DISCUSSION OF PAPER ON "THE METHODS AND POSSIBILITIES OF ROAD-SOIL INVESTIGATIONS"

Opened by C F MARBUT
U S Bureau of Soils, Washington, D C

The investigation of any series of bodies may take place in a number of degrees of intensity depending upon various considerations, among which are the uses to which the results are to be applied. We may, for example, undertake to investigate a series of bodies in all their relationships We may undertake to determine their reaction to the application of forces of all kinds operating through all sorts of processes In other words, we may undertake to investigate them in all their relationships On the other hand we may carry out an investigation on a series of bodies solely for the purpose of some one particular thing In doing this we determine the factors which are of special importance in the particular use to which we intend to apply the results In soils, for example, we may investigate them from the point of view of agriculture alone, or, on the other hand, we may investigate them as foundations for highways

In case we desire to investigate a series of bodies for some special purpose it is apparent that it is advisable to confine ourselves to the particular reactions which are of use to us By undertaking to investigate them from all points of view when we desire results for some particular purpose, we would not only waste time but would doubtless accumulate many results the elimination of which would cause still further loss of time In such a case, therefore, it is of especially great value that we analyze our subject and determine if possible the factors which are of importance to us

In the matter of the use of soils for road subgrades, this has been done with penetrating keenness by Dr Terzaghi in the paper which has been presented to us He has isolated the reactions of soil materials that are highly important as factors in the construction of subgrades for highways The results of his analyses show that these factors are few in number They consist in the change of volume of soil materials due to wetting and drying, and those due to freezing and thawing He has also shown that in connection with these the lag which takes place in the reaction of materials on the application of pressure is of very great importance He has shown that this is due to the two factors of internal adjustment in the material itself and to the expulsion of the moisture contained in that material

This analysis directs our attention to the particular things which should be sought in an examination of soil materials to determine their probable value as highway subgrades This analysis insures a minimum consumption of time and effort and also enables us to avoid an accumulation of a great body of data which has no relation to the subject with which we are concerned

While Dr Terzaghi's analysis shows what these factors are, his analysis is an abstract one It does not show what the reaction of any given material would be under the circumstances It does not show the amount of expansion of any given material on freezing or of contraction on thawing, nor the amount of expansion on absorption of moisture or on drying, nor does it show the lag which takes place as a result of the application of pressure to any particular materials This must be obtained by examination of the materials themselves So the question arises as to how that examination is to take place In order to apply Dr Terzaghi's analysis we must investigate the reactions of given materials with respect to the factors brought out in the analysis The question arises How can this be done? It is evident that it may be done in more than one way For example, it may be done by laboratory work alone, or at least we can assume that it can be done It is pretty certain that the laboratory worker would agree with us that it could be done by this method Since in a laboratory, especially one dealing with earth materials, we can not use the bodies themselves in their natural size and relationships, the question arises then as to how the materials shall be selected for the laboratory work In determining this in a satisfactory way it is necessary to take into consideration the ways in which this material is used in the construction of subgrades for highways It is well to bear in mind that earth materials are used in two fundamentally different conditions in highway subgrades In one of these conditions that material is used as natural material without disturbing the relationship of its members that were present in the material before the subgrade was established The material is not dug up and relaid, but the highway is laid directly on it without disturbing it On the other hand, in many places the subgrade is constructed by digging up this material, mixing it in all sorts of ways and relaying it to form a new subgrade It is perfectly evident to anyone who knows anything about earth materials that the material after treatment in the latter way is not identical with what it was before it was disturbed It is necessary, therefore, in the study of reactions which will take place in highway subgrades to experiment both with material in place or in the same condition which it had while in place and also in that material after it has been thoroughly disturbed and relaid

In this connection attention should be called to the three kinds of materials that are used in highway subgrades Studies of soil character and soil anatomy carried on during the last quarter century have shown very clearly that in any general region there are three layers of material, varying greatly in thickness, superimposed one above the other in the upper part of the earth's crust These always consist of what the soil man designates as the "A" horizon or surface layer, ranging up to something more than a foot in thickness, which is fundamentally a horizon with a low percentage of mineral colloids It may or may not have a considerable percentage of organic colloids Beneath this lies what the soil specialist designates as the "B" horizon, which is a layer containing a considerably higher percentage of mineral colloids than is contained in the "A" horizon It very rarely contains say any considerable percentage of mineral colloids It ranges up to a maximum of four or five feet in thickness Beneath this lies the "C" horizon which consists predominantly of geological material, and its characteristics will depend therefore on the nature of that material as it was originally laid down No broad statement can be made, therefore, regarding its character It may be highly colloidal or may not It may consist of pure sand or heavy clay, or any mixture of those two constituents

In any laboratory studies carried on for the purpose of determining the reaction of materials used as highway subgrades it is highly important that all of these materials in all of their phases should be investigated both as they occur in nature and as broken up or disturbed material It is unnecessary here to discuss the nature of the laboratory work necessary That has been indicated by Dr Terzaghi's analysis and nothing further will be stated here That is a matter that can be determined by the director of the laboratory

After the laboratory work has been done it then becomes necessary to translate the results from the laboratory into nature This is a problem that is always more or less difficult A laboratory is nothing more than an institution which undertakes to reproduce nature and to study its operations and reaction on a small scale The interpretation of their results and their utilization in nature depends upon the proper translation On this question hangs the value of this method of study If the laboratory work can not be properly interpreted and applied to the materials studied as they exist in nature then it is perfectly evident that laboratory investigation is not applicable to the case Whether this is the case or not with reference to road materials has not yet been determined It must be determined by future investigation I desire to pass no judgment as to the general applicability of this method of investiga-

tion to the particular case of highway subgrades I merely call your attention to the fact that it is one possible method of investigation It is essentially equivalent in its fundamental nature to such agricultural soil investigation as was carried on in the western world from the time of Liebig, about the middle of the 19th century, up to about its close

Another method of investigation is what may be designated as the field experimental method This consists in the laying down of experimental roads of as many different kinds as possible on as wide a range of different natural subgrades as can be found, and also on as great a number of differently constructed artificial subgrades as the conditions will permit Such roads can then be placed under a variety of uses and the results noted The results of such use under all the variable conditions which the environment presents, and under all the possible kinds of uses carried on through a considerable period of time, may be determined This is essentially a kind of laboratory investigation In this case, however, the laboratory is out of doors Like laboratory work, the securing of results from all such investigations requires time, and this is no exception

It is apparent on merely superficial observation that the results in this case would be more reliable than those obtained by laboratory work alone, because of the fact that the scale on which the work is done is identical with the scale on which the results must be applied after they have been determined There is no possibility of error, therefore, in translating the results into terms of practical utilization

This method is essentially equivalent to that method of soil investigation in which experiments are carried out on the ground in the fields for the purpose of determining the reaction of soils to all sorts of treatments, to all sorts of managements, and on various kinds of crop plants This is a method that is widely used throughout civilized countries at the present time

A third method of investigation may be designated as the field observational method This consists in the study of the relationship of roads that have actually been built and are now actually in use to the character and condition of materials constituting their subgrades Many different kinds of roads have been built in all parts of the United States They have been built on a wide range of subgrade materials used in both of the conditions which are referred to above These materials have been used in their undisturbed condition as well as in their disturbed condition It is apparent that it is now possible with the roads that have already been built to study the reactions of practically all kinds of materials that exist in the United States which are likely to be used for an indefinite time in the future for highway subgrades This method re-

quires no experimentation It merely consists of an interpretation of what may be designated as the unconscious experiments of the road building program in the United States The roads have been built not as experiments, but for the purpose of use, but an interpretation can be made of the reaction between these roads and the materials on which they were built and conclusions drawn as to the treatment of this material

Such a method of study corresponds to that method of agricultural investigation instituted many years ago under the name "Farm Management Studies" The relationship of these farm management studies to actual soil conditions were not always determined, but the method is somewhat similar.

Whatever the method used for the determination of the reaction of soil materials under the conditions imposed by the building of highways may be, the results do not become practicable if the investigations stop at the points indicated in the description given above The determination of the characteristics of a given material, whether that be done wholly in the laboratory by experiment on the ground, or by observation of unconscious experiments, refers to the particular spot where the experiment was made or where the material was collected Without further investigation it cannot be applied to any other spot, and in order to make it applicable to other spots it is absolutely necessary that the character of the material in other spots be determined in relation to the character of the material in the spots where the experiments were made In other words, the materials giving certain results by these methods must be defined in tangible terms and their distribution, either throughout the whole country or along the lines where it is proposed to build highways, determined This can be done only by a survey The practical utilization of the experimental results are dependent absolutely on the making of a survey on some kind of scale, either large or small, This constitutes the capping stone of such investigations and the whole structure is useless without it The definitions of these various materials which have been investigated in the laboratory or in the field will be defined necessarily in terms of the reactions which have been determined by the investigations They will be identified also on the basis of this definition They will not constitute units, therefore, that will be applicable to all sorts of purposes They will not constitute units whose definition is based on the determination of all sorts of reactions of which these materials are capable The determinations will be based on the particular reactions which are of special value for the particular purposes of subgrade construction.

WINSLOW H HERSCHEL, U S Bureau of Standards, Washington, D C In a paper by Dr Terzaghi entitled "Simplified soil tests for

subgrades and their physical significance,"[1] there occurs the following passage "Since the sole function of the subgrade consists in supporting the road surface, we are merely interested in its mechanical properties, that means in its compressive strength, its elastic properties (swelling), its permeability and in the influence of the moisture content on its resistance The physical meaning of these properties is as well defined as is the meaning of the data used in structural engineering" Without trying to minimize the effects of volumetric changes produced by frost or shrinkage, it seems to me that insufficient emphasis is placed on the fact that failure of road surfaces may be due to the squeezing out of the subsoil Dr. Terzaghi appears to imply that since the subgrade has merely to support a load, this is a problem in statics, but I believe this tells only part of the story If all goes well it is a problem in statics, but if the subsoil is squeezed out and the road surface fails, it becomes more nearly a problem in hydrodynamics

In the literature of subsoils one finds continually such expressions as "compressive strength," "compressibility," "bearing capacity" and the like The phraseology is evidently taken from that of structural materials, but I believe the analogy is not as accurate as is assumed, because soils do not fail by crushing Another analogy which may be offered is that of thrust and journal bearing which also support loads The rotors of hydraulic turbines as well as of vertical shaft steam turbines have often been supported on water under high pressure, and there is no question of compressive strength More frequently in lubricated bearings the oil is less strictly confined, but it is of high enough viscosity so that it is not readily squeezed out of the bearing

In considering the analogy between the oil in a journal bearing and the soil beneath a road surface, it should be noted that there is an important distinction between the two The oil is viscous but the soil is plastic With a viscous liquid the slightest pressure will cause flow, so that oil can support a load only when confined or under forced feed With a plastic material a certain finite force is required to start the flow, this force varying with the size of channel through which the flow is to take place It is this starting pressure of soils which enables them to bear loads even when imperfectly confined

There appears to have been little or no attempt to classify soils according to their resistance to flow, except so far as resistance to flow, or consistency, may be inferred from such tests as dye adsorption, mechanical analysis, moisture equivalent and plasticity index

[1]Public Roads, Vol 7, p 153; 1926

The attempt to determine by inference the consistency of a plastic material is practically hopeless because it depends upon so great a variety of factors If however the direct measurement of consistency is considered, Dr Terzaghi's conclusion hardly appears warranted that "Due to the complexity of the factors on which the phenomenon of plasticity depends, a classification based on the degree of plasticity is certainly not fit for permanent purposes"

Consistency is determined by the size of particles, the shape of particles, the per cent of clay, the per cent of colloidal matter in the clay and the state of flocculation of the colloidal matter in the clay, as well, of course, by the per cent of moisture It seems therefore preferable to measure consistency directly instead of trying to infer the consistency from separate tests of the multitudinous factors which influence it

If it is admitted that resistance to flow or consistency of subsoils is an important factor in the life of a road, and that it is preferable to determine the consistency, at various percentages of moisture, by direct measurement, then in devising a test for this purpose one very important principle must not be lost sight of While viscosity may be expressed by a single numerical value, because the flow is proportional to the pressure, this is not the case with a plastic material for which the relation between flow and pressure is more complex and must be defined by at least two numerical values While tests like the plasticity index and the penetration test for cup greases[2] in which results are reported by a single numerical value, may give information which is adequate for certain technical purposes; however, according to the principle above referred to, they can not give complete information in regard to the consistency of the materials

Various methods of measuring consistency, which embody the essential requirement that successive observations should be made at different rates of shear, are described in various papers in Journal of Physical Chemistry, October, 1925 The exact method to be employed depends upon the stiffness of the material For soils with the per cent of moisture apt to be of interest in road work, it is suggested that a modification of the method of Arndt[3] would probably be satisfactory The essential parts of Arndt's apparatus are a sphere suspended by a cord in a cylinder containing the material to be tested, a counterweight, heavier than the sphere, being attached to the other end of the cord which passes over a frictionless pulley The time is taken for the sphere to rise a given distance When applying

[2] Proc A S T M, Vol 25, part 1, p 701, 1925

[3] Holde-Mueller, Examination of Hydrocarbon Oils, p 11, 1922

this method to plastic materials, the rapidity to rise should be varied in successive runs by changing the counterweight

If it should prove necessary before making the above described test to remove a certain fraction of the soil which does not pass a certain standard mesh screen, this would add to the difficulties of interpretation, but there is no reason to expect that the difficulties would be greater than are met with in the interpretation of shrinkage tests While there is a difficulty due to the structure or degree of compactness of the undisturbed soil being different from the structure of the soil tested in the laboratory, it is a question whether the consistency of undisturbed soil, newly excavated soil, rolled soil, or fills which have become compacted by standing, is the consistency of most significance to the road builder Whatever the decision may be, a consistency test will not merely identify the raw material but will measure the greater or smaller degree of compacting to which the material has been subjected in the laboratory

In conclusion, while classification of soils by consistency may be impossible if consistency is inferred from other tests rather than measured directly, such a classification appears entirely feasible when consistency is regarded as expressed by the relation between the rate of flow and the force which produces it, and is measured by some appropriate method involving successive observations at different rates of shear

F H Eno, Ohio State University, Columbus, Ohio. Many a human being has been relieved by some simple ointment applied to the ailing skin Many times that has been the sole and only remedy needed So, too, while we know all too little about the skin of this old world, it is better to apply some simple application of sand or gravel to an ailing soil and give it strength to support a heavy traffic road than to wait upon science to search out the trouble in a scientific manner and apply the remedy to some other road after this road has gone to the land of departed road souls *Do not give up* the search for scientific remedies, but remember also that granular soil added to fine grain or clayey soils makes an approximate loam than which not many better soils for supporting values exist, and is this not a scientific surgical skin grafting?

But very few soils regardless of their name or origin but that would render sufficient support for good roads if their water content could be maintained below a certain value Therefore, any method of treatment that will secure this condition is a scientific, though perhaps not an economic, solution of the trouble

Dr Terzaghi has clearly analyzed the conditions in the soils which the engineer must meet The perfect impossibility of transferring a live soil sample from the field to the laboratory has been pointed out

Therefore the work of the analyst in the laboratory must lie in a plane possibly parallel to and some distance removed from the plane of operation in the field practice and possibly in a plane tilted at some undetermined angle to the native soil plane However, if it were not for the laboratory research, the field research might be very much prolonged because of the great number of variables so hard to control under continually varying weather and climatic conditions

We must remember, too, that the soil beneath the pavement is but one step nearer the natural soil than the soil in the laboratory, as Dr Terzaghi so clearly shows later on in his paper for the grading processes, the rolling, truck traffic, fresh exposures and all attendant construction details have also changed the subgrade soil into some form of leather instead of skin.

In speaking of this complex state of the soil being confined to the top four or five feet of the soil, Dr Terzaghi has again opened to the engineer the increasing difficulties of the problem, because the engineer must meet not only the A and the B horizons but the C horizon, by reason of his frequent deep cuts, thus increasing the variables and decreasing the opportunity to secure adequate drainage, if the soil be at all drainable

I have shown in my paper upon the moisture content of the soils of Ohio that the water content of the soils beneath the road runs a maximum of about 43 per cent immediately beneath the pavement and an average of 22 to 23 per cent for the greater depth, or about 5 per cent higher than the subsoil upon the road shoulder This is undoubtedly due to the elimination of a part of the evaporation beneath the road slab

In coming to the solution of the problem Dr Terzaghi gives us a vivid picture of the many variables which every man who has handled soils at all very quickly realizes The engineer who has dealt with concrete has a dim idea of the problem, but he needs to add some few odd variables to his own concrete problem before he realizes the real variability of the soil problem Therefore the suggestion that the investigator begin with a simpler material and learn the action of the physical laws with this substance, freed from the enveloping cloud of variables, seems excellent logic

The idea of comparing the seasonal variation in heaving between the undisturbed field soil and the rebuilt condition of the soil beneath the paved road is excellent The difference in action under these two conditions was well illustrated both in the Bates test road and in the subgrade results in the Pittsburg (California) tests

It is fairly well proven that the capillary action in soil is such that the water content of the soil above the water table decreases

as the distance above the table increases Also that evaporation from the surface decreases the capillary moisture content at the surface of a column of soil.

It is further known that as the water content of a soil decreases below a certain limit the stability of that soil increases rapidly

It is quite possible therefore that subdrainage by tile or French drains may lower the water-table sufficiently to reduce the water content of the soil from capillary sources to such an extent as to stabilize it sufficiently for the load it is to bear

The familiar war makeshift of the pontoon bridge for the extremely heavy artillery traffic is proof enough that the distributing value of a 6 or 8 inch layer of sand or gravel beneath a pavement will so reduce the unit load upon the soil surface as to give the soil sufficient supporting value in many cases

Again, in closing, I wish to bear tribute to Dr Terzaghi's clear analysis of the problem which the engineer has to meet in building our future roads in an economical and a more durable manner

CHARLES TERZAGHI (closure) In his very valuable comment on my paper, Dr Marbut makes distinction between three essentially different methods for solving the subgrade problem of the highway engineer (*a*) The laboratory experimental method, (*b*) the field experimental method (experimental roads), and (*c*) the field observational method (condition survey) Based on what experience we already have, we came to the conclusion that our problems can not possibly be solved in a satisfactory manner except by combined application of all three methods

The data furnished by the methods (*b*) and (*c*) undoubtedly have the most direct bearing on the road problem Yet, when attempting to transform the data into actual knowledge, fit to be utilized in future construction work, we face a task comparable to solving a single equation with several unknown quantities The smaller the number of unknown quantities, the more definite will be the character of the information obtained from solving our equation

The equation of subgrade behavior includes among others the physical character of the raw material of the subgrade, that is, all those properties which depend on the size and on the shape of the individual particles, irrespective of their actual arrangement (texture) If we could eliminate this one variable, we would considerably improve the chances for success of the methods (*b*) and (*c*). The logical way for realizing this elimination obviously consists in previous application of the method (*a*) (laboratory experimental method) Thus the task of digesting the condition survey results is hopeless, provided we do not know more about the raw material

of the subgrade than what has been observed in the field and expressed by vague terms as "highly plastic," "very stiff plastic," "feebly plastic" or "friable" If we have to depend on terms of this kind, we can not even know exactly to what extent the observed properties are characteristic for the material itself and to what extent they are due to the local conditions On the other hand, if we previously examine the raw material of the subgrade in the laboratory, regardless of the field conditions, express its physical properties by figures, arrange them into groups, each one of the groups including raw materials with a very similar character, and finally classify the surveyed roads according to the raw material of the subgrade, we have neatly eliminated one important variable quantity. There can not be any doubt about the value of the improvement thus obtained

Another group of unknown quantities concerns the physical causes of obvious road defects If, in a specific case of road failure, we do not know whether the defect is due to excessive compressibility of the soil, to the presence of free outside water or to periodical volume changes, we can not intelligently plan for preventing similar defects on future roads To learn the cause of such defects requires a well defined knowledge of the mechanical effects of the physical causes involved, and the knowledge of the relation between physical causes and mechanical effects can most economically be obtained by systematic experimentation under artificially simplified conditions—in the laboratory

These and similar considerations govern the policy of the Bureau of Public Roads in its subgrade investigations Obtain your data by means of methods (*b*) and (*c*) (experimental roads and condition survey) Then eliminate by means of method (*a*) (laboratory experimental method) as many variables as you can, and finally solve your equations

The center of gravity of Mr Herschel's discussion seems to reside in the following statement "If all goes well it (the subgrade problem) is a problem in statics, but if the subsoil is squeezed out and the road surface fails, it becomes more nearly a problem in hydrodynamics" Hence Mr Herschel recommends a study of the behavior of the soil not only within, but also beyond, the yield point under different ratios of shear

My attitude toward Mr Herschel's suggestion is governed by the following considerations New roads should be constructed such that they do not fail If the pressure acting on the subgrade exceeds the "yield point" under any part of the road, thus causing the material to squeeze out, failure is inevitable In order to prevent such an

accident, no knowledge is required of how the material behaves under pressure above the yield point It is sufficient to know the yield point and to know how the material behaves under a pressure ranging between zero and the yield point Within these limits, the behavior of the subgrade has been carefully investigated and some of the results have recently been published [1] To extend our investigations over the effect of pressures exceeding the yield point would hardly add any information of practical value to what we already know

I heartily agree with Professor Eno concerning the immediate necessity of purely empirical road improvement Better to have an aching tooth pulled by a blacksmith than to continue suffering Yet few people would like to see modern dentistry replaced by the straight-forward method of the blacksmith

[1] Charles Terzaghi, "Determination of the Consistency of Subgrades by Penetration Methods," *Public Roads*, February, 1927