the operation. The fine-grained soils will require longer time for preparation than the sand. It may be possible to run two tests in the same soil bins when small tires are involved. However, in general, the number of tests to be performed will be equal to the number of soil conditions to be prepared.

14. As rapidly as they become available, the data will be assembled and submitted to LLRL and TRECOM for analysis and evaluation. It is possible that some of the tests can be eliminated as the results develop. It also is possible that analysis will indicate that additional tests should be made.

Time Schedule

15. A time schedule is difficult to estimate because there has not been opportunity for sufficient "shake-down" experience in the AMRC small-bin test facility, nor is the facility completely equipped at this time. From the limited experience gained so far, however, the best estimate appears to be one test per day in sand, or two tests per week in fine-grained soils. On the basis of approval as of 1 March 1960, an estimated time schedule is as follows:

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin sand tests</td>
<td>April 1960</td>
</tr>
<tr>
<td>Complete (265) sand tests</td>
<td>February 1961</td>
</tr>
<tr>
<td>Begin fine-grained tests</td>
<td>March 1961</td>
</tr>
<tr>
<td>Complete (530) fine-grained tests</td>
<td>December 1962</td>
</tr>
</tbody>
</table>

Every effort will be made to reduce the over-all time for this program. Hope lies in the possibility of conducting more than one test in the same soil condition, development of towed and self-propelled data in the same run, and increased efficiency in handling and processing soils.

Expected Results of Test Program

General

16. No particular theory of movement of wheels in soft soils was used as background in this test program. However, it is considered that sufficient data will be collected to make progress toward checking or validating existing theories.

17. In general, the test program is expected to provide results that will point the way to the selection of the proper tire size and inflation pressure for a given load and soil condition that will achieve the degree of mobility specified.

Data Presentation

18. All data will also be presented in complete detail in tabular form and in direct comparison plots showing the effects of each variable individually, with all others held constant. A preliminary report, containing all data, will be issued at the conclusion of each of the sand and fine-grained soils testing phases. These will each be followed within three months by a final report, including detail analysis, etc. Reports will be prepared through joint LLRL-TRECOM-WES studies.

3 Incl
1. Photo of Facility
2. Special Test Apparatus
3. Soil Classification Sheet
<table>
<thead>
<tr>
<th>Number</th>
<th>Depth</th>
<th>Natural Moisture</th>
<th>L. L</th>
<th>P. L</th>
<th>P. I</th>
<th>Classification</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>32</td>
<td>24</td>
<td>8</td>
<td>CLAYEY SILT (ML)</td>
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<td></td>
<td>62</td>
<td>24</td>
<td>38</td>
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<tr>
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<td>NONPLASTIC</td>
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<td></td>
<td></td>
<td>SAND (SP)</td>
</tr>
</tbody>
</table>

PLAN OF TESTS
PERFORMANCE OF SOILS UNDER TIRE LOADS
REVISED FEBRUARY 1960

SOILS
<table>
<thead>
<tr>
<th>Role</th>
<th>Location</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commanding General</td>
<td>Army Materiel Command</td>
<td>ATTN: AMCRD-RV-E, Washington, D. C. 20315</td>
</tr>
<tr>
<td>Commanding Officer</td>
<td>USACERREL</td>
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