Principles of Soil Mechanics: VIII—Future Development and Problems

Origin and History of Experimental Study of Soils—Future Objectives—A Theory of Models—Soil Classification—The Method of Equivalents for Engineering Practice

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IN CONTRAST to the rapid advance of engineering science in the fields of statics, dynamics and hydraulics within the last century there has been complete stagnation in the study of soil mechanics. Since Coulomb and Rankine formulated their classical theories of granular earth pressure practically no progress has been made, and the vast field of the mechanics of plastic soils has hardly been touched. Earthwork engineering is in consequence about on that level of efficiency in design at which mechanical and structural engineering found themselves a couple of centuries ago. The reason for this lack of progress lies mainly in the great difficulty of investigation of soil phenomena. In recent years, however, various investigators have turned their attention to the subject. A summary of experimental results obtained by the author has been presented in the preceding articles of this series. Further activities along similar lines are planned, in several institutions of this country, and it may be said (speaking somewhat optimistically) that a general attack upon the unsolved problems of soil mechanics has begun. It will therefore be of value to review the situation briefly.

Engineering Geology—The first efforts were made in the direction of developing engineering geology. A text-book on the subject was written as early as half a century ago (by Dr. D. Braun), though from the present standpoint the work was of little value. Within the last generation or two, many engineers have recognized the need for a better bond between geology and engineering, and have worked to bring it about. Italy and Belgium created special departments for engineering geology. Other states sent their geologists to every important construction enterprise, in order to bring geology and engineering into constructive contact. Meritorious works on engineering geology have been written. Yet the results of the movement are on the whole disappointing.

The more one penetrates the field of engineering geology, the more its innate limitations become evident. In its present state, the science is of service in such matters as locating the sites of structures, or selecting the number and location of test borings, but this is after all only a small part of what is needed. We obtain no exact information concerning the strength and physical properties of the materials composing the several geological strata, and we do not yet find in the teachings of geology any suitable basis for identifying and classifying soils.

Experimental Soil Studies—It thus came to be realized in the course of time that soils must be studied physically as well as geologically, if we are to have a substantial basis for earthwork engineering. It is to the credit of the American Society of Civil Engineers to have made the first conscious step in this direction. In 1913 the society appointed a foundation committee, "to codify present practice on the bearing value of soils for foundations and report upon the physical characteristics of soils in their relation to engineering structures." The committee evidently realized the importance of its task; it has displayed very fruitful activity throughout its existence. By an interesting coincidence, in the same year the Swedish Government Railways appointed a Geotechnical Commission for the purpose of investigating the physical characteristics of materials in unstable slopes and devising remedial measures for slides. Thus, the need for soil investigation found simultaneous recognition on two continents.

During its ten years of existence, the Foundation committee has made many interesting reports. It has conducted friction tests, investigated the compressibility of various soils, and measured the compressive, tensile and shearing strength of undisturbed clay samples, among other things. No general conclusions have yet been reached, and in view of the lack of knowledge concerning the basic relations between the properties of soils it is impossible to make much practical use of the data obtained. The reason is obvious: Each one of the so-called physical properties of soil—internal friction, cohesion, plasticity, compressive strength, and the like—is in itself so utterly complex a phenomenon that it cannot be correlated with any of the others. It would be necessary first to discover the elementary physical factors which determine these properties. Lacking a knowledge of the elementary factors, experiments merely build up a collection of unusable data and give no knowledge of relations.

Investigation in a New Direction—Realizing the necessity for a different kind of physical study of soils, the author in 1917 undertook a program of experimentation in a new direction, beginning with a study of the elastic properties of cohesionless sand. This work was practically isolated, and at the outset found little encouragement, most of the author's friends considering the efforts to be unpromising.

The method which finally led to a considerable degree of success consisted of reducing each problem to its simplest possible terms, and using the result of one test for establishing a tentative hypothesis as to the causes of the phenomena observed, which hypothesis could then be verified or disproved by further tests. No investigation was begun until the preceding one had been carried to some definite conclusion.

Proceeding step by step in this way, the author was able to trace the many physical properties of soils to four underlying factors: (1) Friction between the grain surfaces, including initial friction; (2) viscosity of the capillary water; (3) surface tension of the capillary water; and (4) the influence of the width of voids on the physical properties of the water itself. It was found that the striking differences between cohesive and cohesionless soils could be fully explained in terms of these four physical factors, the intensity of their effects essentially depending upon the size and the shape of the soil particles.

Beginning in 1920 and continued within the last year, the author presented a summary of the action of these four physical factors and how in combination they produce the manifold physical properties of soils, in this journal.[1] A fuller account of the results of the investigation was published in book form a year ago.[2]

Application of Soil Mechanics—For practical application, soil mechanics must be applied in the first instance to the following objectives:

(A) *A theory of models* must be developed. Without such a theory no valid conclusions can be drawn from the results of loading tests on soils or from model tests (as on dams), with respect to full-sized structures.

(B) *Classification of soils* must be accomplished. It should be possible to determine and express quantitatively the relation between two apparently similar soils found in different localities.

(C) *Adequate design data* must be developed. The new science must guide the way toward obtaining all the required data for the economical design of structures consisting of soils or in contact with soils.

A Theory of Models

In modern engineering, theories of models are among the most important and most indispensable tools. To illustrate the necessity of such theories in earthwork engineering, the following example may serve:

The Foundation committee has designed a convenient apparatus for making loading tests on foundation strata, by means of which accurate load-settlement diagrams may be obtained. So far, however, no hint has been given as to how the resulting diagrams can be used. The ultimate bearing capacity of a clean, thoroughly compacted sand amounts to 0.29, 0.42, or 0.61 kg./cm.[2] (Strohschneider), according to whether the diameter of the loaded area is 0.8, 1.25, or 1.78 sq.cm.; and it is known that a circular footing 1 m. in diameter resting on such sand could carry a load several times as great without objectionable settlement, so that it is clear that the bearing capacity of sand increases rapidly with size of loaded area. In the case of plastic clay, on the other hand, the bearing capacity is almost independent of the area of the loaded surface. Soils intermediate between sand and clay will have intermediate properties. Thus, in the absence of a theory of models no conclusions can be drawn from the results of a standard loading test unless a rule of interpretation is established for each of the many kinds of soil encountered.

Even with such rules we would still have the difficulty of identifying the soil at a particular foundation site with one of the standard soils for which the rules were derived. Non-homogeneous or stratified soil deposits further complicate the matter, and make a purely theoretical approach seem hopeless. Therefore the author believed it necessary to approach the theory of models by combined empirical and theoretical attack. In order to do this, each experiment, being in effect a model test, was analyzed theoretically to the point of making clear what physical factors were concerned and developing a formula expressing the law of the result as closely as possible. These formulas were then applied to deriving coefficients having known values for definite limiting conditions (as for plastic clay and for cohesionless sand) and intermediate values for intermediate conditions.

Bearing Capacity of Soil—Some of the results obtained by this course of procedure may be stated as follows: The bearing capacity of a soil depends on its specific gravity and density of structure, the smoothness of the grain surfaces, and the intensity of the capillary pressure, in other words its cohesion. The formulas derived for the bearing capacity of the ground contain as factors the specific gravity w of the soil, the intensity of the capillary pressure p_k, the radius of the loaded surface r, and the ratio t/r between depth of foundation t and radius of loaded surface.

In wet sand, capillary pressure is negligible compared with load stresses, and the ultimate bearing capacity increases directly as the radius r and also increases very rapidly with the depth ratio t/r. In plastic or semi-solid clay, however, the capillary pressure is very large, and the load stresses are negligible in comparison. Application of theory led to the realization that under such conditions the bearing capacity is almost independent of both radius and depth-ratio. Most actual cases will lie between these two limiting cases. For any given ratio p_k/w increasing the size of the loaded area will cause the case to approach the limiting condition of cohesionless sand.

While the theory so far developed accomplishes this much, and also is of assistance in devising special tests for cases of variable soil strata, it is by no means perfect, nor have the laboratory test methods yet been developed to their best form. The results demonstrate, however, that the combined theoretical and empirical method is effective. An interpretation of the results of loading tests is now possible, however much it may still need refining. This could not have been accomplished without laboratory discovery of the fact that the cohesion of clay is due to negative hydrostatic pressure of the capillary water; that the physical properties of capillary water contained in sub-microscopic voids differ from those of water contained in coarser materials; and that the internal friction of soils is a composite of several independent actions.

A theory of models also has other applications. For example, the test loading apparatus proposed by the Foundation committee is intended to be applied to a loaded area 34.7 cm. in diameter, the surrounding ground being covered by a layer of sand 70 cm. deep. Here the ratio t/r is about 4. Looked at empirically, the sand fill is only a protecting layer, and it was actually so intended. Considering the situation theoretically, however, we see that the fill may be without effect on the result of the load test or it may multiply the bearing capacity several times, depending on whether the subsoil has large or very small cohesion. Because of this relation, we are bound to conclude that a loading test intended as a guide for the design of a sand foundation of shallow depth (t/r very small) should be so arranged that the ratio t/r in the test is also small, otherwise the test results may be misleading. The disturbing influence of the protective layer becomes insignificant, however, when the soil has high cohesion.

The lack of a theory of models is responsible for the fact that engineers hold curious and highly arbitrary views as to the interpretation of small-scale experiments on soil or soil structures. Investigators who undertake large-scale experiments and find their results differing widely from those of small-scale experiments commonly explain the disagreement by charging the small-scale experimenter with being unable to appreciate the importance of errors of observation. Such charges are manifestly unfair; the real trouble is the lack of a theory of models, which in turn is due to incomplete knowledge of the physical character of the phenomena involved. Every apparent contradiction between the results of small and of large-scale tests is a symptom of a specific deficiency of our insight. No problem in soil mechanics can be considered solved unless the investigator is in a position to explain fully the cause of such disagreements. For this reason small-scale experiments should be regarded an essential part of and a supplement to every large-scale investigation. Figures alone are practically worthless. What we need is relations.

Soil Classification

Every piece of actual construction work represents an expensive full-scale test. If we are in a position to identify accurately the soil encountered at construction, the value of the test results is inestimable. If, on the other hand, the soil remains unidentified, the same test is practically without any value, so far as future utilization of the test results is concerned. Hence, a method for soil identification is just as important as a theory of models.

It has been shown that variations in character of soils are merely the visible effect of corresponding variations in size and shape of the soil particles, in water content and in structure. If these four factors were known, it would be easy to identify soils. That the importance of these factors was well appreciated is shown by the fact that the Foundation committee's classification system takes them duly into account, though unfortunately in a form not applicable to practical purposes. The properties of most soils depend on those of their smallest (so-called colloidal) particles, and one of the most important characteristics of these particles, the shape, is not susceptible of quantitative expression. Similar difficulties are met in dealing with another factor of outstanding importance, the chemical character of the adsorbed constituents. Due to the utter complexity of colloidal behavior the problem of comparing soils is in some respects like that of comparing the quality of two apples. To solve this problem according to the proposals of the Foundation committee would mean basing the comparison of the apples on the results of a physico-chemical analysis of their organic constituents. Realizing the doubtful benefit to be derived from so elaborate a procedure, the author proposed, symbolically speaking, the more direct method of biting into the apples and tasting them.

Basis of Classification—In the realm of soils, the taste of the apples corresponds to the common physical properties of soil (elasticity, cohesion, permeability and the like). Although these properties are numerous and each represents the combined effect of several causes, they offer the decisive advantage that they are susceptible of accurate numerical expression by coefficients and diagrams.

The accompanying table gives a complete list of these properties. In their totality these properties express every detail of the intricate properties of the soil constituents, somewhat as the elastic properties of a metal express the nature of its intricate molecular structure, or as a man's actions express his character.

Due to the great number of items, an exhaustive study of a soil sample cannot possibly be made except for scientific purposes. However, theory and experience show that the several properties listed in sections *B* and *C* of the table are all interrelated, although the precise nature of this relationship cannot yet be stated. A systematic experimental investigation is required to establish it. If 50 or more soils of widely different character should be tested according to the full schedule of the table, it might be expected that the assembled results would soon reveal the nature of the interdependence of the physical properties. With this knowledge the tests required for furnishing complete data on the character of a particular soil could be so simplified as to make them applicable to every earthwork reconnaissance—a future result likely to be of the utmost value. By a partial unraveling of these relationships I recently succeeded in simplifying the method for estimating the intensity of the capillary pressure acting at different depths of a mud deposit, to such an extent as to save nine-tenths of the time required for testing the drill samples.

This illustrates the gain that may be expected to result from the study of the relations between soil properties. Until these relations have been worked out, however, and test programs framed accordingly, it will be necessary to adapt any phase of soil tests to the particular practical objective of the work in hand.

Adequate Design Data

Design Equivalents—In soil mechanics as in other fields, ready calculation for purposes of approximate analysis and designing requires making use of simplified empirical assumptions. In hydraulics we assume water to be incompressible, and in mechanics of materials we use Hooke's law as if strictly true. Similarly, for soil mechanics we may assume as closely correct the following principles: (1) That the ratio between modulus of elasticity and internal pressure is constant; (2) that the relation between stress and strain, for direct compression with free lateral expansion is parabolic; and (3) that Darcy's law is valid. These assumptions are extremely simple, yet most practical problems are of such nature as to lead to intricate problems in the calculus of variations if an exact solution were attempted. Even if the stress-strain law were linear (Hooke's law) it would be exceedingly difficult to deal with a simple case such as stress distribution in a trapezoidal earth embankment, while with the parabolic law the problem becomes impossible. Obstacles of this kind make necessary a further process of simplification, using *design equivalents*, i.e., approximations similar to those utilized in other fields—as when a steel bridge is assumed to have frictionless joints—and subsequently making separate allowance for the approximation if necessary.

This method of equivalents may be applied as follows: In studying, say, the effect of a load on the supporting soil, or the swelling of clay after driving a tunnel through it, or the effect of time on pile friction, the first step is to study what physical factors are involved in the process, which is readily done if the physics of soils is understood. Then an equivalent is devised, so as to represent an interaction of physical factors closely similar to the actual one, but yet simple enough for mathematical analysis. Formulas based on this equivalent give a clear conception of the relative influence of the several physical factors on the actual process, although they are strictly approximate ones.

To take an example, the equivalent for a circular foundation is a cylindrical soil core surrounded by a cylindrical soil ring. The top of the soil core corresponds to the loaded area. The loaded core presses laterally against the inside of the ring. The proper ratio between radius of core, height of core, and width of ring was estimated from the results obtained by photographing through a glass window the grain movements produced in soil by a superincumbent load. Formulas derived from such an equivalent agree better with test results than the formulas furnished by any other known method, and in addition give other valuable information, such as the influence of rate of load application on bearing capacity (in the case of wet clay), or the influence of the shape of the base (circular or rectangular) on the bearing capacity.

DATA REQUIRED FOR DESCRIBING PHYSICAL PROPERTIES OF HOMOGENEOUS SOILS

A—Material in Original Condition

1. Volume of voids, in per cent of total volume. For clayey soils in addition: microscopic structure (homogeneous, fissured, crumbly, etc.).
2. Moisture content, in per cent of weight of solid matter.

B—Modified Condition

3. Shape of grains (by microscope; include sketches where possible).
4. Specific gravity of grains (by pycnometer).

5a. (For plastic soils.) Limiting moisture content of liquid, plastic, semi-solid and solid consistencies.

5b. (For sand and granular soils.) Limiting void ratio of loosest and densest structure.

6. Coefficient of internal friction (minimum and maximum values determined at zero capillary pressure).
7. Lateral-pressure ratio in confined material (determined at zero capillary pressure).
8. (For plastic soils only.) Compressive strength of cube (dried at 100 deg. C.).

C—Diagram Characteristics

9. Uniformity (grain-size platted on semi-logarithmic chart).
10. Pressure-void diagram under continuous and cyclic loading.
11. (For plastic soils only.) Load-compression diagram for cubes of known water content under continuous and cyclic loading. (The diagrams 10 and 11 combined make it possible to compute the constants of elastic behavior.)
12. Permeability-void diagram.

Aside from its direct use in design, the method of equivalents will be of service in developing a classification of soils for purposes of practice. If the kind and relative importance of the physical factors governing a particular field phenomenon (as stability of slopes, or bearing capacity of ground) is known, a sample of soil may be tested in the laboratory for the particular coefficients which control these physical factors; then it may be concluded that every other soil having approximately the same values for these particular coefficients will behave similarly, so far as this phenomenon is concerned. The other physical factors can be disregarded, without affecting the value of the result.

Proper use of the method also helps to avoid unwarranted generalizations. Such generalizations have been particularly common in connection with the retaining-wall problem. Our classic earth-pressure theories are themselves mere design equivalents, in the sense just discussed; the sand is assumed to have a definite coefficient of internal friction, the effect of soil deformation on pressure distribution is neglected, etc., all of which assumptions are tolerable only for the purpose of the equivalent. Yet most of those who have dealt with retaining-wall experiments and analysis look upon these assumptions as rigidly correct, and in some cases resort to highly advanced mathematics to calculate the curved sliding plane of least resistance, or other details whose importance is negligible compared with the errors involved in neglecting the elastic effects. Again, the attempt has been made many times to apply Rankine's theory to determining bearing capacities, completely overlooking the fact that arching effects prevent the soil particles near the base of the load from yielding laterally.

Or, again, consider the striking remark made by a well-known authority in a recent discussion: "When an experimenter finds the angle of friction greater than the angle of repose, it at once condemns his results and shows that he is not well grounded in theory," which overlooks the radical difference between a change from motion to rest (which determines the angle of repose) or a change from rest to motion (which determines the internal friction). The fact is that the inclination of the surface on which a moving body comes to rest is invariably smaller than the angle at which a body at rest starts to move. If existing theories do not agree with such facts, the theories, not the facts, must be modified. But these examples are sufficient to show the danger of unwarranted generalization in soil mechanics. A proper study of equivalents will help to avoid this danger.

FURTHER DEVELOPMENTS

Engineering practice concerned with soils still depends, as did structural engineering a century or two ago, on the instinctive genius of a few individuals, and on the chance discovery and development of such individuals. Efficient and economical design is still largely a matter of hopeful anticipation rather than actual accomplishment. Moreover, whatever is accomplished in this field by the strength of individual genius remains merely an admirable monument and is of no lasting benefit because we remain powerless to identify the soils available for similar operations in two different localities, and lack methods for interpreting and applying the results of tests.

To improve this condition we need first of all a new generation of earthwork engineers, thoroughly familiar with the essentials of soil physics and trained from the very start for exhaustive analysis of the phenomena which are apt to occur in actual earthwork practice. Considering the amount and the quality of knowledge required for such activities, the courses offered by the colleges in engineering geology and in foundation engineering are obviously inadequate. On the other hand, it does not seem feasible to extend the scope of these courses without simultaneously reducing the time provided for other important subjects. Hence, the only appropriate measure would be to increase the number of traditional civil engineering options (sanitary engineering, structural engineering, etc.) by one. This new option (earthwork and foundation engineering) should include among others a more elaborate course in engineering geology and an elementary course in applied colloid chemistry.

The second essential requirement concerns the activities of engineers engaged in earthwork and foundation engineering. No satisfactory improvement is possible unless at least some of these engineers keep in permanent contact with the science of soil behavior, and try to apply the available information to their observations in the field. Progress in engineering essentially depends on the quality of the data published in professional papers, and thus far, due to inadequate discrimination between essentials and non-essentials, most of the published data have but little value.

Finally the profession needs at least one institute for scientific earthwork engineering, equipped with suitable laboratories and with a trained research staff, preferably incorporated in the organization of the department of civil engineering of some leading university. Besides serving educational and research purposes, such an institute would have two essential functions: to analyze and digest the results of important observations made and communicated by outside engineers, and to develop suitable field methods for preliminary work, based on scientific principles.

If development plans of this kind are followed out, soil mechanics may within a short time become an important factor of engineering science. In the absence of such conscious progress, the experiences of the present generation will be as valueless as those of the past, because of unintelligible records of the properties of soils.

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[1]See an article by the author, "Old Earth Pressure Theories and New Test Results," published in *Engineering News-Record*, Sept. 30, 1920, p. 632; and the preceding articles of the present series, "Principles of Soil Mechanics," as follows: I—Phenomena of Cohesion of Clay, Nov. 5, 1925, p. 742; II—Compressive Strength of Clay, Nov. 12, p. 796; III—Determination of Permeability of Clay, Nov. 19, p. 832; IV—Settlement and Consolidation of Clay, Nov. 26, p. 874; V—Physical Differences Between Sand and Clay, Dec. 3, p. 912; VI—Elastic Behavior of Sand and Clay, Dec. 17, p. 987; and VII—Friction in Sand and Clay, Dec. 24, p. 1026.

[2]"Erdbaumechanik," by Charles Terzaghi (1925).

[3]Transactions, Am. Soc. C. E., 1920-1922.

[4]Transactions, Am. Soc. C. E., 1916, p. 351, Table II.