ENGINEERING GEOLOGY ON THE JOB AND IN THE CLASSROOM*

By Harvey O. Banks† and Laurence B. James‡

DISCUSSION

The author discusses the role of soil mechanics and engineering-geology in foundation and tunnel projects and outlines a course in engineering-geology which he proposes be given to civil engineers. The uncertainties involved in analyzing a soil sampling and testing program in which the geologic characteristics of a site have not been carefully considered, are aptly described. Dr. Terzaghi stresses the need for full appraisal of these uncertainties, and he proposes a course in engineering-geology for the civil engineer which will enable the engineer to recognize those aspects of subsurface conditions which will require the services of a trained engineering-geologist. He expresses the opinion that in the realm of earthwork engineering the instances are rare in which an engineering problem will require the services of an engineering-geologist, provided civil engineers are adequately trained in geology.

Certainly geologic knowledge is highly desirable for civil engineers; however, it would seem questionable that a single course in the subject could provide the background required to recognize significant geologic characteristics at a site or to decide whether further geologic exploration should be considered. In the writers' opinion most such appraisals call for the combined judgment of the engineer in charge of the project and the most competent engineering-geologist available, particularly in connection with projects of significant size. The experience of the California State Department of Water Resources in design and construction of large hydraulic works has shown the wisdom of and advantages of making maximum use of *both* engineering and geologic talent.

Dr. Terzaghi points to the reliability of the exploration program

* Paper printed in April, 1961 JOURNAL, by Dr. Karl Terzaghi.

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and its interpretation as cardinal factors in foundation investigation which the engineer often fails to fully appreciate. It is believed that planning of the sampling program should be integrated with geologic exploration if the results of soils tests are to be meaningful. Probably the greatest contribution of the competent engineering-geologist is the planning, conducting and interpreting exploration programs to produce a reliable picture of the physical conditions that exist at depth. The engineering-geologist's appraisal of surface geology may lead to his recommendation that a meaningful sampling program will be infeasible because of existing complexities. In such instances his further recommendations may be to consider an alternative site or to plan a drilling program to define some critical zone or structure which will control design. Such recommendations may be brief and based largely on judgment, but they are of considerable importance and consequently should be tendered only by the highly skilled. As documented by past failures, the judgment of persons possessing only a smattering of geologic background may lead to tragic events. The price for competent engineering-geologic assistance is generally insignificant in comparison to the costs of construction and certainly in the light of a possible catastrophe. Consequently, it would seem that any major engineering project warrants procurement of competent engineering-geologic services as well as the best engineering talent available.

The author describes certain shortcoming of geologic investigations which he attributes to the geologist's failure to define the physical characteristics of soils. Herein appears to lie the major difference between engineering-geology and the older geologic disciplines. The formations and members shown on most conventional geologic maps may be physically homogeneous; however, often they are defined by age, fossil types, characteristic minerals or other features of the unit which are quite unrelated to engineering properties. Obviously the conventional geologic map or cross-section can be seriously misleading unless the units shown are further differentiated with respect to their physical characteristics. The modern engineering-geologist attempts to refine his mapping so that the engineering significance is brought out. Unfortunately, geologists completely unfamiliar with civil engineering problems are occasionally retained on engineering projects. Their reports and maps sometimes contain information of purely academic interest which is meaningless to the engineer and consequently detrimental to the engineering-geology profession.

Dr. Terzaghi refers to the remote prospects for obtaining adequate information by geophysical methods. In this respects, the experiences of the California Department of Water Resources and U.S. Bureau of Reclamation who report satisfaction with recent seismic refraction methods for delimiting bedrock profiles and measuring elastic modulus of foundations are of interest. The former of these organizations has developed a technique for delimiting buried serpentine bodies with the newly developed nucleonic magnetometer. This procedure appears to offer promise and may eventually be adopted to helicopter surveys of proposed tunnel alignments in regions where the presence of serpentine is suspected. Geophysics was first put to practical use only about 30 years ago and has undergone considerable development since that time —particularly within the last few years. Dr. Terzaghi's prognostication may be somewhat harsh.

In the realm of rock mechanics, the Bureau of Reclamation cites recent successes of considerable economic significance in the design of tunnel linings. These are described in reports covering the Second Annual Rock Mechanics Symposium convened at the Colorado School of Mines, 1957. Similarly the Corps of Engineers reports successful studies at Garrison Dam which resulted in considerable savings in the cost of steel tunnel support. This study is reported in paper No. 3022 of the ASCE Transactions. In view of these and other recent developments, it would seem that progress is being made in this science and that the future promises further application of rock mechanics in the solution of civil engineering problems.

In the Department of Water Resources it has been found that civil engineering problems involving the interpretation of subsurface conditions are sometimes separable into two parts: (1) the delimitation of strata, zones or lenses of like physical properties, and (2) the determination of the engineering properties of these bodies. The first of these parts is largely geological whereas the second lies mostly in the realm of soils mechanics. Where this distinction is found to exist, the engineering-geologist may undertake the planning and supervision of the exploration program and construction of the subsurface picture; while the foundation engineer selects testing procedures, supervises testing and evaluates soil and rock characteristics which govern design. Frequently, however, subsurface problems fall in a "gray area" involving both geologic and engineering considerations in planning the exploration program to minimize uncertainties and yield meaningful results. In these instances, often an effective approach can be made through coordinating the talents and efforts of engineers and engineering-geologists. This team approach has proven particularly effective when team members develop mutual interest and respect for each others' professions.

The course in engineering-geology outlined by Dr. Terzaghi would provide an excellent background in the subject insofar as this can be accomplished in 40 lectures. Consideration might be given to one or two lectures on geophysics, its principals and limitations as applied to the solution of engineering problems. It is possible that one of the major geophysical companies would provide stimulating material lecture on this subject in the interest of promoting further use of geophysics in civil engineering.

It is to be noted that there are many other fields of civil engineering in which geology is important and where the services of properly trained and experienced engineering-geologists can be used to good advantage, including the development and use of ground water supplies, hydrology and subsurface disposal of wastes.

Dr. Terzaghi has done the civil engineering profession a particular service in repeatedly calling attention to the importance of geology in the proper solution of soil mechanics and foundation problems.

DISCUSSION

By Ian Campbell*

Dr. Karl Terzaghi has kindly provided me with a reprint of his article on "Engineering Geology on the Job and in the Classroom," and has invited me to comment from my background of experience both on the job and in the classrooms of a school in which for many years some geology courses were a required part of the civil engineering curriculum and some civil engineering courses were required for all geology majors.

To read this recount of the changing and developing attitude toward geology of such a distinguished engineer is most interesting and—to a geologist—most gratifying. Dr. Terzaghi clearly outlines both the importance and the limitations of geology in its application to engineering problems. Furthermore he implies that the successful engineer must not only know some geology but know also what he does not know. This—to know the limitations of one's own knowledge, and thus to know when (and where!) to seek assistance from colleagues in other professions— is to me certainly the beginning and very probably the hallmark of wisdom.

With Dr. Terzaghi's principal thesis, therefore, I am in complete agreement. He provides, as an important appendix to his discussion, a "lay-out for a one-semester course in Engineering Geology." In this he calls attention to that chronic problem of all curricula—the insufficiency of time for adequate treatment of the subjects. Dr. Terzaghi's selection of the topics to be presented is as good as can be achieved under the limitations of a one-semester course. *Very* properly—indeed, I should say, *necessarily* he presupposes that the engineering student will have had a basic course in physical geology and so is familiar in a general way with geological principles and with geologic materials. He does not discuss the positioning of these courses in the over-all civil engineering curriculum, yet this too is important in the training program. In many schools, the basic geology course is given at the sophomore or even the freshman level; an engineering geology course (if any is given), at the senior or graduate level. In this arrangement the intervening years all too often permit all except the most dedicated students to forget "all they ever learned about geology" by the time they come to the Engineering Geology course.

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As a consequence, a good deal of time that might better have been devoted to discussion of applications must be put into a "review" of fundamentals. To be sure, if time is available, this is all to the good. Fundamentals deserve review and recall and repetition if they are to be thoroughly mastered.

Are there other approaches to these curriculum problems? This question raises the broad problem of college curricula in general. Can we, in four undergraduate years, properly train and educate an engineer (or a scientist) to the point where he can successfully step into the practice of his profession? My answer is, no—save for a few exceptional students. There are then, three approaches: 1) admit only exceptional students—capable of accomplishing the equivalent of five to six years of college and university work in four. (At best, this is an approach that only a few institutions—and only a few individuals—can successfully take.) 2) Admit engineering students for nothing less than a five or six year program. 3) Urge, require, and even perhaps formalize "post-graduate" training on the job. With respect to this last, there are indications that both government and industry, as employers, are becoming actively concerned with "on the job training," "life-time learning" and curricular and educational upgrading of employees. Intriguing as this possibility is, and much as it has to commend it, nevertheless, I believe the time is far in the future before we can accept this as a wholly successful approach to our problem.

So—in common with many other educators—I would urge the need to recognize "2" above as currently the soundest approach. Where does this put engineering geology? I would say, "as late as possible in the curriculum, preferably in the last graduate year." Undergraduate years should be devoted very largely to those things that are basic: mathematics, physics, chemistry, English, history, economics, etc. Apllied mechanics, soil mechanics, structural analysis, hydrology, taken at the graduate level, can then be made far more meaningful. And since geology and engineering geology involve applications of these—as well as applications of physics, chemistry and mathematics—a course in engineering geology can most successfully be presented to the student who has previously mastered these more basic disciplines.

Should a course in physical geology be a prerequisite for a graduate course in engineering geology? My answer is, no. A course in physical geology would be desirable, certainly; but necessary, no.

The mature student, well grounded in the fundamentals of science and engineering, can grasp the basic principles of geology in an astonishingly small fraction of the time that a freshman or sophomore spends struggling with strange terminology and trying to read a topographic or geologic map. At the graduate level, in a course in engineering geology, I believe that principles can be presented (or reviewed) with little loss of time even for the student without any previous training in geology, and, in fact, with some enhancement of the total course. Particularly for the student who has previously had no geology, but as an essential requirement in any case, the course should emphasize (as Dr. Terzaghi also points out) as much field work, case history demonstrations, and training in "seeing into the third dimension" as possible. Yet when all is said and done, it must be recognized that neither geologist, nor engineer, can really *see* any farther below the outcrop or the soil cover than can any other taxpayer—he can only make a "better educated guess"!

DISCUSSION

By Arthur B. Cleaves*

The paper "Engineering Geology on the Job and in the Classroom" by Dr. Terzaghi should have a sobering effect on Civil Engineers and Geologists alike. No one is better qualified to discuss the interrelationships of geology and the applications of various geological disciplines to civil engineering projects than he is. Further than that he shows soil mechanics in its true relationship to foundation problems and its dependence upon understanding of the geological disciplines of sedimentation, stratigraphy and structure. As he states, serious failures have occurred because of complete dependence on "simplifying assumptions concerning the mechanical properties of the natural ground," where, "basic errors involved in these assumptions depended entirely on geological factors!" This writer endorses this statement and can only emphasize that too many soils engineers are quite ignorant of, or choose to ignore the necessity of the applications of basic geological knowledge and experience.

The Geological Engineer and the Engineering Geologist

In any discussion of geological engineering, and engineering geology it should be made clear that the claim to the title geological engineer is made by three distinct and different groups of geologists. These are first, the geologists whose training and practice is applied to civil engineering projects; second, those geologists whose training and practice is applied to mining operation; and a third group that is in the petroleum industry.

This writer is of the belief that disastrous results could accrue from the reliance upon mining or petroleum geological engineers for advice on many civil engineering projects. This is due primarily to the slanting of the training of such specialists which may ignore basic civil engineering subjects and concepts. There are some universities, however, that give a geological engineering degree in which the basic background is a civil engineering curriculum, with a geological major. Further, within the geological major options may be taken in such disciplines as geophysics and geochemistry. The programs are sufficiently flexible so that the student has a fundamentally sound back-

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ground which enables him to enter diverse fields of applied and even theoretical engineering.

The single course given to civil engineers in the applications of geology to civil engineering, based on a single course in elementary physical geology, can do no more than alert the civil engineer to an appreciation of the significance of the geological disciplines. The value of such a course of forty lectures, as outlined by Dr. Terzaghi, is proportional to the experience of the teacher. Because the number of geologists qualified to give such an applied course is small Dr. Terzaghi's suggestion of visiting, qualified lecturers is excellent.

The young geological engineer today is one who holds a geological engineering degree from a school, accredited probably by ECPD examiners. What of the Engineering Geologist? Various definitions for this title have been proposed, but one may say broadly that he is a person who may have a college degree in some engineering discipline, and adequate preparation in geology, or he may be a Liberal Arts degree holder, with a major in geology. In the latter case he has additional training in various engineering areas and, or by study and application, has mastered a reasonable knowledge of engineering disciplines.

In the United States today there are at least five universities where highly qualified geologists are training students, undergraduate and graduate, in the applications of geology to civil engineering. As Dr. Terzaghi point out, in spite of this training, some of these students may never contribute satisfactory services because of lack of judgement, imagination, or the ability to equate the significant aspects of the geological and engineering problems involved. Further than that the appreciation by the geologist of his position as an advisor to the engineer is never to be forgotten.

Geological Disciplines in Earthwork Engineering

One would think that the assistance of the geologist in embankment construction would be very minor, especially after the contributions made by the soils engineer. However, as examples, the mineralogy and geological origin of the embankment materials may be of fundamental significance in the successful completion of an embankment.

The writer has witnessed attempts to achieve required compaction in a fill with a sheepsfoot roller when large quantities of tiny mica flakes were present. Compaction was impossible with the sheepsfoot roller but when a flat-wheeled roller was used, and the lifts placed in four-inch increments instead of six, successful compaction was achieved.

The impact of clay-mineralogy on embankment construction has also become an important factor. The clay minerals illite, kaolinite, chlorite and montmorillonite in embankments may give extremely diverse test results in the fill and the laboratory from those in place prior to excavation. More and more research in this clay-mineral, geological discipline, promises to be of enormous practical value.

An instance of the importance of clay-mineralogy in earthwork engineering was demonstrated in the excavation and placement of the basal (lodgement) till on projects of the St. Lawrence Seaway. The tenacity and "toughness" of this type of till was unknown to the Seaway contractors, and the clay-mineral content of this till was chiefly responsible for the serious excavation and embankment costs encountered. The physical properties of this material in place, and after excavation and placement in embankments are dynamically different.

Dr. Terzaghi has emphasized the significance of non-homogeniety, soil-fabric differences, and similar phenomena in unlithified and often non-consolidated natural earth deposits. Because of particle orientation and sedimentation features and their relationships to permeability and shear phenomena, recognition of the nature and origin of such deposits is of inestimable value in interpreting and planning the soil testing program.

These are but a few of the recognized areas in which sound geological work can enormously simplify the answers the engineer must have.

Role In Rock Engineering

The writer would be remiss not to mention vital roles in which geological disciplines are now, and promise in the future, to contribute to underground excavation in rock. Dr. Terzaghi has shown succinctly the values of, and the ways in which geological knowledge can be applied to rock engineering, especially in relationship to subsurface excavation (Terzaghi, 1946). His work in this field is unexcelled. He has also indicated the limited applications of both seismic and electrical resistivity techniques to the revealing of various types of subsurface earth structures such as fractures, crevices, and solution channel and cavity phenomena. Nevertheless, whole new methods of approach and techniques are appearing that promise much in ascertaining various types of rock structures and problems to be met with in underground excavations. The relatively new field is appropriately called rock mechanics. Because research in this field has been only sporadic and uncoordinated not a great deal has been accomplished, but the direction research and study must take is clearly indicated. The first great area to be exhaustively explored is that of the basic physical properties of rock and the changes that take place in these properties under different pressures, temperatures, and subsurface environments. The second great area of investigation embraces the effect upon excavation, in rock at depth, of unrelieved tectonic (mountain building), and rock rebound stresses from crustal unloading. The latter, in some areas may come from the melting of the continental ice-caps, but in others it may come from differential unloading near the surface by erosion, or even excavation. It is thought by some that a shallow, residual or transported soil cover may "insulate" the rock and create a dampening effect, and that observable rebound occurs when this cover is removed.

In the case of tectonic stresses the use of especial strain-gage techniques in spherical or cylindrical pressure cells, placed in bore holes, may, at least give indication of such stress. The application of photo-elastic techniques to rock thin-sections taken from rock core may offer a method of approach. With a better knowledge of the physical properties of rock petrographic techniques may become more effective.

These and other methods, once proved, can be of tremendous benefit to the design engineer in that stress phenomena may be anticipated in advance of actual tunnel and chamber excavation. Some of the fine work in the field of stresses in rock about cavities has been done by Dr. Terzaghi (Terzaghi and Richart, 1952), and applications of this work were made with success in the construction of the "T.1 Underground Power Station in the Snowy Mountains of Australia." (Moye, 1959)

Conclusion

These remarks only amplify and add emphasis to the general and modest coverage of engineering geology described by Dr. Terzaghi.

His pioneering efforts in this field have lighted beacons which show the paths of research and practice that may most usefully be followed. Even more, his work emphasizes the interrelationships of geology and soil mechanics in their service to civil engineering.

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DISCUSSION

By Don U. Deere*

The writer is in full accord with most of the points stressed by Professor Terzaghi in his stimulating paper—in particular, (1) his division of engineering geology into areas concerned with earthwork engineering and with rock engineering, (2) the suggested requirement of a basic course in physical geology as a prerequisite for the engineering geology course, and (3) his statement of one of the important functions of the engineering geology course being that ". . . of focusing the attention of the engineer on the nature and importance of the uncertainties involved in the design of foundations and tunnel supports on the basis of test results and computation." Professor Terzaghi in his visiting lectures at the University of Illinois emphasized especially this third point, usually rather dramatically.

His first lecture, of a series of two or three lectures which he gave each semester, was almost entirely geological in nature. He would treat a particular genetic type of deposit, residual soil and weathered rock, for instance. After discussing the processes involved in the evolution of the deposit he would describe in detail the pattern of stratification and the lateral and vertical variations. The second and third lectures of each series dealt with actual case histories in subsurface engineering involving the type of geological deposit previously discussed. The effects of the uniformity or inherent lack of uniformity of the deposit, and the variations in the significant engineering properties of the different geological materials, on the planning and carrying out of the exploration program, on the design and the construction of the project, and on the reliability of the performance forecast were accentuated.

The writer can vouch for the success of Professor Terzaghi's method of treatment. Apart from the interest and enthusiasm generated in the audience—always by-products of Professor Terzaghi's lectures —one gained factual geological information and, more important, a philosophy of attack of the engineering problem notwithstanding the geological uncertainties involved. In the present paper the writer is happy to note that the author continues to stress the influence of geological factors on the uncertainties involved in the simplifying assumptions used in subsurface engineering.

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At the beginning of his paper the author defines engineering geology as ". . . that small fraction of the sum total of geological knowledge which the civil engineer engaged in design and construction of subsurface structures such as foundations and tunnels must possess in order to practice his profession competently." Even for the purposes of the paper this definition seems too restrictive, particularly in its exclusion of geologists. The author broadens the scope, however, in his later discussion of engineering geology as a profession (pp. 105-106) in which he apparently recognizes engineering geology as a branch of geology and an engineering geologist as a professionally trained geologist.

It is pointed out that an engineering geologist should have mastery of the techniques of geological mapping, a sound knowledge of those rather elementary geological facts which are needed for practicing those techniques, a course in engineering geology for civil engineers in order to become acquainted with those geological facts which are of significance in engineering, and an elementary knowledge of foundation engineering and soil mechanics. The writer is not in agreement with the author's apparent emphasis on the need of a knowledge of only ". . . those rather elementary geological facts. . . ." A competent engineering geologist has to be first of all a competent geologist, thoroughly familiar with all branches of geology. Field mapping cannot be divorced from interpretation of the geological data, and only by interpretation of all the observations by a keen, geologically-trained mind can the geology of a site be worked out. In his experience as a consulting engineering geologist—and in working with other engineering geologists on several projects—the writer has found that almost every aspect of geology has entered into one or other of the projects in some form. These aspects have included principles and information from the areas of structural geology, stratigraphy, historical geology, geomorphology, and sedimentary petrography, among others.

Only when the geological history at a site is reasonably well worked out, including a knowledge of the occurrence of the various geological materials and of the rock defects in terms of joints, faults, bedding planes, and zones of rock alteration, can the influence of these geological features on the contemplated project be assessed. It is the ability to make such assessment that distinguishes the professional engineering geologist from a professional geologist untrained in engineering geology. The latter would, of course, be able to work out the geology of an area but he would be unable to tell which features were of engineering significance. The engineering geologist, on the other hand, either by his academic training or by his professional experience of long association with engineering projects, can realize and point out in his report to the engineer in charge those geological features which will have an influence on the project—whether it be during the planning, exploration, design and construction, or performance stage. In most cases, however, he can give only a qualitative estimate of the influence of the significant geological features. He is also aware of the degree to which the geological history of a site has to be developed and understood in order to make the significant geological observations.

From the foregoing discussion, and from points brought out in Professor Terzaghi's paper, it is apparent that the engineering geology of a project site can be handled in one of three ways. On the one hand, the work may be carried out by a civil engineer who has had a basic course in physical geology and a course in engineering geology similar to the one proposed by the author. The engineer would be aware of those general geological features which were of engineering significance to his project and depending upon his ability and the adequacy of his geological training, and upon the complexity of the site geology, might or might not arrive at a correct solution. On the majority of cases involving small projects and simple geology this approach may be justified.

The second method of attack is simply a modification of the first in which, because of the complexity of the project or of the geology, the civil engineer seeks the aid of a geologist (but not an engineering geologist). The success of this attack is dependent upon the civil engineer's ability of asking the significant geological questions to the geologist and the correct interpretation of the answers. This method cannot be expected to be highly successful in the writer's opinion, partially because of the problem of communication between the two but, more so, because of the large responsibility placed on the civil engineer in an area that is on the borderline of his realm of knowledge.

In the third approach to the problem the civil engineer works with a competent engineering geologist, who raises the pertinent questions himself and also answers them in terms meaningful to the engineer. This method does not depend as much as the others on the civil engineer's knowledge of engineering geology. The greater is that knowledge, however, the more will he gain from the engineering geologist, the better will be his interpretations, and the more will the project benefit.

In the present practice of engineering geology this third method is certainly the preferred one. The writer feels, however, that the ideal method has not as yet developed. It is regrettable that the function of the geologist is limited to that of an advisory capacity, which is almost always the case. Professor Terzaghi states regarding this question, "However, under no circumstances should he try, or be asked, to tell the engineer how to proceed." The writer has no choice but to agree with this statement in view of the present academic division of displines.

It is perhaps opportune to point out that engineering firms now more than ever before are concerned with rock engineering in deep cuts, underground penstocks, pressure tunnels, power plants, missile silos, and other underground military installations. Dynamic as well as static behavior is important. The writer suggests that a new discipline may be need—one that includes a knowledge of the origin, occurrence, and variation of geological materials; a knowledge of the properties of these materials; and a knowledge of the behavior of these materials under the new stress environment imposed by the project. This discipline would go beyond what is normally included in the individual areas of geological engineering, mining engineering, civil engineering, or geology but would include courses in all these fields. In addition to several courses in basic geology, courses in soil mechanics, foundation engineering, engineering geology, and ground water geology would be needed. It is expected that competence in geology equivalent to the M.S. degree level would be a necessity. The extensive training required for the proposed discipline could only be carried out in graduate college, probably at the Ph.D. degree level. The prerequisite for such a course of study would logically be a B.S. degree in geological, mining, or civil engineering.

The above course of study (subsurface engineering or perhaps geotechnical engineeding?) followed by appropriate experience should allow the two positions filled by the civil engineer and the geologist in the hypothetical situations previously described to be handled by the one so-trained individual. Gone would be the positions of split responsibility with the problem of communication and jealousy between disciplines. Instead would be the individual who would have the responsibility of working out the geology of the site, of determining the engineering significance of the geological features, and of making specific engineering design and construction recommendations. The writer is of the opinion that such trained individuals are needed and, consequently, would go several steps beyond Professor Terzaghi's recommended training of the civil engineer.

DISCUSSION

By Victor Dolmage*

Dr. Terzaghi has suggested that I contribute some personal views on a question arising out of his recent paper "Engineering Geology on the Job and in the Classroom." The question is "What geological training ought the civil engineer receive that he might better appreciate the practical implications of geological conditions?" My opinions are those of a practising geologist who knows very little about teaching and almost nothing about engineering curricula.

Geological Training

The term "geological training " as understood by a geologist can best be explained by the following definition: A geologist is one who knows most of what is known about the composition and structure of the earth's crust, and also most of what is known about the natural processes such as erosion, sedimentation, igneous intrusion, volcanism, glacialism, etc., by which the various units of the crust were formed and arrived at the places and attitudes in which we now find them. Professor Lindgren used to tell us that until one has gone out into an unmapped area and come back with a pretty complete account of what has happened there from the time the oldest rocks were formed down to the present time, he hardly merits the title of geologist. I should like to emphasize that little phrase "what has happened there." It may sound like a big order, but to the geologist it is routine and from my own experience I have learned that when I know "what has happened there" I can give pretty good answers to most of the questions the engineer might ask. I might suggest here that a good approach for the engineer is to present the geologist a list of questions he would like answered. This was the method recommended by Professor Mead.

The Civil Engineer

I shall not attempt a definition of the civil engineer except to point out that those specializing in foundation and earth works engineering will have greater need than the others of an acquaintance with geology. From the time a foundation site is selected until the structure is completed to the ground level, he will be dealing with

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"geological phenomena exactly as nature laid them down in all her innumerable varieties and unpredictable moods and which, because of their great size and complexity, must of necessity be the concern of a number of men." Because of one statement in Dr. Terzaghi's article to the effect that in the realm of earth work engineering the instances are rare in which an engineering problem requires the services of an engineering geologist, I would like to emphasize that of all geological phenomena there is none in which nature has displayed to a greater degree her freakish unpredictability than in unconsolidated soils, particularly glacial and fluvioglacial deposits.

That neat little parcel of mathematical computations, figures and unqualified and numerically precise answers known as "slope stability analysis" made in areas which have been glaciated and whose history is unknown to the computor can be the most dangerously comforting and misleading of all engineering predictions. One of these which came to my attention recently proved, no doubt to the satisfaction of the computor, that a certain slope had a specified numerical factor of safety in a region in which many slides have occurred and which has all the built-in mechanisms necessary and sufficient for future slides.

Geological Training for the Engineer

This problem is just another example of the common inter-disciplinary problem which plagues curriculum committees in many University departments. A common answer to the problem is to require the students of discipline A to take the introductory course of discipline B; in this case Introductory Geology usually catalogued as Geology 1. This has been done in some universities but it is my opinion, and that of all the engineers I have consulted, that this is the wrong answer. It may be an easy one for the curriculum committee men, but is a great injustice to the engineering students and gross waste of valuable time.

I believe, for a number of reasons, that in the time available it is nearly impossible to teach a civil engineer in the classroom any useful amount of the science of geology. First, in his crowded under-graduate years he has only a bare minimum of time for studies outside his own discipline, and any spare time he might find could, very probably, be better spent in more advanced work in his own field or in extending his knowledge of the basic sciences, physics and mathematics, which are so vital to his own discipline and seldom, if ever, learned outside the classroom. Second, geology is a natural science embracing a wide range of subjects, such as mineralogy, petrography, sedimentation, morphology, etc., and these should be taught in a definite sequence to be properly understood. Many of these subjects are of little or no value to the engineer and are encumbered with elaborate and awkward vocabularies. Third, it is an inexact science and requires a habit or mode of thinking quite foreign to engineers. Fourth, geology is essentially a field subject and in that environment it is lively, stimulating, and very appealing to the inquisitive mind, whereas in the classroom it is often dull and dry and, to an extent, incomprehensible.

I question whether it is advisable to give the civil engineer any formal classroom geological training. Dr. Terzaghi has given the best reason and perhaps the only reason for geological training: namely, that the civil engineer might better appreciate the implications of geological conditions and be fully appraised of wide and unpredictable variations common to all geological phenomena. A course of lectures might not be the only or the best way of impressing this knowledge on the mind of the engineer.

There are other objections. A little knowledge, and particularly if it is simplified or abridged or out of context, is a dangerous thing. It may be just sufficient to get the engineer into trouble. If Dr. Terzaghi were about to employ a geologist and were asked how much engineering he would require the geologist to know I think his answer might be "the less the better." I am quite sure that if I as a geologist seeking the services of an engineer were asked how much geology I would require him to have, my answer would be, "Preferably none, but there must be no gaps or weaknesses in his training and experience as an engineer."

I offer the following suggestions with some temerity:

(1) Do not attempt in the classroom to teach the engineer any geology as such.
(2) Advise him that in many engineering problems he will do well to consult a geologist.
(3) Give him a number of examples of engineering problems in the solutions of which geology played a conspicuous part.
(4) Give him some examples of failures that could have been averted by the use of a geologist's knowledge and experiences. In explaining the

above examples some geological language and ideas will have to be introduced but I believe this could be effectively done.

(5) I would strongly recommend that the students be taken on numerous field trips and shown many types of foundations in various stages of excavation and in a variety of geological settings. The attention of the students should be focused on the extreme variations to be found in any geological formation and how these might affect foundations.

(6) Let the engineer learn his geology by working in the field with geologists employed on engineering projects.

We all know that our proficiency in our respective professions depends more on what we learn from our practice after graduation than what we learned in University and I see no reason why this method should not provide most, if not all, the geological education the engineer may require. In the field the engineer soon becomes interested in geological phenomena and quickly begins to observe features to which he was previously completely oblivious. Almost without effort he absorbs a knowledge of geology and its functions sufficient to give him a good appreciation of the practical implications of geological conditions, and it will not be done at the expense of training in his own field.

(7) I would, however, suggest one exception, namely: soils mechanics engineers now work with a soils classification based exclusively on grain size, ignoring the wide differences in the chemical and physical properties of the many mineral species composing the soils. It would appear to me that they would derive considerable benefit from a course in rock and soil mineralogy which would emphasize the physical and chemical behavior of the minerals, particularly towards water. *Some* of the chapters from Grim's "Clay Mineralogy" could be included in such a course.

Engineering Geology

I sometimes question the validity of the term "Engineering Geology" as currently used. To me, if it means anything, it means geology applied to engineering problems just as economic geology means geology applied to the finding and extracting of minerals. In both cases it is one and the same kind of geology, not two kinds; the same minerals, rocks, soils acted on and produced by the same agents and processes. As it is not elementary or simplified or abridged but advanced mature geology learned largely from field experience.

Like the engineer, the geologist has not the time in his undergraduate years for any engineering other than his courses in surveying methods. The small amount of elementary engineering which he might squeeze into his program would be of very little value as compared to the extra geological or basic science training he could acquire in the same time. If the geologist is properly trained he will have a good grounding in physics and mathematics, particularly in these days of geophysics and, with this as a basis, he should be able to acquire the desirable engineering viewpoint by working with the engineer on his problems. In engineering problems let the geology be supplied by the broadly trained and experienced geologist. The engineer will supply the engineering skills; only a genius could master both disciplines. Dr. Terzaghi is such a genius.

DISCUSSION

By C. P. Dunn*

The writer knows that it is ordinarily a bit out of place to include personal remarks in a technical discussion. However, the following is something that he very earnestly desires to say, and in this case it "belongs":

On reading "Engineering Geology on the Job and in the Classroom," the impression which comes to the reader is "here is a real Engineer—one of the few truly great Engineers whose customary habits is original thinking in a straight line toward a correct answer." He has originated and organized the science, a part of which is at the moment being discussed as "Engineering Geology," and he has carried it forward to the point where he has made a certain amount of precision available, and he is earnestly disturbed because many of those who will follow him have a tendency toward too much dependence on the appearance of precision, and are failing to think straight in a way that fully encompasses the problems.

The fields of "soil mechanics," "rock mechanics," and "engineering geology" are extremely important. The structures man builds are either in the earth, on the earth, or composed of materials of which the earth is built. Engineers find that the beautiful precision of structural design is relatively easy, and is interesting and satisfying work, and all too frequently they avoid the discomfort of thinking about the less precise problems which are really inseparable from the design of structures.

This man Terzaghi has contributed in very large measure to the welfare of humans, worldwide, by his stubborn insistence on paying attention to the difficult problems involved in consideration of the characteristics of the materials of the earth upon which structures rest. He has been the reason for many structures being successful instead of failures. No one can say just how much that means in dollars and human lives, but the amount is very great. He now appeals to those who will carry his work forward to reappraise themselves and adopt habits of clear thinking and common sense. Let us not disappoint him.

The writer will not presume to attempt to add anything to the

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paper which is under discussion, but it may be constructive to emphasize some of the points.

To quote:—"an evaluation of the inevitable uncertainties involved in the interpretation of the results of the subsoil exploration." These words deserve to be read a number of times, with emphasis on the word evaluation and on inevitable uncertainties.

The "layout for a one-semester course in engineering geology" obviously has a lot of thought behind it. It points up the fact that in considerable measure "engineering" and "geology" are inseparable. They belong together in the accomplishment of a complete design. It is not reasonable to expect one person to be completely skilled in both subjects. Therefore, the most successful teacher will be the one who can teach the technique of blending the skills of several people.

The writer agrees with the thought that "extensive practical experience can hardly be expected (in a teacher). Therefore, some of the lectures should be given by visiting lecturers with suitable qualifications." On this subject, let the use of visitors be as extensive as may be practical.

DISCUSSION

By Charles R. Kolb*

Dr. Terzaghi's lucid and pertinent observations on those phases of geology which the practicing civil engineer should know are refreshing and the course of instruction he recommends in the Appendix is certainly one that should significantly benefit the young engineer. As important as the technical content, are the attitudes such a course should instill in the student, e.g., (1) an appreciation of the uncertainties involved in the assumptions on which his computations are based and the dangers inherent in dogmatically applying these computations to subsurface engineering problems, and (2) a respect for the value of an imaginative approach in interpreting the complexities of natural stratification, whether in rock or in soil.

I am inclined to disagree with Dr. Terzaghi's evaluation of the role of the geologist or the engineering geologist in the separate fields of rock and earthwork engineering. He advises geologic assistance in the former field, but on p 106 he states "In the realm of earthwork engineering the instances are rare in which an engineering problem requires the services of an engineering geologist, provided the civil engineer is adequately trained." The thinking that the geologist should confine his responsibility to interpretation of rock conditions and leave the interpretation of the soil sequence to the engineer is not uncommon in many civil engineering circles. Many published geologic profiles included in engineering reports leave uninterpreted that part of the profile above the sound-rock line. This, I believe, is a wasteful misuse of talents of the geologist. Sedimentary rock, after all, is only lithified soil and the same principles of sedimentation which can be applied in correlating rock strata apply with equal validity of the correlation of soil strata. Indeed, they usually apply with greater validity since the study of environments of deposition are normally conducted in unindurated materials—soil—and principles learned in such studies are often used in identifying and correlating rock strata.

A more specific disagreement with the concept that a geologist is not needed in the soil phase interpretation is that it tends to nullify my training and that of other geologists like myself who for years have worked with engineers on problems encountered in the deep soils of

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alluvial, deltaic, aeolian, and coastal plain areas. This applies equally to engineering geologists who have worked primarily in areas deeply blanketed with glacial or residual soils. Most of us have spent years in studying the processes of sedimentation, weathering, and soil formation in such areas and furnishing this knowledge in proper form to the engineer for solution of problems of earthwork engineering.

For years earthwork engineering problems associated with the U. S. Army Corps of Engineers' projects within the Mississippi Alluvial Valley have had the benefit of geologic interpretation. Much basic work has been done in determining the environments of deposition that exist within the alluvial and the deltaic plain, the soils associated with each environment, and their subsurface distribution and engineering characteristics. Methods have been developed for recognizing these environments through study of air photos and the use of a limited number of borings. An example of the use of geology in determining the cause of a particularly persistent earthwork engineering problem and the subsequent use of geologic interpretation to prevent reoccurrence of this problem is in the prevention of seepage beneath the massive Mississippi River levees. More than 2000 miles of these levees are in existence, many of them are 40 ft high, and they, thus, represent a costly and important engineering effort. When water rises against the river side of the levee during rising river stages, it causes an artesian head in the substratum sand which is always present beneath a relatively thin and impermeable topstratum. Seepage emerges at and beyond the landward toe of the levee. If the hydrostatic pressure in the pervious substratum landward of a levee becomes greater than the submerged weight of the fine-grained topstratum, the uplift pressure will cause heaving of this relatively impervious blanket and it may rupture at weak spots with resulting concentration of seepage flow, piping, and the formation of sand boils or mounds of sand where the seepage water emerges at the surface. A study[1] of the occurrence of sand boils along the river indicated that they are largely controlled by the distribution of the alluvial environments of deposition. Cognizance of these geologic environments in design can prevent costly and often disastrous levee failures.

Fig. 1 illustrates two examples (taken from WES TM 3-424) of the control that shallow, clay-filled swales and deeper clay-filled

[1] U. S. Army Engineer Waterways Experiment Station, "Investigation of Underseepage and Its Control, Lower Mississippi River Levees," Technical Memorandum No. 3-424, in two volumes, Vicksburg, Miss., October 1956.

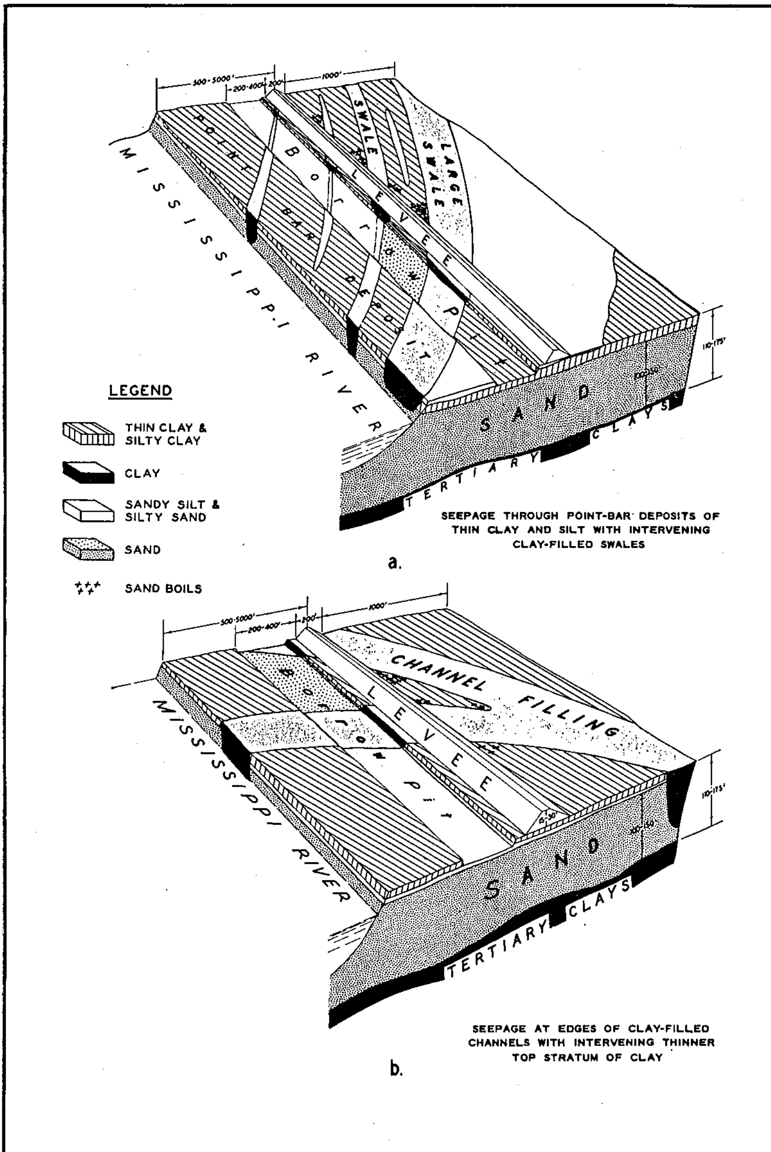

FIG. 1. TWO EXAMPLES OF THE CONTROL OF GEOLOGIC ENVIRONMENTS ON UNDERSEEPAGE BENEATH MISSISSIPPI RIVER LEVEES. MODIFIED FROM WES TM 3-424.

channel fillings exercise on sand-boil concentration landward of the levee. Seepage is normally most severe in those instances where the long dimension of these clay-filled environments parallel the levee or intersect the levee toe at a small angle. Note that in fig. 1a seepage is concentrated in the sandy ridges within the acute angle where the edges of the swales intersect the levee toe. Where the clay bodies are deeper and wider, as in the case of the channel fill deposits, the severity of underseepage increases. The severe condition shown in fig. 1b is due to channeling of seepage between two arms of an abandoned channel fill. Corrective measures used in levee construction and maintenance include alignment of levee setbacks so as to take advantage of the distribution of the geologic environments, and where this is not possible, the use of impervious landside berms or pressure relief wells to prevent seepage in potential sand-boil areas. Of importance is the selective location of riverside borrow pits to prevent exposing permeable substratum sands close to the levee.

It has been my experience that the civil or the soil mechanics engineer is usually so burdened with the responsibilities of his job and with keeping abreast of the innovations in his field that he has little time to master the complexities of sedimentary processes or the weathering phenomena that produce the soil mantle. Where the experience of the engineer in a particular area is sufficiently comprehensive or where the project under study is too small to justify the expenditure, the services and advice of a geologist may not be warranted. Unfortunately, however, it is the novice engineer or the so-called "practical" civil engineer who is most inclined, even on major projects, to attempt his own geologic interpretations.

That the results can be embarrassing and costly has been amply illustrated by examples Dr. Terzaghi cites in many of his papers. He points out numerous instances in which faulty design can result from improper interpretation of borings or the over-simplification of soil conditions and the blind application of the principles of soil mechanics to these generalizations. In his paper "Past and Future of Applied Soils Mechanics,"[2] Dr. Terzaghi lists a number of cases, under the heading of "Misuse of Soil Mechanics," in which a proper geologic interpretation of subsurface soil conditions would have called attention to the possible existence or irregularities in the soil profile and prevented costly miscalculations in earthwork engineering.

[2] Terzaghi, Karl, "Past and Future of Applied Soil Mechanics," JOURNAL, Boston Society of Civil Engineers, Vol. 48, pp. 110-139, April 1961.

There are few people who have reached, or who can hope to reach, the enviable position held by Dr. Terzaghi in the fields of both geology and civil engineering. Most of us must content ourselves with trying to keep up with our particular and more restricted field. I concur, therefore, with the passage he quotes from Berkey, that "The position of a geologist is analogous to that of an advisor to the court. He may formulate the opinion but never render the final decision. . . . It is his duty to discover, warn, explain, without assuming the particular responsibility of the engineer who has to design the structure and determine how to meet all the conditions present." I submit, however, that the geologist should "discover, warn, and explain" the intricacies of soils as well as the complexities of rock. Let the engineer assume the responsibility of designing the structure to meet the conditions, but let him utilize the geologist's help in planning subsurface exploration and his talents in determining what the conditions are. The two disciplines can work together nicely, and as Dr. Terzaghi indicates in so many of his writings, a proper assessment of the geologic situation can fundamentally alter the engineer's design or radically affect the cost or safety of his structure. Where the size of the project and the complexity of stratification warrant it, such an assessment of the geologic condition should not be expected of the civil engineer without formal and extensive training in geology.

DISCUSSION

By Ralph B. Peck*

Every opinion regarding the place of geology in subsurface engineering and regarding the manner in which geology should be taught to prospective subsurface engineers is necessarily colored by the background of the individual who holds the opinion. The writer was trained in both his undergraduate and graduate instruction as a structural engineer. As an undergraduate his only exposure to geology was a single course in his sophomore year labeled engineering geology and consisting of a study of Ries and Watson, lectures covering the same ground but including a description of the physiographic provinces of the United States, and laboratory exercises in mineralogy and rock identification. As a graduate student, quite by chance, he enrolled in an elementary course in historical geology, fortunately taught more with an eye to stratigraphy than paleontology. The course fired his interest in geology and introduced him to geologic literature. A single three-day field trip in upper New York State opened his eyes to the fascination of Pleistocene geology, but it could hardly provide more than an eye-opener. Nevertheless, this utterly inadequate training in geology probably exceeded that of most civil engineering students by 100%.

After a brief interlude as a structural detailer, the writer had the opportunity to study soil mechanics. Yet, although Harvard possessed a Department of Geology of highest rank, the demands of the formal curriculum in soil mechanics fully occupied the writer's time at Harvard so that it can fairly be said that his training in soil mechanics did not add to his knowledge of geology. Dr Terzaghi's course in Engineering Geology had not yet been initiated.

It was only after he began his professional life in the practice of subsurface engineering that the writer's further introduction to geology began. For three years the writer viewed the glacial deposits encountered in tunneling beneath Chicago in half a dozen or more tunnel headings almost daily and was faced with the consequences of the presence of some of the materials. He found it mandatory to learn all that could be discovered from the literature concerning the regional geology and, to a lesser extent concerning Pleistocene geology

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in general. The information proved enlightening and useful but it did not provide all the enlightenment hoped for. Fortunately, at the same time, the writer began his personal association on several projects with practicing geologists and had the opportunity to work with geologists and to observe their method of operation. The opportunity to be continually associated with geologists, as they carried out their professional assignments and conducted their research, has provided the writer's real education in geology, such as it may be. It has led to the conclusion that there are really two aspects of geology: a *system* of knowledge; and a *method*.

The results of the labors of several generations of geologists have crystallized in a history of our planet with respect to its physical development and to the development of the life that it supports. It is hard to conceive that a person could consider himself educated without an acquaintance with this system of knowledge. The picture that the geologist has created of the world in which we live to a considerable extent understood, by any intelligent layman. He does not need to understand the techniques used by the geologist in arriving at the conclusions. He does not even need to dwell upon the evidence for the conclusions. Most of the geology that finds its way into textbooks, and even into many professional geological papers, is part of the system. It represents the results of the geologist's work, not the work itself. It constitutes a body of knowledge consisting of concepts and generalizations, certainly of interest to the engineer and often very useful to him, but it does not by any means represent the whole of geology.

The civil engineer working beneath the ground surface needs a framework based on this knowledge. He needs to know the principles of physical geology; he needs to know the geologic time scale and something about the sequence of formations in the earth's crust. This information helps him to digest geological literature that may be pertinent to an area or a site in which he is working. The processes of sedimentation, erosion and weathering must be understood if reasonable interpretations of exploratory programs are to be made. Therefore, in short, the civil engineering student needs the classical course in physical geology and some smattering of historical geology.

But the method of geology is also important to the civil engineer. The inspection of a site by a civil engineer is all too often little more than a scenic excursion unless the engineer knows what to observe and how to observe it. At the majority of sites there are landforms or exposures to be recognized and scrutinized. Their relevance to the job at hand may not be immediately obvious. Only by the use of geological methods can the significant relations be brought out.

The writer, while recognizing the immediate and direct importance of a knowledge of the geological method, has often speculated about a most interesting and useful by-product of this knowledge. He has concluded that the geological method is a most desirable and possibly a necessary prerequisite to the successful pursuit of the observational procedure in subsurface engineering. He suspects that Dr. Terzaghi's development of this method and his artistry in the practice of it may be a consequence of his own training in geology which went considerably beyond the elementary courses just mentioned. Indeed, it may have been Dr. Terzaghi's association with geologists rather than his study of geology, even while still a student, that may have turned his mind toward the observational method.

In the field, the geologist's procedure consists first of all to collect facts and evidence. He makes observations. He does not know at the time that he makes the observations whether all of them will be pertinent or useful, but he examines his exposures in great detail. He then organizes his information. Often the organization consists of constructing a geologic map on which he simply records all the known information. Only then is he ready to study the map and the other organized information in order to form hypotheses regarding the development of the region. After he has formed hypotheses, he tests them against the evidence he has collected. He also sees other tests that should be applied and returns to the field to obtain further evidence, which he again organizes and compares with his hypothesis. In this fashion he arrives at a conclusion, which he rarely regards as final because he knows that subsequent information will be obtained that will require alteration of his concept.

The civil engineer, and particularly the structural engineer, is not trained in this fashion. He is not accustomed to collecting or being presented with a mass of detail which must be organized before conclusions can be drawn or before decisions regarding design and construction can be reached. Yet, the application of the observational procedure almost always involves precisely this sequence of events. Consider for example the work represented by Dr. Terzaghi's analysis of the stability of the Upper Ore Yard in Cleveland.[1] The preparation of the report on this project followed the gathering of many kinds of data: innumerable observations of horizontal movement, tilt, and settlement of the various constituents of the ore yard; profiles of the piles of ore in the year at various dates; determination of piezometric levels at various times and places; and a knowledge of the design and construction of the facilities themselves. The observations of movement alone are recorded on more than 30 sheets of closely spaced notations, each sheet over 6 sq ft in area. All this information had to be organized, condensed, plotted, and rearranged in several ways until it became useful. Before any correlations could be attempted between load and movement, the observations of contours of the ore piles had to be converted to average loads on various areas considered significant with respect to the movement. The work involved in this condensation could hardly be regarded as anything more than routine. It involved no great pleasure except the knowledge that it had to be accomplished before significant relationships would appear, and the knowledge that unless one did such work himself he would not be likely to get the real feel of the job. After all the data were organized, many of the conclusions undoubtedly became almost self-evident. A few general concepts concerning the relations between stress, strain, and time, derived from soil mechanics, probably also assisted in the formulation of the hypotheses and conclusions.

The routine work associated with the ore yard observations is not dissimilar to that carried out by the geologist in collecting his information concerning dips and strikes, entering it onto maps, and studying possible correlations. It might be regarded as standard procedure for a working geologist but it is by no means standard procedure for most civil engineers. Civil engineers do not like to do routine work of this sort, nor are they likely to see its significance. They are likely to feel that it belongs to the range of the subprofessional or technician. No geologist would feel this way.

Thus, it appears that successful practice of the observational procedure, which has been so fruitful in subsurface engineering, involves a method which is essentially that of the geologist even when it deals only remotely with geological problems. Hence, courses in geology could serve a useful supplementary purpose by introducing

[1] Final Report on the Performance of the Ore Yard of the RFC Plancor 257 during the service period 1943 to 1948. Included in "From Theory to Practice in Soil Mechanics," Wiley (1960), pp. 299-337.

the engineer to a different approach for the solution of problems than that to which he has otherwise been exposed.

As a consequence, the writer feels that courses in engineering geology for civil engineers should at least include a few well-planned field trips in which the methodology of geology is emphasized. Although one can hardly add to the present crowded curricula, a summer field camp in geology, devoted to developing the geology of an area, would be a tremendous asset to the future subsurface engineer.

While it is too much to be hoped that engineers can receive thorough training in the geologic method, much could be accomplished if courses in geology were taught with emphasis on the method as well as on the organized system of knowledge. Once the engineer becomes aware of the manner in which the geologist works, and sees through application in engineering courses the manner in which the method can be utilized by the civil engineer, he may discover the vital contribution that geology has made to civil engineering in the form of the observational method.

It would, of course, be an unwarranted conclusion that geological field methods should be taught to civil engineers primarily because the subject would serve as a means of teaching the observational method. This is no more justifiable than would be the teaching of French solely because knowledge of a foreign language is helpful to the understanding of English grammar. Nevertheless, the benefits of the geological method constitute an extremely useful by-product of geological training for civil engineers.

The writer does not believe that the boundaries of engineering geology should be defined too rigidly. The distinctions among applied soil mechanics, engineering geology, and applied rock mechanics are more arbitrary than natural. In the graduate program at the University of Illinois, all doctoral candidates specializing in soil mechanics are expected to take at least two courses in geology at the graduate level (out of a normal total of sixteen courses), and many present a full minor in geology (four or more courses). Conversely, all doctoral candidates in geology who are interested in engineering applications are expected to take the two basic courses in soil mechanics, and many present full minors in the subsurface aspects of civil engineering. These men, on completion of their graduate study, have found a wide range of professional activity, in geological surveys as engineering geologists, in mining engineering, in underground construction for industrial and protective purposes, in the general practice of foundation engineering. The combination of training is fruitful; the ultimate success of the man appears to depend little on whether his degree is in geology or in civil engineering. The man will eventually carve out his own career that may not fit neatly into any definition of engineering geology, including that suggested by Dr. Terzaghi. The essential ingredients are sound training in the significant aspects of both disciplines.

DISCUSSION

BY CHARLES F. RIPLEY*

Dr. Terzaghi has opened discussion on an important aspect of engineering education and professional practice with his paper, "Engineering Geology on the Job and in the Classroom." This is an important addition to his recent notable papers on the practice of subsurface engineering. (Terzaghi 1957, 1958, 1959, 1961) The paper is direct and objective, presenting a carefully thought out analysis based on his long experience as an educator and as a practising engineer. Because it is concise, it requires more than one careful reading to appreciate and understand the context.

The paper is a valuable reference for all civil engineers, geologists and educators concerned with the practice of subsurface engineering. No other engineer has so successfully bridged the gap of knowledge which formerly existed between the fields of civil engineering and geology, as Dr. Terzaghi; in fact his career has been notable for his forging of the "missing link." Therefore his opinions serve as a welcome guidepost to the civil engineering student and to the recent graduate, concerning the extent to which they should seek training in geology. Also, for those older and more experienced civil engineers not trained in subsurface engineering, but who utilize the services of subsurface engineers and geologists, the paper will be helpful in clarifying the relative roles of each.

The comments of this discussor, civil engineer and former student of Dr. Terzaghi, are derived from his experience as a consultant in the field of subsurface engineering in British Columbia. The overburden soils here often have great thickness and their geology is complex. The soil profiles commonly reveal complex interfingering of marine, alluvial and glacial deposits, reflecting a history of repeated glaciation and fluctuating ocean levels. Because the geology of the overburden varies from one valley to another, and in fact even between closely spaced cross-sections in the same valley, the information available to the engineer in published geological reports is meagre. The arrangement of the various deposits and the patterns of stratification at an individual section are usually sufficiently complicated to require a professional geologist with extensive field experience in

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Pleistocene geology, to sort out the picture. Therefore the writer has obtained the advice of professional geologists on all his major projects. In so doing, he has developed satisfactory and harmonious working relationships with these consulting geologists, to the betterment of the ultimate projects.

The particular services the writer has requested of the geologist in connection with problems of foundations for dams and foundations for industrial plant sites, have been:

i. To identify the major deposits and geologic features within the total overburden present at a site, which are recognizable from drill holes and examination of surface exposures.

ii. To establish a general picture of the geologic history and sequence of deposition of the overburden soils in the particular valley or regional area in question.

iii. To suggest the probable areal extent of the deposits; also the probable three dimensional configuration of each deposit in relation to the other deposits with which it may be in contact.

iv. To point out geologic conditions, which from previous experiences in the area, the geologist believes may be present and which may be significant to the engineering problem.

At the present time few civil engineers have "adequate training" to fulfill these functions, where the geology of the overburden is complex. Properly fulfilled, these functions require a more extensive training in geology than is given to a civil engineer in his university training. Furthermore, they require extensive field experience in Pleistocene geology.

Even though the advice of a professional geologist has been required, the necessity for the writer, a civil engineer, to have and to use adequate geologic training on the project has not been diminished. The application of his geologic training has been required in a manner that is complementary to the work of the geologist. On important projects the writer has not attempted to perform the functions of a geologist. His knowledge of geology has been used to recognize that the site conditions required the examination of a geologist; also to select a geologist suitably qualified for the particular problem. The other major functions to which his knowledge of geology have been applied, include those mentioned by Terzaghi in his paper:

i. To make sure that he understands the information provided by the geologist; in particular, to know the boundaries between fact and conjecture in the over-all geologic picture developed by the geologist.

ii. To recognize from the geologic information, those aspects of the subsurface conditions that are significant to the engineering problem; that are significant to the engineering problem; that is, to recognize the strata that may be safely ignored and the strata that require more detailed engineering investigation.

iii. To anticipate the probable range of variations in the hydraulic and mechanical properties within the individual deposits, arising from geologic factors.

iv. To assess the uncertainties involved in his design studies and his prediction of the soil behaviour which result from his use of test results, theoretical analyses, and computations.

The assistance of the geologist has been obtained in planning the exploration program throughout its various stages. The preliminary stages are generally directed toward determination of geologic conditions whereas the subsequent stages will more often be directed to investigation of engineering factors. Subsequently, the geologist has been invited to review the conditions exposed at the site during the construction stages, after the site has been opened up. This has provided an opportunity for him to review the accuracy of his initial forecast of the site conditions and to point out any significant geologic factors not previously anticipated. In the relationship described above, the services provided by the geologist might appear to overlap slightly those provided by the civil engineer. However, this is desirable on all important projects where geologic factors have a significant influence, in contrast to having a gap exist in the services provided. A gap represents an incalculable risk to the safety of the structure.

Perhaps the strongest statement in Terzaghi's paper and surely the one most likely to be misunderstood unless it is read carefully, and given appropriate thought, is that on page 106:—"Hence in the realm of earthwork engineering the instances are rare in which an engineering problem requires the services of an engineering geologist, provided the civil engineer is adequately trained." Opinions as to what is the appropriate role of the engineering geologist in the practice of subsurface engineering will vary widely among practising engineers, geologists and educators, depending upon their educational background, and their professional experiences. The intended meaning of the term "engineering geologist" is not clear to this writer. That is, he does not know whether the term was intended to refer exclusively to a geologist with engineering training, or, to refer more broadly to a professional geologist irrespective of his engineering knowledge.

The civil engineer should be cautioned about concluding from the paper that the services of a geologist are seldom required in the realm of earthwork engineering. Dr. Terzaghi's statement contains a clear and definite qualification on this point, namely, "provided the civil engineer is adequately trained." For the benefit of those civil engineer readers who might be inclined to lightly dismiss the all important qualifying remark, the following information may be useful. During the past 10 years the writer has worked closely with Dr. Terzaghi on a dozen major projects in the realm of earthwork engineering in British Columbia, each at a different site. In all cases, Terzaghi himself either sought or endorsed the writer's seeking of the advice of the most experienced geologist in the area. Certainly if Terzaghi with his vast experience and training in geology, finds it helpful to obtain professional geologic advice in connection with earthwork problems, then the average civil engineer should be cautious in deciding the extent to which his own limited geologic training is adequate for his own problems. The decision on a particular project whether professional geologic advice is necessary will obviously depend upon three factors: the relative importance of the project, the complexity of the regional geology, and the extent of geologic training and experience of the civil engineer concerned.

Terzaghi rightly emphasizes the need of better engineering geology courses for civil engineering students. Important as this first stage of training is, it can hardly be considered "adequate training," in the sense used by Terzaghi. Adequate training of the civil engineer in engineering geology can be thought of as a two stage process that can be developed only with field experience. The second stage carries on from the university course through the professional life of the engineer. It consists of developing and maintaining a keen interest in geology by persistent and critical observation of the products of the various geologic processes, which are evident in the area of his work. The engineer should examine virtually every cut slope and exposure he passes by, to acquaint himself with as wide a range of patterns of stratification and variations within soil deposits as possible. He should also develop his knowledge of the geologic processes and environments that have given rise to the variations he has seen in soil deposits, so that he may better know when and where to expect them. This latter knowledge can be most easily developed if the engineer has contact in his work with a competent and experienced field geologist. Equal benefits from such contact may be derived by the geologist, for he will obtain a better understanding of the relative engineering significance of the geologic features at a site.

The technical level of applied problems that the civil engineer can capably solve, will depend on his knowledge of geology as well as his knowledge of his civil engineering subjects. The solution of difficult problems requires the exercise not only of a certain minimum level of knowledge, but also of imagination and self-confidence as well. Of equal importance is selfrestraint and the understanding of his own limitations. He should therefore not hesitate to seek the advice of a geologist on projects of importance or with difficult geologic conditions. With the increasing use of applied soil mechanics in earthwork problems, there is a great need at most universities of better courses in engineering geology for the civil engineer. However, the university course is not the end point but merely the beginning of his geologic training, if he is to achieve "adequate training" in the sense used by Terzaghi.

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DISCUSSION

By P. J. West*

The writer has been aware in his own experience that the best solutions to most subsurface problems usually are obtained by applying a blend of both engineering and geologic principles. It was gratifying to find that Dr. Terzaghi, early in his professional career discovered the necessity to recognize and adequately interpret geologic factors affecting subsurface engineering. He further realized that purely qualitative and rather generalized geologic findings could not be effectively translated by the engineer into a form which could be readily utilized in engineering practice. Hence, he developed methods to correlate geologic processes with experimentally determined information on the engineering properties of the products of such processes, wherefrom geologic principles could be then applied to practical engineering problems.

The general procedure followed by the author in dealing with problems of earthwork engineering as presented in the paper under the section entitled, "Role of Engineering Geologist in Earthwork Engineering," was of especial interest to the writer. In his association with the author on two major hydroelectric projects in California during the past decade, the writer has been in the fortunate position of being able to closely observe the author apply this multiple working procedure.

The author developed such procedure following his realization that the nature and importance of the uncertainties associated with the results of subsurface exploration depend entirely upon the geologic characteristics; and that design assumptions and computations are valid only insofar as these characteristics are understood and properly evaluated.

It is the writer's firm belief that students and practitioners of engineering geology alike should prepare themselves to apply as routine the cardinal points of this procedure to their project investigations. To be capable of doing so, the engineering geologist should be equipped with a knowledge of civil engineering principles and practices and must have the fundamentals of geology thoroughly in mind.

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While perhaps being somewhat repetitious, the writer wishes to paraphrase the author's words and briefly present the procedure for purposes of emphasis, in outline form later in this discussion. Sufficient to say, the procedure as witnessed by the writer in its various phases, emerges as a most workable and useful guide in coping with problems of earthwork engineering. The steps of this procedure should be carefully considered by both engineers and geologists involved in earthwork and foundation design. If rigorously pursued, it forces one, perhaps against one's natural reluctance, to recognize the importance of geologic factors in rationally evaluating the engineering characteristics of the subsoil.

Presently utilized techniques of exploration, testing, design, and construction may vary and undoubtedly improve over the years to come, yet the propositions established by the author on which his deductive thought processes are based will not undergo any change.

Outline of Author's General Procedure in Dealing With Problems of Earthwork Engineering

First Step

1. Collect all the information regarding the geologic characteristics of the site from resident geologists and from publications, supplemented by a personal examination of the site.
2. Interpret the findings based on comparison of the products of the various geologic processes at the site with the products produced by similar processes elsewhere, wherein the engineering properties at the latter have been obtained by experimental determination.
3. Determine the maximum depth at which the seat of potential trouble may be located (i.e., compressible layers, aquifer of high artesian pressure, avenues for the escape of water from a reservoir, etc.)

Second Step

1. Estimate the position of the horizontal and vertical boundaries of the source of potential trouble by means of exploratory borings and the pattern of stratification.
   (a) If the source of potential trouble is relatively homogeneous, an elaborate subsurface investigation and laboratory testing program of undisturbed samples may be

justified, from which settlement or stability computations can be made.

(b) If a condition of heterogeneity is encountered, very little can be gained by accumulating test data in addition to those which disclosed the absence of homogeneity.

Third Step (Providing the usual case of heterogeneity exists)

1. Evaluate the uncertainties involved in the interpretation of the results of the subsoil exploration. (Such uncertainties depend on the geologic characteristics of the site.)
   (a) Design must be based on the most unfavorable possibilities compatible with the known geologic characteristics.
   (b) If the project permits modification of the design during construction, adopt an observational procedure which requires that the gaps in the initial knowledge of the significant properties of the subsoil be closed by observation during construction.

CLOSURE TO THE DISCUSSION

By Karl Terzaghi

When the writer prepared the paper under discussion he was fully aware of the fact that many of his statements were strongly influenced by his professional background and personal preferences. In order to eliminate these shortcomings of his paper, he invited men with very different professional backgrounds to give the readers the benefit of their opinions concerning the subjects covered by the paper. Among those who responded to the invitation are three who are educators as well as consultants, Professors Cleaves, Deere and Peck, three professional engineers, Messrs. Banks, Dunn and Ripley, and four consulting geologists, Messrs. Campbell, Dolmage, Kolb, Laurence and West. All of them are known to the writer as being exceptionally competent in the fields of their activity. Therefore the discussions turned out to be even more instructive than the writer could reasonably have hoped. The following paragraphs contain a summary of the opinions expressed by the discussers.

Engineering Geology in the Curriculae for Civil Engineers

The place and space which should be assigned to engineering geology in the curriculum for civil engineers is still a highly controversial subject. This fact is clearly reflected by the diversity of opinions.

According to Messrs. Kolb and Laurence "it would seem questionable that a single course in the subject could provide the background required to recognize significant geologic characteristics at a site or to decide whether further geologic exploration should be considered." Mr. Dolmage questions "whether it is advisable to give the civil engineer any formal classroom geological training" and adds that "a little knowledge, and particularly if it is simplified or abridged or out of context, is a dangerous thing." Professor Peck is one among the many civil engineers who left college without having received any geological training and describes in detail how he acquired a working knowledge and interest in geology in later life, from observation on his jobs and particularly from his personal contacts with the geologists assigned to these jobs. This procedure for acquiring a working knowledge in engineering geology is strictly in accordance with Mr.

Dolmage's recommendations. However for every engineer who learned his lesson on the job the writer could name five others who have been designing foundations for many years without even suspecting the existence and the importance of "geological factors," and without realizing the difference between designing a foundation and designing a steel bridge. Professor Peck is well aware of this condition. Hence when he took charge of the Department of Soil Mechanics at the University of Illinois he lost no time in introducing engineering geology into the curriculum of his students. Professor Cleaves believes that "the single course given to civil engineers in the applications of geology to civil engineering, based on a single course in elementary physical geology, can do more than alert the civil engineer to an appreciation of the significance of the geological disciplines." On the other hand Mr. Campbell expressed the opinion that "the mature student, well grounded in the fundamentals of science and engineering, can grasp the basic principles of geology in an astonishingly small fraction of the time that a freshman or sophomore spends struggling with strange terminology . . ." and adds: "I believe that principles can be presented (or reviewed) with little loss of time even for the student without any previous training in geology and, in fact, with some enhancement of the total course." Mr. Campbell, presently Chief of the Division of Mines in the State of California has taught Economic Geology for many years at the California Institute of Technology and his statements, like those of the other discussers, are derived from broad experience.

In spite of the diversity of opinions expressed by the discussers, several important statements can be made, none of which is incompatible with these opinions.

1. The performance of subsurface structures depends to a large extent on geological factors. Hence if these factors and their engineering implications are not recognized the consequences can, and often have been, catastrophic.

2. On many jobs other than major ones the owners would not even consider paying the fees of a geologist in addition to those of the architect and the engineer. Hence if the engineer in charge of the design of the subsurface portion of the structure in unaware of the importance of the geological factors he must be considered incompetent and can do a lot of harm.

3. Some engineers may, but most of them do not, discover after graduation the practical importance of geological factors and acquire the capacity to understand and correctly interpret geological reports. Therefore a course in engineering geology must be considered an essential ingredient of every curriculum of civil engineers who may, in their future professional career, be entrusted with the design of subsurface structures.

4. The success of the course depends entirely on the degree to which the students have realized the inevitable uncertainties associated with forecasts in the realm of subsurface engineering and not on the amount of geological knowledge they have acquired. To teach such a course most effectively the teacher should be thoroughly familiar with both the geological and the engineering aspects of subsurface engineering. Yet the demand for such men is far in excess of the supply. If no teacher is available with such qualifications an engineer who is interested in the subject and has acquired most of his knowledge of the geological aspects of subsurface engineering from intelligently reading suitable case records is definitely preferable to a geologist with very limited connections with the engineering profession or none at all.

5. The application of the principles of geology to problems of subsurface engineering requires a "habit or mode of thinking quite foreign to that of the engineer" (Mr. Dolmage). In all the other courses the engineer is trained in only one mode of thinking and to grasp the essence of an entirely different one in the short time allotted to the course requires a relatively high degree of maturity. Therefore the course should be taught as late as practicable, preferably on the graduate level.

6. Most of the divergencies between the expressed opinions center about the question as to how much a student can learn in a single course. The answer depends to a large extent on the qualifications of the teacher, the degree of maturity of the students and, to a large extent, on the mental characteristics of the individual students. Some students may be utterly incapable of learning how to think in "both modes" though in other fields such as applied mathematics they may be outstanding.

7. The heads of the Departments of Civil Engineering must adapt their decisions to the qualifications of the available personnel,

the available funds and to the time limitations imposed upon them by the crowded curricula. Therefore they have little influence on the degree of efficacy of the courses in engineering geology. Yet on account of the serious consequences of complete ignorance in this field a moderately successful course is definitely preferable to none at all.

As an example of how a course in engineering geology can be fitted into the general program for the training of civil engineers the writer's course at Harvard University may serve. The crowded curriculum rendered it impracticable to make previous training in physical geology a hard-and-fast prerequisite. To compensate for this limitation the writer gave his course at the very end of the training period. Since most of his students were graduates they had already reached the level of maturity postulated by Mr. Campbell when he made the statements quoted at the end of the preceding summary of the discussers. The topics covered by the course are listed in an Appendix to the paper. Yet 40 hours are very short and the topics are numerous. Therefore he devoted most of the time at his disposal to the engineering aspects of geology in the manner described by Professor Deere in the first part of his discussion. However he supplemented his course by reading assignments in a suitable textbook on physical geology, occasional field trips and a few afternoon sessions in the Department of Geology where the students had an opportunity to examine and identify hand specimens of the most important types of rocks. In his first lecture he informed his students that the course should be considered an antidote to theoretical soil mechanics and in the last one he advised those among them who failed to grasp the essence of his teachings to keep away from subsurface engineering. Unfortunately some of them did not follow the writer's advice. Judging from letters the writer received from former students, years after they had started to practice subsurface engineering, some students have derived from the course lasting benefits, whereas others had merely grasped the words but not the spirit and these could probably not be improved by educational efforts of any kind.

Function of the Geologist in Earthwork Engineering

On p. 106 the writer made the following statement: "Hence in the realm of earthwork engineering the instances are rare in which an engineering problem requires the services of an engineering geologist, provided the civil engineer is adequately trained." This statement was emphatically contested by both geologists and engineers. According to Messrs. Banks and Laurence "probably the greatest contribution of the competent engineering-geologist is the planning, conducting and interpreting exploration programs to produce a reliable picture of the physical conditions that exist at depth." They also consider the writer's appraisal of the practical value of geophysical methods of subsoil exploration too "harsh." Mr. Kolb emphasized the importance of the benefits derived from a geological study of sedimentary deposits and illustrated his statements by a well-chosen example. Mr. Ripley, a consulting engineer whose professional activities are chiefly associated with glacial deposits in western Canada takes advantage of geological advice on all his projects. He presented a list of the uses he makes of his own geological knowledge and another one of the benefits he has derived from his co-operation with professional geologists. Finally he mentions the fact that even the writer himself took advantage of the services of Mr. Dolmage, whenever he operated in the formerly glaciated areas of British Columbia.

Impressed by the unanimity of the reactions to his statement, the writer reviewed his own past to discover the source of what began to look like a misjudgment. While he was a student in mechanical engineering he became so interested in geology that he skipped most of his classes and attended courses in geology instead. After graduation he entered the services of a general contractor, hoping for an opportunity to keep in contact with his favorite science. His first publications, 1906 and 1907, were devoted to purely geological subjects, and during the following half-century his interest in geology never faded. Thus it became clear to him that his statement was biased. He took it subconsciously for granted that once an engineer is exposed to geology he cannot help falling in love with it and acquiring the geologist's mental attitude towards all those problems of subsurface engineering which cannot be solved by mathematical procedures. The discussers opened his eyes and he heartily concurs with their statements, with the following qualifications.

The "harsh" attitude of the writer towards geophysical methods (Messrs. Banks and Laurence) grew out of a long series of disappointments, starting in 1930 with the failure of the electric-potential method to furnish any useful information concerning the location of the buried rocksurface at a damsite in Algeria. Persistent setbacks are not easily forgotten and justify a certain degree of skepticism. However the writer does not deny that the reliability of the procedures may increase as the techniques are improved.

Professor Cleaves illustrates the importance of the knowledge of the mineralogical composition of embankment materials by two case records. In both instances the geologist is credited with the discovery of properties which could not possibly escape the attention of a competent soil-testing engineer. He also describes the benefits derived by the engineering profession from clay-mineralogical investigations. These studies aroused the writer's interest as soon as he read about them for the first time, some thirty years ago. At the outset he felt as optimistic about them as Professor Cleaves does at present. However he gradually found out that two clays with identical clay-mineralogical composition can have radically different physical properties. Hence he concluded that it is much cheaper and more expedient to determine the significant properties of clay by direct testing. Clay-mineralogical investigations may furnish very interesting information concerning the causes of unusual physical properties to a given clay after its properties were disclosed by soil tests (see for instance Terzaghi 1958) but so far they have no legitimate place in subsoil exploration.

Rock Mechanics

Messrs. Banks and Laurence call the reader's attention to the important contributions of rock mechanics to subsurface engineering, and Professor Cleaves refers specifically to the practical value of the photo-elastic method and of the procedures for measuring stresses in rock.

Rock mechanics is based on the same reasoning which led the writer to establish the fundamental principles of soil mechanics, but it started at a very much later date. Therefore by extrapolation its future development can be predicted fairly reliably from that of soil mechanics, which has briefly been described quite recently by the writer in a paper (Terzaghi 1961).

At the present time rock mechanics is primarily concerned with filling the existing gaps in our knowledge of the physical properties of the rocks, in inventing new methods of rock exploration, and developing new theoretical procedures. Thus a vast store of information is accumulated, which is of inestimable value as a basis for judgment. However these activities, which are analogous to those in soil mechanics in the thirties, divert the attention of engineers from the inevitable uncertainties involved in all the forecasts concerning the performance of rocks and lead to practices similar to those which the writer called in the aforementioned review paper the "misuse of soil mechanics."

The danger of misusing rock mechanics is aggravated by the following fact. The significant physical properties of most rock formations which can conceivably be the cause of engineering difficulties have a striking resemblance to those of sedimentary deposits with an erratic pattern of stratification. Therefore they cannot be determined reliably in advance of construction by any practicable means. Some of the engineering consequences of this condition will be described by the writer in a paper "Measurement of Stresses in Rock," to be published in 1962 in Géotechnique. Therefore those engineers who are presently engaged in rock mechanics are strongly advised to take advantage of the experiences in applied soil mechanics.

Mental Processes Involved in Subsurface Engineering

In his discussion Mr. Dolmage pointed out very aptly that geology "is an inexact science and requires a habit or mode of thinking quite foreign to engineers." Yet the successful handling of problems of subsurface engineering requires efficient reasoning in both domains. On account of the importance of this fact three of the discussers concentrate their attention almost entirely on this aspect of subsurface engineering. Professor Peck distinguishes between "system" and "method" and emphasizes the importance of thorough acquaintance with the "method." Mr. Ripley deals with the role of "geological thinking" in his professional work, and Mr. West summarizes the successive steps in dealing with subsurface problems. All the opinions expressed by the discussers concerning this subject are fully in accordance with the corresponding statements in the paper and contribute a valuable supplement. The means for introducing the student into the double aspect of the subject and to make him familiar with the "method" have been discussed under the heading "Engineering Geology in the Classroom."

Engineering Geology as a Profession

Professor Cleaves "is of the belief that disastrous results could accrue from the reliance upon mining or petroleum engineers for advice on many civil engineering projects." This statement calls for qualification. For instance Mr. Campbell is primarily an economic geologist. Yet he was an esteemed advisor of the Southern California Edison Co. on numerous civil engineering projects. Mr. Dolmage, a mining engineer, has been associated with many civil engineering undertakings in British Columbia, and the writer has co-operated with both these gentlemen most satisfactorily on major projects involving glacial geology. The reason is obvious. If a geologist of any category is really competent and the engineer knows enough about geology to formulate his questions intelligently it makes very little difference in which fields the consulting geologist operates.

At the end of his discussion Mr. Dolmage even questions "the validity of the term Engineering Geology as currently used." To him, "if it means anything, it means geology applied to engineering problems just as economic geology means geology applied to the finding and extracting of minerals. In both cases it is the same kind of geology. . . ." He continues: "Like the engineer the geologist has not the time in his undergraduate years for any engineering other than his courses in surveying methods. The small amount of elementary engineering which he might squeeze into his program would be of very little value. . . ."

In contrast to Mr. Dolmage Professor Deere takes Engineering Geology very seriously. After reviewing the present relationships between engineer and geologist, and their inadequacies he recommends a very bold step: The training of engineering geologists who are competent to perform the services of both geologists and engineers. He even outlines the curriculum for prospective candidates.

In the writer's opinion the step proposed by Professor Deere is a dangerous one and could lead to very disappointing results, for the following reasons. Experience has shown that many individuals are unable to acquire the capacity of reasoning equally efficiently in the way required by geology and in the realm of exact sciences such as engineering. While still at college the student has no opportunity to find out whether or not he possesses this capacity. If he has majored in civil engineering without having this capacity he can specialize for instance in bridge design and if he has majored in geology he can join a geological survey. However if he is a graduate "Engineering Geologist" he has no choice and may turn into a public danger.

Furthermore, the two fields, engineering and geology, are so vast, that no one person can be equally competent in both of them. This the writer knows from personal experience. His "formal education" in geology is far above the average and he followed the developments in geology throughout his life as closely as his time permitted. Yet he did not even try to become an expert in this field, because every attempt to learn still more about geology would have been at the expense of his expertship in one of the many domains of civil engineering. Hence time and again he considered it indicated to avail himself of the advice of a competent geologist. The geologist is in a similar position with reference to engineering.

If a young geologist was born with the qualifications of an engineering geologist he will be drawn into this field by the force of gravity as Dr. Berkey was, and many after him, without formal education in engineering. He will become familiar with the geological problems of subsurface engineering through his contact with engineers in the field and render most valuable services, provided he does not attempt to invade the domains of the engineer. Quoting from Mr. Campbell's discussion: "This—to know the limitations of one's own knowledge, and thus to know when (and where!) to seek assistance from colleagues in other professions—is to me certainly the beginning and very probably the hallmark of wisdom."

Acknowledgements

The writer wishes to express his gratitude to the discussers for the services they have rendered to the engineering profession by seriously contemplating the subjects covered by the paper and correcting or endorsing the writer's statements. The paper was intended to, and did act as a catalyst. Owing to the cooperation of the discussers, the discussions are more instructive than the paper, because they reflect the consensus of opinion, and not the opinions of an individual.

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