PAST AND FUTURE OF APPLIED SOIL MECHANICS*

DISCUSSION

By Ralph B. Peck†

One paragraph in Dr. Terzaghi's stimulating paper deserves to be reproduced and to hang in the office of every subsurface engineer:

"Many problems of structural engineering can be solved solely on the basis of information contained in textbooks, and the designer can start using this information as soon as he has formulated his problem. By contrast, in applied soil mechanics, a large amount of original brain work has to be performed before the procedures described in the textbooks can safely be used. If the engineer in charge of earthwork design does not have the required geological training, imagination and common sense, his knowledge of soil mechanics may do more harm than good. Instead of using soil mechanics he will abuse it."

The abuse of soil mechanics has received attention in several publications by Dr. Terzaghi and others. It is a matter of serious concern to all those engaged in the practice of subsurface engineering. Abuse may occur to different degrees and on different levels. This discussion is concerned with the possible abuse of soil mechanics in the observational procedure.

The observational procedure so well described in Dr. Terzaghi's paper is one of the most notable and useful contributions of applied soil mechanics. It often permits a very economical solution of a difficult problem at an adequate and known factor of safety. As the method is popularly understood by subsurface engineers, it consists of basing a design or construction procedure on average conditions, or on conditions considered to be most probable, rather than on the most unfavorable conditions that are compatible with the conditions at the site. Field observations are then devised to give adequate warning regarding undesirable deviations from the assumed conditions. If necessary, modifications or corrective measures are introduced as indicated by the observations.

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One essential feature of the observational method is omitted in this conception. The engineer must not only assess the average or most probable conditions, but he must also carefully assess the most unfavorable conceivable conditions. Moreover, he must have a sound plan for coping with the unfavorable conditions if they should actually develop. This plan may consist, as Dr. Terzaghi suggested in one of his examples, of making known to the owner the consequences of exceptionally unfavorable conditions, because the owner may be willing to take the risk. Under many circumstances, however, the unfavorable conditions, if they should prevail, would require radical changes in design or in construction procedure. If such changes are required, but if the engineer has not planned in advance what they should be, the consequences may be serious indeed. The writer suspects that some designs and construction procedures that have been advocated in the name of the observational procedure have been proposed without giving proper attention to the steps that would be taken if unfavorable conditions developed. The laws of probability indicate that such designs or procedures would be adequate in most instances, whereupon the designer gets the credit for proceeding in an economical fashion. Such a modus operandi is an abuse of soil mechanics and should not be tolerated.

A second requirement in planning an observational approach to a design is that field measurements can be planned and executed that will disclose significant unfavorable developments. Considerable ingenuity may often be required in determining what measurements should be made and how to make them. The nature of some problems, however, may preclude measurements that will give the necessary information in time to permit appropriate action. Under these circumstances the observational procedure should not be applied.

As an example, the foundations for two grain elevators, A and B, may be considered. The soil conditions at both sites were virtually identical; indeed the two sites were in close proximity to each other. Both structures carried approximately the same loads. Both were supported on vertical piles driven through loose fill and relatively soft cohesive deposits to a firm base. Along one side of each structure was a sheet pile bulkhead; against the opposite side was a fill supporting railroad tracks. Lateral movements of structure A became perceptible after about 20 years of service and were measured from time to time. The amount of movement was found to be doubling at about five year intervals, and reached a total of more than one foot. Because of the acceleration, the interested parties became alarmed and provided additional support for the structure before any serious consequences developed.

On the other hand, structure B gave no visible evidence of appreciable lateral movement. Therefore, it was considered to be more stable than structure A and no periodic observations or remedial measures were considered necessary. Nevertheless, after comparatively minor incidents that may have slightly altered the loads on the structure or its foundations, the structure suddenly underwent very large lateral deformations and within a period of one or two days suffered a complete collapse and foundation failure.

The principal difference between the two structures was the presence of a relatively small number to timber batter piles beneath structure B. These piles had evidently supplied sufficient resistance to prevent the development of the large lateral movements observed at structure A. In resisting the movements, however, they were very highly stressed. When some relatively minor incident caused one or a few of these piles to fail, the subsoil could not quickly accommodate itself to the changed conditions and an almost immediate collapse occurred.

Had the writer been requested, prior to the collapse, to investigate the stability of structure B, he would quite possibly have suggested refined observations, such as careful measurements of lateral movements and the installation of slope indicators, to detect the beginnings of movement. He would probably have recommended that observations be made at frequent intervals and that no remedial measures should be taken unless the structure began to accelerate. Had this prescription been advocated and followed, it is quite certain that the collapse would have occurred precisely as it did.

The defect in the use of the observational procedure, as suggested at site B, lies in the presence of what might be termed brittle and rigid elements in the foundation. These elements had sufficient rigidity to prevent a movement in the early stages but not sufficient strength to withstand the forces that developed as time went by. It is doubtful that suitable deformation measurements could have been devised to give adequate warning of the failure that occurred, because the brittle load-carrying component could not have deformed perceptibly before failure. On the other hand, a structural analysis of the behavior of the foundation, even from a qualitative point of view, would have led to the conclusion that the batter piles must have been highly loaded and that they constituted danger spots. A proper analysis and assessment of the conditions would, in other words, have led the engineer to the conclusion that the usual observational procedures might be misleading and unconservative in this instance.

This illustration points out that the subsurface engineer dealing with the observational method needs an additional ingredient besides a knowledge of the geology of the site and a knowledge of the soil conditions. He also needs a good conception of structural behavior and of the interaction between soil and structure. He must be especially wary of elements that may carry dangerously high loads without being able to deflect appreciably in comparison with the deflection required to mobilize the strength of the other elements.

A second type of problem in which current observational procedures may not lead to a sound conclusion involves the stability of slopes. During the construction of earth dams, or during the placement of fills, it has become rather customary to install pore pressure devices in the fill and in the foundation materials. One purpose of the pore pressure devices is to determine if, or when, the rate of filling must be decreased in order to eliminate the possibility of a slope or base failure. Under some simple circumstances, for example, if the piezometer is located beyond the toe of the embankment and registers a pressure approaching the weight of the overburden, a fairly clear cut statement may be made regarding the factor of safety. In most instances, however, the relationships between the measured pore pressures and the factor of safety against failure are by no means simple. The pore pressure observations unquestionably lead to a better understanding of the subsurface conditions and of the stability of the slope. They may not, however, lead directly to an indication of the factor of safety. If they are made, but if inadequate thought has been given to the way in which they are to be interpreted, reliance on them as part of an observational procedure may also be considered an abuse of soil mechanics.

In short, the observational procedure must be planned with great care. The engineer must be certain that he can cope with the consequences of learning that the real conditions are extremely unfavorable. He must also assure himself that the observations he intends to make will actually disclose the state of affairs in sufficent time and with sufficient clarity to indicate the degree of safety. If the engineer overlooks these matters, the observational procedure may lead to a catastrophe made all the less defensible because the techniques at first glance might appear to represent the latest developments in the application of soil mechanics.

DISCUSSION

By James H. Stratton*

In my early exposure to soil mechanics in the period of service in the Corps of Engineers it seemed for a time that all answers to our problems were to be found in the laboratory. There was at that time a hierarchy of the blessed, that is, of those with recent undergraduate and graduate training in soil mechanics, who seemed disposed to set themselves apart from the rest of the profession and to deny to others the right or duty to raise questions. If one had the temerity to express opinion or misgiving, he risked finding himself foundering in technical argument based on the mathematics of theory or on the interpretation of laboratory results. This was, of course, embarrassing to the uninitiated and scarcely served to further the practical use of this newly gained knowledge.

While the techniques of modern soil mechanics were still in their infancy of application, the Corps of Engineers experienced two dam failures, one of which was described in various engineering publications. (1) These incidents, although unfortunate in themselves, proved not to be setbacks to soil mechanics and indeed were responsible to a very large degree for changes in attitudes. One could sense a new-found humbleness on the one side and on the other an agreement that explanation of these failures did not lie within the province of engineering knowledge that existed before the advent of modern soil mechanics. Both sides recognized that "Acts of God" explanations would not suffice, and as a consequence there was instituted a new and enlarged program covering explorations and sampling, testing and basic research into the behavior of soils and foundations under stress. In addition there was stimulated a new interest in observations during and after construction.

In the following years in public service and later in private consulting practice, I have witnessed a continuing reconciliation of views to the common purpose of furthering the development and use of soil mechanics. That Dr. Terzaghi has been largely responsible for the reconciliation of attitudes there can be no question, just as there is no question that the attitudes of some of his early disciples were self-induced aberrations arising both from the conceit induced by

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newly gained knowledge and from the resistance offered by old-line engineers to change from what to them had been good enough.

In the section of this paper, Conclusions and Outlook, the words,

> "Once an engineer has left his alma mater his mind is likely to become dogmatic. Therefore, he must be warned against the misuse of soil mechanics at an early date."

express what I deem to be its thesis.

However, one may fairly assume that Dr. Terzaghi had no thought of restricting his message solely to a warning to the young against the misuse of soil mechanics since he foresees danger in "ultimate dogmatic attitudes" which will stultify both the proper use of available knowledge in soil mechanics and its further progress. Failure to heed would be to court troubles of the sort he has pictured so vividly. His own good fortune in being of a natural philosophical turn of mind led him throughout his professional practice constantly to seek fuller understanding of the materials, forces and virtually every other phenomena in nature he has encountered and thus has protected him from the dogmatic tendencies that seem to grow in most of us with the accumulation of years.

There is a rare forcefulness in the writings of Dr. Terzaghi which should, and I believe does, have deep appeal not only to those educated in soil mechanics, but also to those senior in years in the profession who to some degree are responsible for the work of specialists in the field of soils and foundation engineering. Such expressions as:

> "Therefore, the misuse of soil mechanics will continue unless the center of gravity of the course in engineering geology is shifted from the geological facts to their engineering consequences."

and,

> ". . . in applied soil mechanics a large amount of original brain work has to be performed before the procedures described in the textbooks can safely be used."

are warnings from which the engineer exposed to soils and foundation problems can profit regardless of the level of his responsibility or the intimacy of his acquaintance with or the mastery of theory and testing techniques and analyses.

It is our good fortune that Dr. Terzaghi did not restrict his interests to the development of theory and soils testing techniques, to which in his early years he contributed so much, at the expense of the full use of his natural talent for observation and analytical evaluation, in a practical sense, for had he done so this paper and others in recent years would not have been possible.

Dr. Terzaghi shows that time-honored "type solutions," even though supported by available theory or the results of experience elsewhere, should not be accepted on faith, but only after the "brain work" which he commends. His example (Case No. 7) of the inadequacies of grouting (a time-honored practice on which in recent years there have been found to have decided limitations) where controlled drainage was properly the solution, is a case in point. Dr. A. Casagrande in a recent paper has also described the limitations of grouting. (2)

It is a tribute to the profession that Dr. Terzaghi not only has had the will, but has found the time to exercise his innate attributes as a teacher in sharing his knowledge and experience. The citations out of his long practice of engineering indicate his unwillingness and perhaps inability ever to rest on his accomplishments and successes of the moment, or for that matter, on the laurels which have come his way because of his great contributions to soil mechanics, which in another would surely have led to complacency. His rare faculty of fitting each soil and foundation problem encountered and the solution he has devised into a framework with a clear glass front are masterpieces in themselves. If viewed through opaque glasses fitted to prescriptions related to fixations in theory, idolatry for the results of testing or to prejudices or penchants for past solutions in which there is no real parallelism, then understanding will be lost and the viewing profitless. His command of the language and pungent expression serve the good fortune of the reader who doffs his opaque spectacles.

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2. CASAGRANDE, ARTHUR, "Control of Seepage Through Foundations and Abutments of Dams" *Geotechnique*, September, 1961.

DISCUSSION

By W. J. Turnbull*

The discusser has with great pleasure read Dr. Terzaghi's paper on "Past and Future of Soil Mechanics" and must, as always, compliment him on the interesting data presented and his very readable style of writing. His papers are particularly impressive because the principles and points under discussion are brilliantly illustrated by case histories.

In this paper, Dr. Terzaghi proceeds from a description of the "Old Code" of foundation engineering and the often embarrassing consequence of its application through the humble beginnings of soil mechanics to its current general acceptance and frequent misuse. The latter is often the result of improper interpretation of geological data, oversimplification of soil profiles, poor soil sampling, inadequate testing of the samples, and poor supervision and control of these operations. Dr. Terzaghi concludes: "Hence it is not surprising that the application of soil mechanics to practical problems occasionally leads to very disappointing results."

In the following section of his paper Dr. Terzaghi then proceeds to illustrate how a knowledge of the principles of soil mechanics, common sense, and keen observations before and during construction can lead to safe and economical design without elaborate field exploration, soil testing, or theoretical computations. At the peril of appearing to introduce a new subject, the discusser would like to broaden the topics of Dr. Terzaghi's paper to a field of soil mechanics which all too often is being neglected by our best soil mechanics practitioners.

This field deals with proper supervision or control of the construction phase of projects. Presumably at the end of the design and the beginning of the construction phase the soil mechanics features of the design have been integrated into over-all plans and specifications. Unfortunately it must be acknowledged that the soil mechanics design features of projects still vary from good to poor. Regardless of this, if the completed project is not as good as that called for in the plans and specifications, then I feel that this also constitutes another type of misuse of soil mechanics.

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For many years it has seemed to the discusser that it is so senseless and useless to spend the time and effort to develop a reasonably good design and have it nullified to a large extent in construction by a lack of understanding or appreciation of the critical features often involved in soil mechanics. It is realized there is a need to continue basic and applied research in soil mechanics and particularly to widen such information among engineers practicing soil mechanics, but it is emphasized that there is a need for more soil mechanics engineers who have fairly continuous contact with construction to give more attention to the follow-through between specifications and plans, and construction. It is felt that many soil mechanics engineers are guilty of developing plans and specifications in which the broad-brush treatment is given in their development and proper emphasis is not given those portions which are critical to the final behavior of the prototype structure. Instead, many words may be devoted in the specifications to relatively noncritical features of soil mechanics, whereas the treatment of a critical feature may be much briefer. As result of this, the interpretation of plans and specifications is left more or less to the field construction engineers and contractors. On almost every contract job, at least with which the discusser has been associated, certain problems arise which usually require some change and result in a "give or take" proposition between the engineers and the contractor. If this "give or take" happens to involve a critical soil mechanics feature, all too often the latter is compromised, usually in the interest of construction expediency.

A few examples will be cited demonstrating this poor field control which have happened in the discusser's own practice. In the instance of building an important structure, the engineers and contractors were careful to do very little concreting in cold weather and that which they did do was carefully protected. In the reverse, on the basis of the statement that the job must progress, there was no hesitation between them in going ahead with earthwork construction during wet winter weather when it was impossible to process the soils properly; thus the resultant soil placement was of very poor quality. Such a condition is brought about by the lack of emphasis that we in soil mechanics have given to the dangers in stability by compacting soils in a too wet state, whereas the concrete designers have more effectively pointed out the dangers to the strength of concrete of freezing temperatures.

On an airfield project, in the interest of construction expediency a contractor was allowed to place plastic fines in an otherwise reasonably good nonplastic base course material. The reason, of course, in placing the fines in this material was to make it behave better under the operations of the compaction equipment. The fines increased plastic deformations and resulted in detrimental failures in the pavement. The danger of plastic fines, beyond a certain percentage, even in coarse granular material, has long been known by soil mechanics engineers. This danger limit was incorporated in the specifications but to no avail. Again, proper emphasis on and understanding of this critical feature were lacking.

In a third instance, the relatively simple item of improper compaction produced detrimental settlement of the finished structure. In this particular instance the engineers deluded themselves that proper compaction was being obtained, which was brought about by not having proper inspection of backfill materials and compaction procedures. Proper material and procedures were called for by the specifications, but their importance was not emphasized.

All three of above-cited conditions, which must be considered as just plain errors, occurred because of rigid job completion dates and the lack of understanding on the part of the engineers of the critical features being violated. While these examples are fortunately the exception and not the rule, the discusser feels that they do occur too often on important projects and that many more engineers engaged in soil mechanics should pay more attention to the proper control of construction.

Conditions exist on certain projects which cover a broad range of soil conditions, such as several miles of highway construction or several miles of canal construction with the appurtenant structures, where it is infeasible to completely site-adapt the plans and specifications. In other words, the cost of making sufficient field borings and laboratory tests to cover each and every feature of the project in detail would be excessive both in money and time. On such projects it is necessary to somewhat generalize in the plans and specifications. The purpose in such plans and specifications is to give the engineer the prerogative of using good judgment when encountering changed or unexpected soil conditions. Unfortunately while this is contemplated, it often is not explicitly spelled out in the specifications, and the engineer in trying to make necessary changes or site-adapt the specifications when needed, finds himself again handicapped by a rigid completion date, lack of understanding on the part of the supervising engineers and administrators, and their general antipathy toward change orders; and sometimes an obdurate contractor, if forced to change, may try to take undue financial advantage of such change.

In this last situation cited, the discusser feels that soil mechanics practicing engineers interested in construction are lax in not insisting that civil engineers and contractors in general give proper recognition to the fact that plans and specifications on such jobs are not completely site-adapted and therefore changed soil conditions, to some limited degree, must be expected and provided for when these changed conditions are encountered.

The ideas of the discusser on this subject are more broadly expressed in a paper, "The Practical Application of Soil Mechanics," presented in the panel discussion in Section 7 on "Various Questions, Best laboratory-works relationship" of the Fifth International Conference on Soil Mechanics and Foundation Engineering.

CLOSURE TO THE DISCUSSION

By Karl Terzaghi

The paper under discussion was primarily written for the purpose of calling the reader's attention to the causes of the various kinds of "Misuse of Soil Mechanics," and to the available means of preventing such misuse. The author's statements were based exclusively on his personal experiences and observations. Therefore it is most gratifying to have them supplemented by the accounts of three experienced engineers with very different professional backgrounds.

Professor Peck concentrated his attention on the author's description of the "observational procedures." He pointed out that the author has failed to mention the importance of observations disclosing the increase of the stresses in rigid members of a structure in contact with bodies of soil subject to progressive deformation and illustrates his comments by an example.

An engineer who is already used to "feel" with the structures he designs will not fail to consider the interaction between soil and structure and to plan his means for observation accordingly. For instance on a job with which the author was associated, one of his principal concerns centered about the performance of foundation piles embedded in a thick clay stratum subject to progressive deformation. He planned his means for observation accordingly. The observational records which now cover a period of 15 years disclose very clearly the performance of the piles and the influence of the deformation on their factor of safety with respect to failure by bending. In this case the state of stress in the piles was determined by the settlement of the pile heads, their horizontal displacement and the angular displacement of the uppermost portion of the piles. Instructions were issued to prevent further increase of the deformation of the clay stratum by reducing the surcharge on the ground surface next to the pile foundation if the stresses in the piles should approach a critical value.

In connection with the grain elevator B referred to in his discussion, Professor Peck points out correctly that "a structural analysis of the behaviour of the foundation . . . would have led to the conclusion that the batter piles must have been heavily loaded and that they constituted danger spots." Since the piles were embedded in plastic material subject to progressive deformation under the weight of the railway embankment, the structural analysis would also have shown that the piles would fail by buckling and not on account of an increase of the axial load because their two ends are fixed whereas their middle portion moves with the soil. The buckling failure is preceded by a progressive displacement of the upper portion of each pile by rotation about its fixed upper end. Hence if local conditions precluded reliable detection of such rotational movement, sound engineering would have required the assumption of the most unfavorable possibility and the initiation of remedial measures as soon as the source of danger was recognized.

Professor Peck also calls the reader's attention to the fact that even the results of field observations may leave a wide margin for interpretation. Hence even if observational procedures are used, much depends on the capacity of the engineer to interpret the observational data and to adapt his decisions to the residual uncertainties. In the field of applied soil mechanics nothing can safely be done without supplementing the standardized procedures by the results of original brainwork and common sense.

Mr. Stratton describes vividly the conceit which grew out of the early successes of soil mechanics among those members of the U. S. Corps of Engineers who had the benefit of formal training in this field and the salutary effects of the first setbacks.

Mr. Turnbull point out the fact that the benefits derived from soil mechanics can be nullified by improper supervision and control in the construction phase of a project. This possibility was not mentioned in the paper but it was dealt with in detail in an earlier one (Terzaghi 1958) under the heading "Design Assumptions and Field Conditions," and the writer is grateful to Mr. Turnbull for having called the reader's attention to it. If the soil conditions at a given site are not very simple, at least minor modifications of the project during construction are inevitable. If this necessity arises "the construction engineer may make then changes in accordance with his own judgment, which he believes is sound, although it may be very poor. Important changes of this kind have even been made on the job without indicating the change on the field set of construction drawings." (1.c., p. 8.)

Still today it is quite common, in connection with foundations and dams, to consider construction drawings and specifications to be the last word and to turn these documents over to the construction superintendent who had no connections with the design; the designer takes it for granted that the project will be carried out strictly in accordance with his intentions. In structural engineering this procedure is perfectly satisfactory, but in subsurface engineering it can have very detrimental consequences. Therefore Mr. Turnbull is perfectly justified in stating that it "constitutes another type of misuse of soil mechanics."

The author wishes to express his gratitude to the discussers for their valuable contributions to the paper.

REFERENCE

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