COMMENTS ON MOBILITY RESEARCH

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Vicksburg, Mississippi

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PREFACE

The study reported herein is part of a program being conducted under Department of the Army Project 1-T-0-21701-A-046, "Trafficability and Mobility Research," Task 1-T-0-21701-A-046-03, "Mobility Fundamentals and Model Studies." The work was performed by personnel of the Army Mobility Research Branch, Mobility and Environmental Division, U. S. Army Engineer Waterways Experiment Station, under the supervision of Mr. W. J. Turnbull, Technical Assistant for Soils and Environmental Engineering, and Mr. W. G. Shockley, Chief of the Mobility and Environmental Division, and under the sponsorship and guidance of the Directorate of Research and Development, Headquarters U. S. Army Materiel Command. Mr. S. J. Knight, Chief of the Army Mobility Research Branch, and Mr. D. R. Freitag, Chief of the Mobility Section, prepared this paper for presentation at the Automotive Engineering Congress of the Society of Automotive Engineers in Detroit, Michigan, 13-17 January 1964.

Col. Alex G. Sutton, Jr., CE, was Director of the Waterways Experiment Station during the conduct of this study. Mr. J. B. Tiffany was Technical Director.

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COMMENTS ON MOBILITY RESEARCH

Abstract

The scientific knowledge necessary for engineers to design mobility characteristics into a vehicle does not exist. In their attempts to fill this need, mobility engineers have failed to apply basic scientific methods and principles in a consistent manner. Some of the shortcomings evident in mobility research methods are pointed out. New knowledge obtained from mobility-oriented studies now in progress at the U. S. Army Engineer Waterways Experiment Station is presented to illustrate the importance of basic scientific studies.

COMMENTS ON MOBILITY RESEARCH

by

S. J. Knight* and D. R. Freitag**

The lament is often heard that no suitable methods exist for designing military vehicles that will have maximum off-road mobility and at the same time meet stipulated requirements for size, armor, firepower, etc. The fact that there is no set of vehicle-soil laws, no mobility design handbook for engineers, has been blamed on everything from lack of motivation to failure to provide sufficient funds for research. Furthermore, the argument is wearing thin that the ever-growing network of roads has stifled the incentive to build better off-road vehicles. More than adequate motivation was provided twenty years ago by the well-known setbacks caused by poor off-road mobility of vehicles on the Iwo Jima beach, the Italian dirt roads, and the North African deserts. Military leaders, considering the possibility of nuclear warfare with its concepts of widely dispersed units assembling rapidly for attack and then redispersing to avoid retaliatory measures, have been crying for better off-road vehicles since the Hiroshima atomic bomb ushered in the nuclear age eighteen years ago. "Insufficient funds" is no longer a valid excuse for slow progress in vehicle mobility research. Today, millions of dollars are being spent in this field by both government and industry.

Why, then, does it appear that progress has been slow? Why does the design of an off-road vehicle seem to be more of an art than a science? Undoubtedly, the answer is that the problem is extremely complex and as yet beyond our grasp.

In the field of vehicle mobility research, barren for so long, any accomplishment that advances knowledge, no matter how little, ranks as something of an achievement. In fact, the mere definition of the mobility

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problem has baffled and eluded researchers for years, and an acceptable definition, especially in quantitative terms, would be a major achievement because it would establish a concrete, specific goal.

But even if the desired end product were defined clearly and precisely, the normal tools required for mobility design seem to be lacking. There are no mathematical models that can be said to describe truly the behavior of a vehicle-soil system; there are few "tried and true" equations, and the properties of the materials involved cannot always be expressed in quantitative terms, particularly not as stress-strain relations. In short, many of the scientific foundations, the "laws" that govern the system behavior and are the basis of all engineering, are absent or do not seem to be applicable. It seems clear, then, that the deficiencies that exist are really scientific ones exceeding the scope of normal engineering effort.

To quote an Engineering News-Record editorial,[2*] "Science is an activity aimed at discovering new facts and enlarging knowledge while engineering is an activity concerned with using knowledge to create something." The engineer must use every bit of knowledge at his disposal, and since his primary guide is accomplishment, he does the best he can with this knowledge. But if the knowledge turns out to be inadequate, he has two alternatives; he can wait for science to fill the gap, or he can turn scientist for long enough to do it himself.

Historically, many noteworthy scientific contributions have been made by men who were primarily engineers but who created a science with which to work. Von Karman's work in aerodynamics and Heaviside's developments in operational mathematics come readily to mind as examples. However, to operate as a scientist with a fairly high probability of success, the engineer must recognize the "ground rules" of science that have evolved over the years. There is more to scientific study than the collection of information or the writing of mathematical expressions.

In reviewing the mobility studies that have been made, it is apparent that most of the work has been directed by engineers. With a few exceptions, their ingrained desire to achieve a solution seems to have led them to ignore some fundamental scientific concepts. Three shortcomings,

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* Raised numbers refer to similarly numbered entries in the list of references at end of paper.

individually or severally, predominate. They are: (a) failure to make adequate measurements or, in other words, to develop adequate experimental data; (b) failure to formulate hypotheses; and (c) failure to draw deductions from hypotheses and to test them.

The necessity of making some sort of measurements in connection with any research seems almost self-evident. Lord Kelvin[3] said, "In physical science a first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it. I often say that when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science whatever the matter may be."

In the mobility literature there are numerous instances of tests for which no measurements were made of factors of considerable importance to the interpretation of the test results. Sometimes the omission of measurements is due to lack of awareness of the importance of the factor, as for example, in many tire tests the deflection of the tire carcass is not measured. More frequently, however, the reason apparently is the belief that it would be practically impossible to obtain a meaningful measurement. This is particularly true with regard to providing quantitative evaluations of soil properties. In many instances, the investigators provide only barest verbal descriptions of the soil conditions, such as "tilled soil" or "soft mud." On such a basis, it is virtually impossible for results of studies at different times or places to be correlated or compared. How can the test results be understood if the conditions cannot be measured; and, most important, how can new concepts be formulated except in terms of measurable values? If adequate measurements cannot be made, then it would seem to be imperative that research in mobility begin with the development of means of making adequate measurements. Even though the measurements may be crude at first, continual effort to improve them should lead to an increased depth of knowledge.

The importance of measurements in the expansion of knowledge is illustrated in the history of Joseph Black's investigation of the nature of

heat.[1] A very vital part of this study was the thermometer, a relatively crude device that merely offered a set of arbitrarily selected but uniformly spaced divisions between two identifiable points along the path of a variable. But with this device, numerical values could be assigned for certain conditions; and with it, Black could describe the changes that took place as he conducted his experiments. The thermometer measured the equilibrium achieved in mixing substances of different kinds or in different states. It allowed significant measurements to be made in connection with the phenomena of freezing and boiling of liquids. These all led Black to the recognition of the concepts of latent heat and specific heat. No amount of qualitative comparisons could have provided the basis for this insight.

It seems safe to state that two of the most necessary and most difficult-to-make measurements in vehicle mobility studies are soil strength and the behavior of the soil under load. The three-phase systems upon which vehicles travel cannot as yet be characterized in a precise manner. Soil stress-strain relations that are needed if the laws of mechanics are to be applied to the mobility study have not been adequately measured and related to the behavior of even simple, statically loaded areas. Yet, in the almost total absence of soil stress-strain data and any correlation between laboratory and prototype, some of the simple empirical soil tests have proved useful in the study of mobility problems. These tests have provided a basis for some reasonably comprehensive studies; and at the same time, their obvious shortcomings have given stimulus to even more detailed investigations.

The second shortcoming commonly encountered in assessing the results of vehicle studies is the failure to formulate hypotheses after assembling vast quantities of test results. Poincaré wrote,[4] "Le savant doit ordonner; on fait la science avec des faits comme une maison avec des pieires; mais une accumulation de faits n'est pas plus une science qu'un tas de pieires n'est une maison."* And Conant[1] states, "I have heard an argument that runs essentially as follows: devise a measuring instrument,

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* "The scientist must organize; one builds science with facts just as a house (is built) with stones but an accumulation of facts is not science as a pile of stones is not a house."

make a vast number of measurements with control of all the various variables, classify the results, and lo and behold! out will pop a new scientific principle! This is nonsense, a caricature of one type of phenomenon in the history of science."

In the field of vehicle mobility research, there have been a number of programs that, among other things, have resulted in the accumulation of a vast collection of data. Although in each case there may have been good reasons why so much data were collected, every organization must be on guard against the collection of data simply for the sake of collection. Sometimes programs have been initiated upon vaguely expressed hypotheses. For example, it may be proposed that, since a certain factor probably exerts a principal effect on vehicle performance, if enough tests are conducted, the relation between factor and effect will inevitably emerge. From this, volumes of reports are published that are largely tabulations of the results of tests. Usually there is some attempt to show graphically that the results follow some pattern and vary in response to one or more of the test variables, but even this is not always the case. Possibly, the hoped-for relation is submerged in experimental error and in the influences of other factors. In any event, the results remain quite specific and the needed generalizations remain hidden in the data.

It is conceded that it is not always possible to arrive full-blown at a concept from either a small or a large collection of data. Nor is it always necessary to begin with more than a very broad hypothesis. However, it must be realized, also, that the act of compiling a volume of data or even of grouping the data into some semblance of order is not of itself a useful result. It may lead to one, however, as will be pointed out subsequently; and the collections of data should not be dismissed offhand as a waste of time and money.

The annals of astronomy provide a striking example of the potentials of data collecting. The Danish astronomer Tycho Brahe (1546-1601) gained considerable renown for his painstaking records of the relative movements of the planets. He collected many volumes of observations that he endeavored to fit into the earth-centered epicycles popular in astronomy at that time. However, these volumes came into the hands of Johannes Kepler, a correspondent of Galileo and one who had the advantage of Copernicus'

heliocentric concepts. Kepler, guided principally by intuition well-laced with religious superstition and faith in the order of things, was able to derive empirically from these data the laws of the planetary orbits that now bear his name. And yet even more remarkable, Brahe's data, generalized by Kepler, provided the spark that led Newton to the insights that are now the basis of our earthly mechanics.

The need for fitting all test data into an overall generally applicable hypothesis must be recognized by those working on mobility studies. Whenever possible, tests and analyses of tests must be made in a manner that will have the effect of evaluating, changing, or extending a hypothesis. Nevertheless, it seems likely that urgent needs at higher levels will continue to force the initiation of programs to collect volumes of data in the hope that they will solve the problems at hand. However, if the test programs are carefully performed, are well documented, and contain enough measurements, the concept has one saving grace; there is always the possibility that the data may provide the source from which a vehicle mobility Kepler or Newton will find inspiration and insight.

The third common shortcoming in mobility research is the failure to draw a deduction from a hypothesis and to put it, and thus the hypothesis, to the test of experimental evidence. This process has acquired such stature as to be virtually the cornerstone of modern science. The testing of each step and each component of a hypothesis is the essence of scientific reasoning. If the tests confirm the deductions in a consistent and repeatable manner, the hypothesis may gain the stature of a theory. But the process of deduction and testing must continue in every phase. It is in this manner that old concepts are clarified and new ones developed.

In developing a hypothesis, particularly on a so-called "theoretical basis," it is common for a set of conditions or assumptions to be stated as the beginning point for subsequent development. These assumptions must be scrutinized carefully, as it sometimes happens that they imply a state of affairs that bears little relation to reality. In reviewing the requirements for acceptable theories in soil mechanics, Terzaghi[5] stated, "The second requirement for an acceptable theory consists in the presence of adequate evidence for the assumptions. If these assumptions were obtained by a radical simplification of reality, which is the rule in connection

with theories pertaining to soils, the evidence for the results must be presented. Whatever evidence is available can be classed into one of the following five categories; (a) no evidence whatsoever, (b) evidence obtained by distorting the facts, (c) unbalanced evidence; that is, evidence obtained by eliminating all those facts which do not sustain the claim, (d) inadequate evidence, covering the entire range of present knowledge, yet insufficient to exclude the possibility of a subsequent discovery of contradictory facts, and (e) adequate evidence."

Terzaghi goes on to state, "No honest business man and no self-respecting scientist can be expected to put forth a new scheme or a new theory as a 'working proposition' unless it is sustained by at least fairly adequate evidence. In any case, we expect him to inform us on the uncertainties involved. Therefore, it is surprising to find upon closer scrutiny that many of the accepted rules of foundation engineering are based either on no evidence whatsoever or on unbalanced evidence."

This observation seems quite appropriate now with respect to mobility research. It is particularly so when a brief examination reveals that many of the assumptions used in developing hypotheses involve the behavior of soils under loading. The rules and assumptions now being advanced in mobility work take on an aura of respectability when produced in print, even though the authors may state clearly the limitations implied. Extreme care should be taken that evidence be obtained to test the extent of the validity of each hypothesis and each assumption before other hypotheses are constructed upon them.

In the same article[5] quoted from above, Terzaghi points out that theories of earth pressure require that the lateral pressure of the soil on the back of a supporting structure increase in direct proportion to the depth below the surface. Under certain conditions this is so, but under others (such as at the sides of a timbered trench) the distribution of pressure is quite different from this pattern. Evidence of this difference has been frequently ignored, sometimes with dire results.

What, then, is the course that mobility research must follow to take on the stature of an engineering science? It must be conceded that most major steps forward come about either as a result of a sudden insight or inspiration on the part of an individual or as the result of patient,

painstaking sifting of carefully collected facts and measurements. In the absence of a blinding flash of revelatory genius, a careful, systematic program consisting of (a) reviewing all pertinent data, (b) forming a hypothesis, (c) validating the assumptions, (d) deducing a consequence, and (e) testing to see if the consequence indeed occurs seems to be the only active and positive approach that can be made.

The statement of such a program makes the performance sound simple; but as is well recognized, it is not. In the very first step, the recognition of what is pertinent is a critical factor. It is a very complete set of data indeed that includes all the information needed to evaluate a theory that had not been conceived at the time the data were taken. Quite often, recognition of the factors that are truly relevant to the study does not occur until after much work has been done. Testing of assumptions or of consequences can involve measurements that appear impossible, and the research effort, initially at least, is reduced to that of devising measurement techniques. If, for reasons of complexity, measurements are made that are less precise than desirable, the testing sequence must continue until the weight of evidence becomes statistically significant.

The foregoing discussion has not developed any new ideas, but has simply brought them to light once more. Every worker in the field is intuitively aware of the shortcomings that have plagued vehicle mobility research and the scientific course that should be pursued if the research is to advance. Unfortunately, there is another factor that has considerable influence on the course of mobility research--money. All too often the flow of funds toward a mobility research project has been in direct proportion to the urgency of the need for the solution to a particular problem. Automatically, programs are planned to obtain fast, usable answers to meet the needs of the moment, and it is not surprising that scientific attainment has suffered. However, even such programs are not without scientific benefits, for frequently they require side excursions into more basic areas in order to focus the results of the main program.

Associated with the mobility-oriented research now under way at the Waterways Experiment Station are several investigations that are believed to be contributing significantly to the store of basic knowledge. Two in particular are relevant to this discussion, as they emphasize the

importance of evaluating assumptions and of making pertinent measurements.

One of the studies is concerned with measuring pressure-distribution patterns at the interface of a pneumatic tire and the soil. The principal test instrument is a single-wheel dynamometer carriage in which is mounted a buffed-smooth pneumatic tire with seven 0.75-in.-diameter pressure cells embedded in its surface (fig. 1). Tests are run with towed and powered wheels under various conditions of load and tire-inflation pressure. Both sand and clay test soils are used, and they are specially prepared to provide test data over a range of conditions (i.e. strengths) from very soft to quite firm. To date, the results of this study (fig. 2) show quite well that the magnitude and distribution of interface pressures are not wholly dependent upon the tire-inflation pressure and the load. The pressures are influenced by a number of factors including notably the relative firmness of the soil. It is also evident from the data that pressures predicted by the application of the Bernstein equation or similar expressions derived from plate tests which are sometimes used in theoretical analyses do not actually occur. In fact, the direct application of these equations does not provide a good approximation of the actual distribution of pressures under wheels (fig. 3). While this result does not prove the Bernstein equation invalid, it does convincingly demonstrate that if the equation does have an application in wheel mobility work, it must be applied with more finesse than has been used to date. On the other hand, it cannot be reported yet that the pressure-distribution studies have resulted in a broad new working hypothesis. The data show that the problem is quite complicated and that consideration may also have to be given such things as relative slip and tire construction. However, the data do suggest that there may be simplifying assumptions that can be made with a reasonable degree of validity that could allow a general hypothesis to be made eventually. This is the goal of this research, and a solid effort will be made to reach it.

Another study that offers promise of eventual gains in the knowledge of wheel-soil systems is concerned with measuring tire deformations. This work is an example of the stimulus that can be provided by a need to make certain measurements. The position of the pressure cells embedded in the test tire must be located precisely in the contact interface if the

measurements they yield are to be interpreted meaningfully. This demands, among other things, that the shape the tire assumes as it moves in soft, yielding soil be known. A similar need arose during the routine testing of the performance of pneumatic tires in soft, dry sand. It happened frequently that the ruts formed by the wheel filled in immediately after its passage. Therefore, in order to determine the depth of sinkage of the tire, measurements had to be made by other means. The relative positions of the wheel axle and the original soil surface could be determined readily; thus, if the shape of the tire in sand also was determined, the sinkage could be determined.

The deformation of a tire in the present studies is sensed by a gage placed inside the tire through a port in the rim and fixed to the rim so that it rotates with the wheel (fig. 4). The gage is a combined circular and linear potentiometer. The linear part measures translational movements in a direction generally normal to the tire surface. The circular part measures rotational movements in the plane of the gage which may be either parallel to or perpendicular to the direction of motion, depending on the measurements desired. With these gages, the shape of the tire has been ascertained for various torques, loads, and inflations and in all sorts of soil conditions. In addition, the trajectory that a point on the tire surface follows to attain the resultant tire shape and the path of the point relative to the soil can be described.

An immediate result of this work was the recognition that a tire in soft soil does not simply flatten out on the bottom as is sometimes assumed in theoretical studies (fig. 5). Actually, the shape a tire assumes represents a balance between the resistance to deformation in the tire and in the soil. Where these studies will lead is not yet clear, but there seems to be a good prospect that soil stress and deformation patterns will be defined more precisely than heretofore believed possible.

Other studies have been initiated (or are in the planning stage) to determine the relation of soil properties to the behavior under load of relatively simple shapes such as bearing plates or uniform shear surfaces. The results collected to date are meager and are inconclusive, but they do show that the existing theories do not adequately describe the

behavior of even these relatively uncomplicated shapes, except in certain restricted circumstances.

The few examples given illustrate that a more methodical, more scientific approach can expand the base of knowledge upon which further mobility work can be founded. However, this is only a beginning, and there obviously is much more to be done. Every person engaged in mobility research should thoughtfully reappraise his work and ask himself some questions. He should clearly restate to himself the goals he is seeking and the reason he has for his approach to their attainment; he should ask himself if his working assumptions are well founded or, at least, their limitations known; he should inquire if his measurements are precise and as meaningful as he can make them; he should ask himself why the results turned out as they did and what deeper meanings lie beneath; and above all he should regularly ask if his initial concepts should not be modified, or even discarded, to be in accord with his findings. In short, if each one will conduct his work with a scientific attitude, it is believed that vehicle mobility will sooner achieve the status of an engineering accomplishment.

References

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4. Poincaré, H., quoted in Principles of Mechanics, by J. L. Synge and B. A. Griffith. McGraw-Hill Book Co., Inc., New York, N. Y., 1959.

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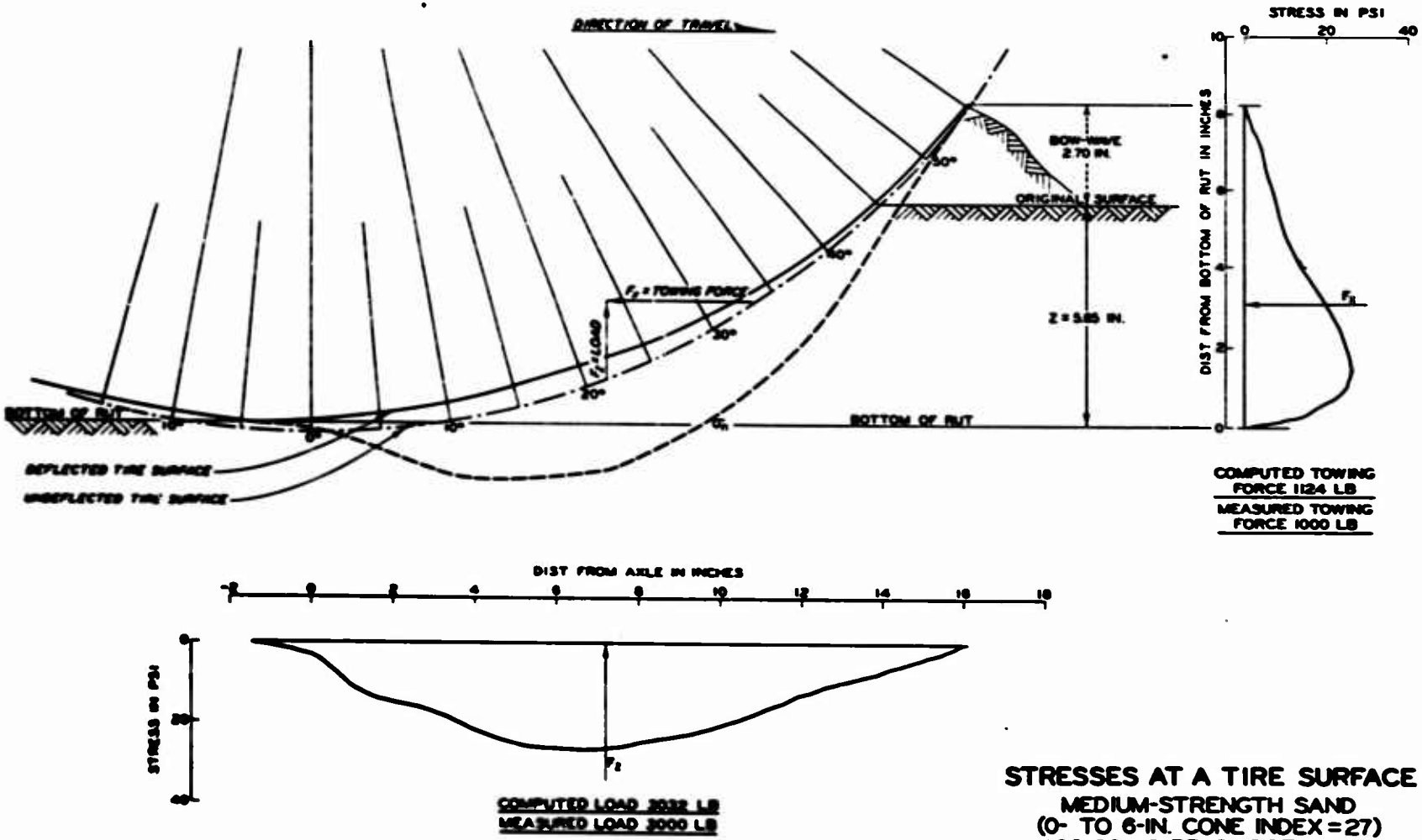
Fig. 1. Pressure cell installation



STRESSES AT A TIRE SURFACE
MEDIUM-STRENGTH SAND
(0- TO 6-IN. CONE INDEX = 27)
11.00-20, 12-PR SMOOTH TIRE
3000-LB WHEEL LOAD
60-PSI INFLATION PRESSURE

Fig. 2

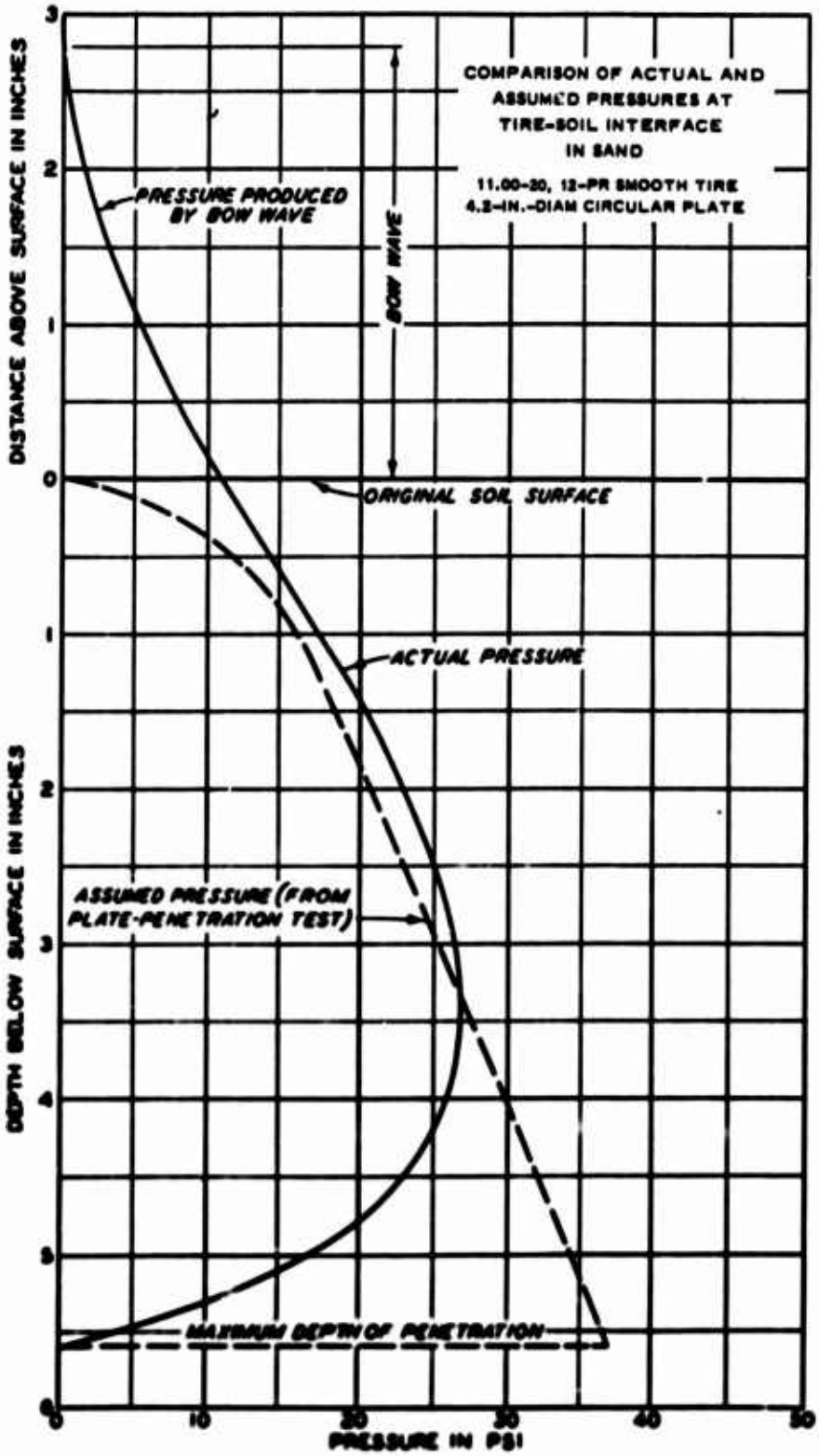
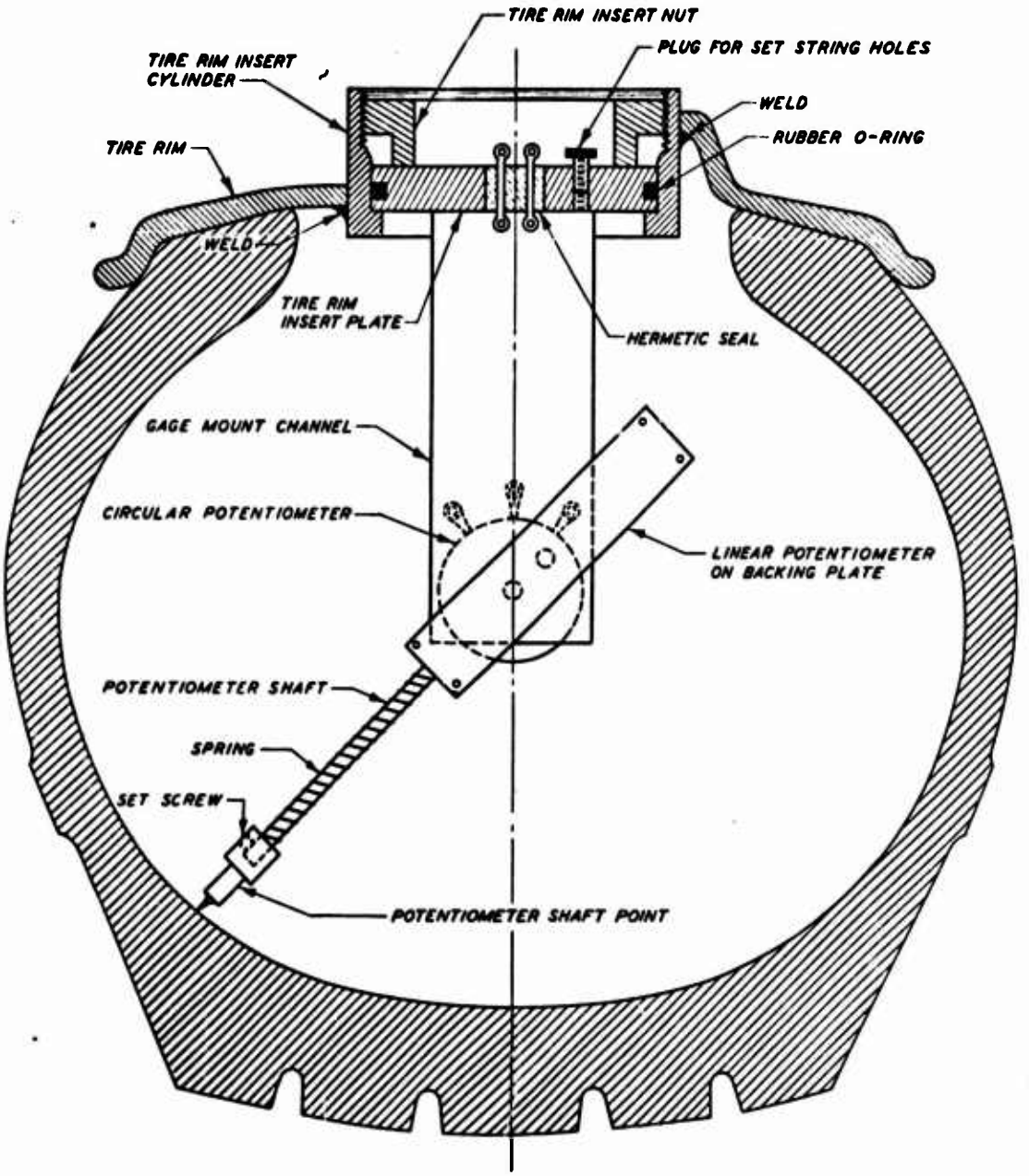

COMPARISON OF ACTUAL AND ASSUMED PRESSURES AT TIRE-SOIL INTERFACE IN SAND
11.00-20, 12-PR SMOOTH TIRE
4.2-IN.-DIAM CIRCULAR PLATE
PRESSURE PRODUCED BY BOW WAVE
BOW WAVE
ORIGINAL SOIL SURFACE
ACTUAL PRESSURE
ASSUMED PRESSURE (FROM PLATE-PENETRATION TEST)
MAXIMUM DEPTH OF PENETRATION
DISTANCE ABOVE SURFACE IN INCHES
DEPTH BELOW SURFACE IN INCHES
PRESSURE IN PSI
3
2
1
0
1
2
3
4
5
6
0
10
20
30
40
50

Fig. 3



TIRE DEFLECTION GAGE AND MOUNT

12.00-22.5, 12-PR TUBELESS TIRE

111958-A

Fig. 4

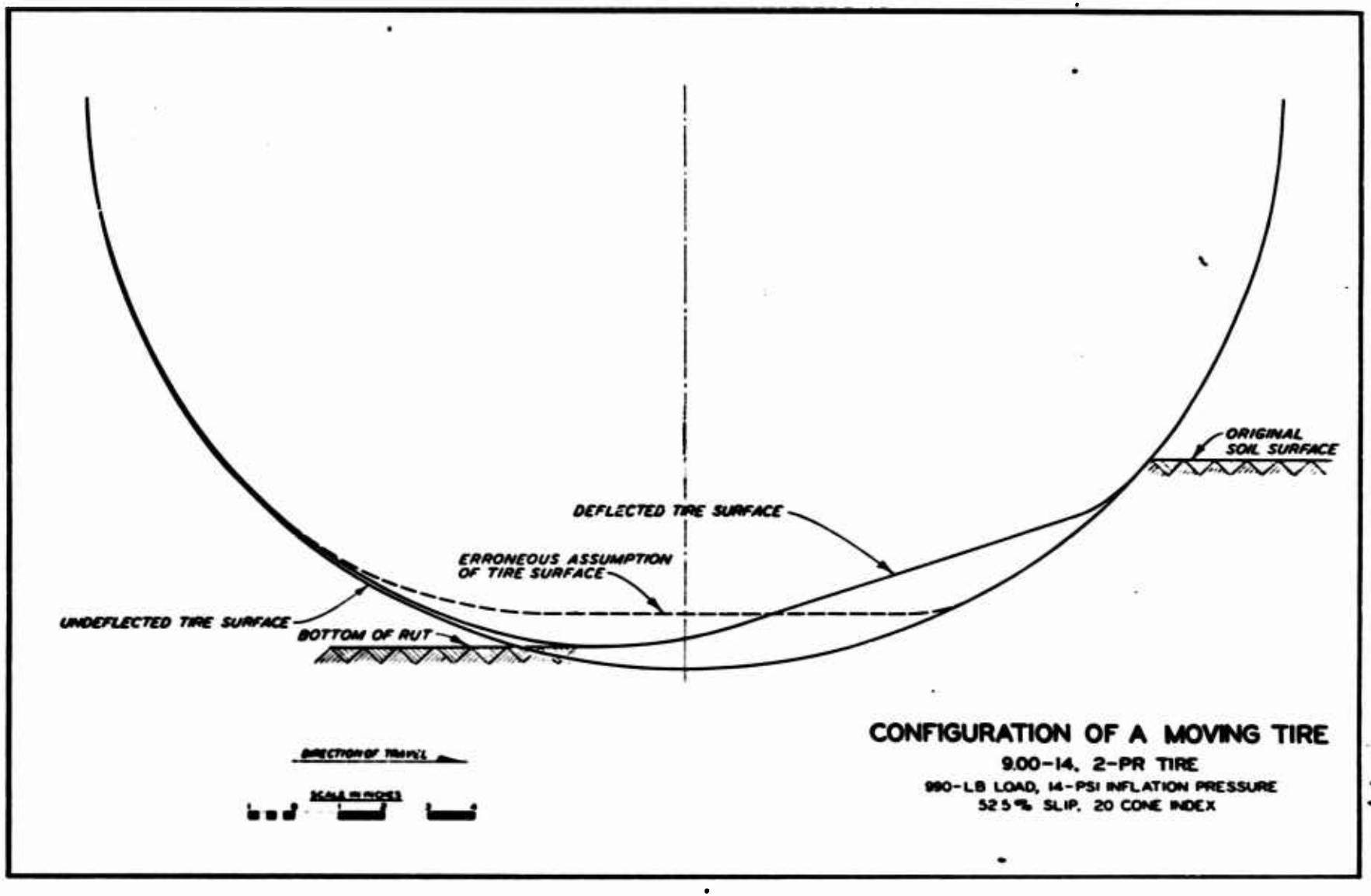

ORIGINAL SOIL SURFACE
DEFLECTED TIRE SURFACE
ERRONEOUS ASSUMPTION OF TIRE SURFACE
UNDEFLECTED TIRE SURFACE
BOTTOM OF RUT
DIRECTION OF TRAVEL
SCALE IN INCHES
CONFIGURATION OF A MOVING TIRE
9.00-14, 2-PR TIRE
990-LB LOAD, 14-PSI INFLATION PRESSURE
52.5% SLIP, 20 CONE INDEX

Fig. 5