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ENGINEERING GEOLOGY - A FIFTY YEAR REVIEW

BY

ROBERT F. LEGGET

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ENGINEERING GEOLOGY—A FIFTY YEAR REVIEW

ROBERT F. LEGGET

ABSTRACT

Progress in the application of geology to the practice of civil engineering is reflected in the papers on this subject which have appeared in the first 50 volumes of ECONOMIC GEOLOGY. The influence of geological work in two world wars is shown by the increase in the number of published papers following the two wartime periods. These published papers show that substantial advance has only been made in the last two decades. During these recent years the literature of the subject has greatly expanded. This is reviewed and typical papers are noted with special reference to the main branches of civil engineering work. Trends in present developments are discussed, notably the way in which engineering works are providing geologists with new information. The contributions of soil mechanics as an intermediate discipline are becoming more widely appreciated and give promise for further advance both for the application of geology in engineering and for the contributions of engineering studies to geological sciences.

THE appearance of this paper in this special anniversary volume is an indication of the steady extension, within recent years, of the field of Economic Geology. There are still many to whom this term indicates the application of geological work to mining activity only, but their number is decreasing. Even in his own limited experience, however, the writer has heard a distinguished economic geologist ask why civil engineers should even be admitted to a geological gathering. The record presented in the following pages may go some way in answering such pedantic views but the invitation to the writer to prepare and submit this review is clear indication of a very different standpoint on the part of those who now guide the destinies of ECONOMIC GEOLOGY.

It would be well to define at the outset two terms that will frequently have to be used. The first is that taken as the title of this paper. It is one that the writer does not like but one which is adopted since it has become common usage in a well defined way. "Engineering Geology" is now generally held to mean that branch of economic geology involving the application of geology in the design and construction of civil engineering works. In the writer's view, this involves the use of no special brand of geology but only the rather specialized application of standard geological knowledge and techniques in a field of unusual economic importance. This paper, accordingly, will be found to deal only with unusual applications of geology and not with any new or unusual geological theory or technique.

"Soil Mechanics" is the other term that will have to be used throughout this review (even though a special paper is to be devoted exclusively to this subject). The expression is a rather ugly translation of the German word *erdbaumechanik* which has come into universally accepted use to describe

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Anniversary Volume

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PART II

the engineering study of all the unconsolidated material in the earth's crust. The word "soil" is therefore being applied in its original general sense (as used, for example, by William Smith, as early as 1815) and not in the very restricted sense in which it is today used, for example, by agricultural soil scientists. This confusion in the use of this simple word is unfortunate but has to be accepted.

Discussion of these two terms inevitably directs attention to the vast scope of engineering geology embracing, as it does, the whole practice of civil engineering. Such a review as this, therefore, can touch upon only some of the highlights of the last fifty years, indicating the major trends in development as they have been seen by the writer in the latter half of this period and as they are reflected in the relevant literature, to which this paper can be but an introduction.

It would seem to be appropriate to take as a starting point the volumes of *ECONOMIC GEOLOGY*. Careful study of the contents of the first forty-nine volumes has shown that such a course is not only appropriate but one which reveals, in a quite surprising manner, the unusual development of engineering geology during the last half century. For convenience, a chronological list of the significant papers in the field of engineering geology which have appeared in *ECONOMIC GEOLOGY* accompanies this paper.

The first issue of this journal (1905) starts off with a general review by F. L. Ransome on "The Present Standing of Applied Geology" and features a special letter by J. D. Irving on the university training of engineers in economic geology. In neither of these contributions is civil engineering even so much as mentioned. (Incidentally, the appearance of the first issue is generally similar to that of an issue of today, a refreshing change from the chameleon-like format of many other scientific journals.)

This narrow interpretation of the coverage of the new publication was soon challenged, however, for later in the same first volume appears a trenchant article by D. W. Johnson entitled "The Scope of Applied Geology and Its Place in the Technical School" (1). The restricted outlook in the first issue is questioned and the importance of geology in civil engineering is discussed and illustrated. Johnson states that a course in applied geology had, even then, been given for several years to civil engineering students at M.I.T., and he gives the titles of two books which had included some attention to engineering geology.

So important is this pioneer paper that a direct quotation seems desirable. This is an abbreviated version of what Johnson had to say, in 1906, about the scope of engineering geology and necessary training for it:

The civil engineer must be prepared to meet many problems involving geological factors, and must therefore be equipped with an adequate geological training. As a foundation a general course in the fundamental principles of geology seems essential. Familiarity with the different rock species, and a knowledge of their relative values as building material, road metal, etc., will save the engineer from many costly errors. The effect of rock characters and rock structures on tunnelling, the need of lining tunnels which penetrate certain rocks which at first appear massive and strong, the danger of caving where shearing planes dip toward the excavation, the possibility of continued slipping of morainal deposits along

a railroad cut in such material, the probable changes that may be expected in a river meandering in its floodplain, the possibility of locating water-bearing beds, building stones and cement rock even when they do not appear at the surface, the conditions essential for the accumulation of artesian waters and the methods of forecasting the probable behavior of wells to be drilled,—these and many other subjects afford abundant material which may be brought to the attention of the civil engineering student with profit. . . . The sanitary engineer finds that he must have certain kinds of soil for various processes of sewage disposal and water purification. Where the loose sands of glacial deltas, outwash plains, or other deposits of like composition are available certain of these processes may prove practicable, but where only beds of compact clay or till are found the cost would be prohibitive. The draining of swamps that prove a menace to public health may sometimes be accomplished by boring through to underlying beds of loose sand or gravel, from which the waters find a ready outlet. The direction in dip of the rock structures may determine the liability of cess-pools to contaminate sources of drinking water at considerable distances. The direction of flow of underground waters may cause or prevent such contamination. Such are a few of the considerations that appeal to the interest of the sanitary engineer. . . . The many applications of geology to these and other branches of engineering cannot be enumerated here, the points above mentioned merely serving to indicate in a general way the extensive scope of the subject. The methods of presenting these practical considerations to the students must vary with every school and every instructor. . . . The important thing is to open the eyes of the men to the fact that in the past a knowledge of geology has made possible the solution of many difficult engineering problems.

This was a prophetic statement for 1906, but, like many another statement by a prophet, it had to wait many years for even its partial realization. What is the more surprising is that twelve years were to pass before there was any other reference of any sort to engineering geology in *ECONOMIC GEOLOGY*, with one notable and quite special exception. And it was not until 1921 (Volume 16) that the first original paper on an engineering geological subject appeared.

The exception just noted was a paper by Ernest Howe in Volume 2 (1907) on "Isthmian Geology and the Panama Canal" which was stated to be a summary of an official report made by the author to the Canal Commission, following a five-month tour of the Canal area in July 1906 (2). In the Report of the President's Commission of Inquiry (N.R.C.) on the slides in the Culebra Cut, it is pointed out that Dr. Howe's observations were generally of a preliminary character only. It must, however, be recorded that in the paper cited, these statements appear: "The physical character of the Culebra beds, consisting as they do of alternating layers of sandstone and shale, is peculiarly favorable to landslides. Structurally, however, the strata are so nearly horizontal . . . that movements involving larger masses of rock are improbable. . . . All the rocks in Gold Hill are now very hard and firm (so that) landslides are most unlikely." So many years have passed since these words appeared, and since the first disastrous Culebra slides did occur, closing the Canal for almost ten years, that it is impossible even to conjecture as to their effect upon professional engineering opinion about engineering geology. Although the ultimate result of all the troubles at Panama was probably salutary (especially after the publication of the N.R.C. Report), it would not be surprising if the initial reaction of civil engineers, at least to

the disasters, was to perpetuate the neglect of geology in their work, despite the fact that it is only by the proper application of geology that such disasters can be foreseen and so prevented.

But the neglect persisted, despite the few papers of the twenties shortly to be mentioned, being dramatically illustrated by F. L. Ransome's paper of 1928 (Vol. 23) on the "Geology of the St. Francis Dam Site" which appeared soon after this great structure had failed (12). "So far as can be ascertained, no geological examination was made of the dam-site before construction began. . . . How the true nature of this rock (conglomerate) failed to become apparent . . . is difficult to understand." This disaster must have had an immediate effect on the use of engineering geology, at least with respect to dam foundations, but this change in outlook was not reflected in the pages of *ECONOMIC GEOLOGY* until after the second World War, only three other papers in this field appearing before the recent war years.

The incidence of both world wars was clearly reflected in the journal. In 1917 (Vol. 12) Alan M. Bateman contributed a note on "The Geologist in War Times—The Training of Artillery Officers." Although this dealt only with topographical work, it led to three letters in the succeeding volume which did touch upon military geology and so indirectly upon engineering geology. Older readers will recall that it was in 1918 that the first Editor, John Duer Irving, was killed in France while serving in the U. S. Corps of Engineers, in which he was applying his knowledge of geology to wartime building problems.

Despite the diversion of so much geological effort to meet the practical demands of war, the return of peace seems to have been a return to the pre-1914 neglect of geology on civil engineering works. During the two inter-war decades, there appeared only seven papers (in addition to that on the St. Francis Dam Site) which can in any way be regarded as dealing with engineering geology. Four of these dealt with studies of the geology of dam and reservoir sites, two in Texas, and one each in Wyoming and Maryland. The Wyoming study (15) was carried out by W. H. Bradley of the U. S. Geological Survey for the U. S. Bureau of Reclamation and that in Maryland (16) by E. B. Eckel, also of the Survey staff, for the U. S. Corps of Engineers. Eckel states that his assignment, in 1936, to this task "proved to be typical of the modern trend in the use of geology by engineers, in that the geologist had a voice not only in the original choice of site but was consulted throughout the period of exploration and design." Thirty years had passed since Johnson's first suggestion of such cooperation but Eckel's was a report of action, action which was now becoming general practice. In Volume 34 (1939) appears the first indication of the final step in the development of engineering geology, this being an abstract of a paper on the "Geology of the Hiwassee Dam Site" by B. C. Moneymaker who wrote as a geologist on the staff of the Tennessee Valley Authority, one of the first major organizations to employ its own geological staff for use exclusively on engineering and construction work.

Before dealing with other relatively recent progress, reference must be made to two other earlier developments. The only two papers to be pub-

lished on the applications of geology to highway work were, strangely enough, the second and third engineering geology papers in *ECONOMIC GEOLOGY*. The first (5) (Vol. 13, 1918) was a contribution from the Geological Survey of Canada, a review by L. Reinecke of "Non-Bituminous Road Materials," and the second (Vol. 16, 1921) a general discussion of "Economic Geology and Highway Construction" by E. F. Bean of the Wisconsin Geological and Natural History Survey (9). It is stated in this paper that the entire output of graduates from the Department of Geology at the University of Wisconsin in 1922 was to be used on geological studies for highway work.

An editorial of this period (Vol. 14, 1919) on "Economic Geology as a Profession" brings the name of Waldemar Lindgren into this review since it contains a succinct yet comprehensive statement on the challenge of engineering geology (6). It elicited no replies in correspondence as did certain other editorials and a short letter from G. J. Mitchell (Vol. 12, 1917) on "The Need for Accurate Rock Classification in Engineering Contracts" (3). Two letters (7 and 8) on the same subject followed in Volume 14 (1919), the second (from L. V. Pirsson) suggesting what is now a common solution to this most difficult problem in civil engineering construction, classification on the basis of the way in which rocks can be removed, the contractor having no geological interest in rocks as such!

The number and interest of published letters vary considerably but Volume 24 (1929) contains two significant communications. Both comment upon groundwater papers which appeared in the previous volume. Their significance arises from the fact that they were written by Dr. Terzaghi, then writing from Massachusetts Institute of Technology and but recently arrived in North America. The father of the modern study of soil mechanics, Dr. Terzaghi based his pioneer contributions in this field upon his earlier geological studies. It is somewhat surprising, therefore, to find that his name does not again appear as author in *ECONOMIC GEOLOGY*, despite the close links which always have and must exist between soil mechanics and engineering geology.

It was not until 1942 (Vol. 37) that the first soil mechanics paper appeared, this being "An Engineering Study of Glacial Drift for an Earth Dam near Fergus, Ontario" by R. F. Legget (17). The next was a study of "Some Engineering Aspects of River Sand Deposits" by D. P. Krynine (Vol. 39, 1944) (18). More recently another paper by M. W. Bartley and the present writer has appeared presenting "An Engineering Study of Glacial Deposits at Steep Rock Lake, Ontario, Canada" (30).

These papers feature descriptions of soil types and test results obtained in soil mechanics work but other papers have dealt with the troubles which soils can create for the engineer, especially when they start to move as in landslides. W. R. T. Wagner describes, in Volume 39 (1944), "A Landslide Area in the Little Salmon River Canyon, Idaho" and illustrates the difficulties here caused in connection with highway construction (19). From the other side of the world came the next landslide paper, a detailed account by W. N. Benson in Volume 41 (1946) of "Landslides and their Relation to Engineering in the Dunedin District, New Zealand" (21). The stabilizing of

rockslides in Tennessee is described by R. A. Laurence in the next paper of this group (Vol. 46, 1951), these slides being caused by thin shale layers interbedded with sandstones (27). Finally, in the next volume, D. R. Crandell has described in great detail the occurrence of Landslides and Rapid Flowage Phenomena in South Dakota (29).

One paper only has been published dealing with the engineering geology of tunnels, this being an account of the studies made for the Broadway Tunnel in Berkeley Hills, California, by Ben M. Page (Vol. 45, 1950) (24). Only one more paper on dam foundations has appeared, this being an account by J. W. Frink of the studies made by the Tennessee Valley Authority, and the subsequent remedial work which finally did seal off the leakage beneath the Hales Bar dam which has, for long, been cited as an almost "classic" example of poor foundation conditions (22). This appears in Volume 41 (1946) and in the same volume is the only paper which has yet appeared dealing with the geology of a foundation failure. This is a contribution from two members of the engineering geology staff of the U.S. Bureau of Reclamation (R. C. Mielenz and C. J. Okeson) who describe foundation displacements along the Malheur River Syphon due to the swelling of bentonitic shales; the paper also includes useful laboratory test data on the shales (20).

One other paper has appeared dealing with building materials, this being another contribution from the Reclamation Bureau staff (R. C. Meilenz, K. T. Greene and N. C. Schieltz) (26). It is a concise yet comprehensive review of "Natural Pozzolans for Concrete" (Vol. 46, 1951).

Finally, special mention must be made of the attention paid to geophysical subsurface investigation techniques through papers published in *ECONOMIC GEOLOGY*. A letter on the subject appeared as early as 1923 (Vol. 18), this being from Sherwin F. Kelly and dealing with the introduction into North America of Schlumberger's "electrical prospecting" methods. An application of a similar technique to the "Reconnaissance of Buried River Gorges" in the Minneapolis-St. Paul area is described by S. W. Wilcox and G. M. Schwartz (Vol. 29, 1934), the authors concluding that it is possible to determine with a fair degree of accuracy the depth of glacial drift over a rock surface and even to determine to some degree the soil type dominant in the drift (14). A more recent application is described in Volume 47 (1952) in a paper by R. H. Wesley dealing with "Geophysical Exploration in Michigan" (28).

The dates and volume numbers cited in this summary review will have shown the concentration of papers on engineering geology in the most recently published volumes. Although not too surprising, in view of the very slow way in which engineering geological studies have come to be accepted, the picture is not quite as dark as these figures would suggest. A more reasonable picture is given by the abstracts of papers on engineering geology which have been included in the sets of such abstracts which have appeared almost yearly since 1937, in connection with the annual meetings of the Society of Economic Geologists. These have included almost fifty engineering geological titles. Although irregular in number at each meeting, papers of

this type are now clearly well accepted at the gatherings of the Society which is allied so closely with this journal.

Finally, the special significance of Volume 43 in this review must be discussed. In this volume (for 1948) appears a review of a new journal in a parallel field, the review expressing a most cordial welcome to the newcomer. *Géotechnique* is the title of the new journal, first published independently in England but now an official publication of the Institution of Civil Engineers. It is described as an "International Journal on Soil Mechanics" (being one of the few technical papers to publish papers in both English and French); it is maintaining its expressed aims in a most satisfactory manner. Its title is significant in this review, a title conveying as only a French word can a clear indication of its service to engineering geology in a scientific sense. Published now four times a year, its progress is a good indication of the maturity of engineering geology and of its recognition in the world of science.

By a happy coincidence, this same volume contains the first Report of the Committee on Research in Engineering Geology of the Society of Economic Geologists, prepared by Sidney Paige and Roger Rhodes (23). This report was part of a general survey of the status of research in all fields of economic geology, sponsored by the Society of Economic Geologists. It was one of the most comprehensive of the several similar reports which were published in this journal. Although attributable to the interest and enthusiasm of the authors, the wide coverage of the report was also an indication of the encouraging extension of the application of geology in civil engineering work in North America. Useful definitions are presented and a brief but significant discussion of "fields of overlap" in geology and engineering, those suggested being Soil Mechanics, Concrete and Concrete Aggregate, Construction Materials in general and Sedimentation. Organizational advances are reported and finally a summary of current research in ten different branches of work.

It might appear strange to some that such attention should have been given to research in one of the last fields of economic geology to be recognized. It may be noted, therefore, that there has been at least one other paper on the same subject. This is the record of the Presidential Address of E. B. Eckel to the Colorado Scientific Society, delivered in December 1950 (51). Eckel reviewed the many directions in which he saw the need for research in applications of geology in civil engineering. One of the research projects which he suggests is a solution to "the essentially human problem of how to present geologic facts to engineers so that they will understand and use them to maximum advantage." Writing as a geologist, he courteously refrained from mentioning the reciprocal problem of developing in civil engineers an appreciation of the vital importance of geology in all of their construction operations.

Another of the S.E.G. research reports was that by S. H. Lohman for the Subcommittee on Ground Water (64). This was the second such report, the first having been submitted by O. E. Meinzer (71). Together, they provide a comprehensive review of widespread research activity in a field so closely related to engineering geology that at least six of the nine research

topics listed in the second report are directly related to engineering work, the other three having close, although possibly more indirect, links with it.

Ground water is, however, the subject of a separate paper in this volume, so great is its importance in its own right. This review would not, however, be complete without at least a general reference to the subject, so critical can it be in civil engineering operations. To list even some of the types of project in which ground water may be a determining factor would be to digress too far. Reference should, therefore, be made to the companion paper for an appreciation of the geology of ground water as also to some of the many papers which have been published in *ECONOMIC GEOLOGY* on engineering aspects of ground water. Some of these deal directly with civil engineering works, planned or constructed. Specific reference may, perhaps, be made to one of these papers, if only to introduce into this record the name of Sidney Paige as an author, his discussion of the probable effects of the proposed Florida Ship Canal upon ground water conditions in Florida giving rise to the most extensive discussion (by means of correspondence) which has yet been featured in *ECONOMIC GEOLOGY* (78).

Another name, that of a man who can rightly be regarded as the dean of engineering geologists of North America, if not indeed, of a wider sphere, is strangely missing from the pages of former volumes of this journal. Charles P. Berkey carried out his first investigation in engineering geology before the first volume of *ECONOMIC GEOLOGY* was published. As these words are written, he is happily still active. His working professional life therefore spans the full period of this review. His wide interests and the broad scope of his work as a consulting geologist on major civil engineering works embrace most of the topics covered within these pages. His election as President of the Geological Society of America (in 1941) was therefore an encouragement to all who shared his lively interest in this utilitarian application of the science of geology; his retiring Presidential Address (38) is a paper which already may justly be regarded as a classic statement.

Speaking of the real start of his own specialist career, on the geological study for the first Catskill Tunnel for the Board of Water Supply of the City of New York, he had this to say:

For those early days on the Board of Water Supply were almost the beginnings of the recognition of the geologist in the construction of great engineering works in the United States. Up to that time such geology as was practised was chiefly that of the engineer himself supported only with an occasional call upon a geologist for a special study or an opinion on some unexpected trouble. To my best belief this was the first time in the history of the science in America that a geologist was given free rein from the very beginning to make such studies as he thought advisable and to stay with the project to the end. In this instance he was given the privilege of originating suggestions and was allowed to follow them up to determine whether the service had been worth while. In that way the case was finally proven for Engineering Geology (38 p. 515).

If one single paper had to be suggested as an introduction to the subject now under review, this address of Dr. Berkey's could well be a first choice.

Possibly because of his active life, his own writings have been to a large extent private in character. His comprehensive review of the geology of the

Quabbin Water Supply system, however, is almost a textbook in itself, so comprehensive is its coverage (40). The leading publication associated with the name of Charles Berkey, however, is the "Berkey Volume" published in his honor by the G. S. A. (77). Following a relatively brief personal tribute, the book contains a succession of lengthy and authoritative papers on such topics as the application of Geology in Dam Construction, the construction of Tunnels, Beach Engineering and Ground Water, authors such as Karl Terzaghi, O. E. Meinzer and W. C. Krumbein being warranty enough for the value of the contents of this unique volume.

In an earlier special publication of the Geological Society of America, engineering geology had already been given useful recognition. In 1939, a Fiftieth Anniversary volume was published by the Society ("Geology 1888-1938"), the concluding paper in which is a short and very general review of "Engineering Geology" by W. J. Mead (70). Later in the same year, the G. S. A. issued as a special bulletin the record of a series of anniversary radio talks which included one by C. P. Berkey on "Geology in Engineering" (39).

With such precedents available, it was not therefore surprising that the G. S. A. should have authorized the establishment, within its own framework, of a Division of Engineering Geology. First meeting at Ottawa in 1947, the Division has steadily increased its participation in the annual meetings of the Society. Although the papers presented at the Divisional sessions are still published only in abstract form, the influence of the Division is probably responsible, at least in part, for the first appearance of papers on engineering geology in the *Bulletin* of the G. S. A. The fact that this distinguished scientific journal has published any papers in this applied field is encouraging but the start has been a modest one, a paper on the engineering use of aerial reconnaissance by Belcher (35), and a general discussion of the engineering geology of San Francisco Bay by Trask and Ralston (91) constituting almost the full record to date.

Such restricted attention to an important application of geology is a common feature of the leading publications which serve so well the field of pure geology. The *Journal of Geology*, for example, appears to have published in its sixty volumes only two papers which deal directly with engineering geology, a useful review by H. F. Winterkorn of the "Applications of Modern Clay Research in Construction Engineering" (104) and a significant paper by Rominger and Rutledge to which a more detailed reference will be made later (83). This Journal has pioneered, to a degree, in publishing papers dealing with snow, ice and permafrost, all subjects now of vital importance in civil engineering practice in view of northern development. These papers, all naturally in recent volumes, have been scientific in nature but inevitably they have some practical connotation.

A record even more surprising, at first sight, is found when comparable volumes of civil engineering journals are examined. Pride of place, in North America, must naturally be given to the annual volumes of Transactions of the American Society of Civil Engineers, now numbering well over the hundred. Since the volumes now contain well over a thousand pages each, they represent a most impressive record of civil engineering practice on this

continent. Despite this, they contain less than a dozen papers which deal directly with engineering geology and these appear in the volumes for 1923, 1936, 1940, 1944, 1945, 1947, 1948, 1951 and 1953, a pattern very similar indeed to that found in the volumes of *ECONOMIC GEOLOGY*. The paper of 1923 was an abridgment by Berkey and Sanborn of their classic account of the geology of the Catskill Water Supply schemes for New York (41). Irving B. Crosby, another well known engineering geologist, contributed in 1940 a paper on dam foundations (48). Subsequent papers have included rather general treatments of geology as applied to highway engineering (61) (105), landslides (57), tunnelling (102) and earthwork (56). An important paper on seismic prospecting along the St. Lawrence River was published in 1944 (84), and in 1951 an interesting discussion by a geologist, A. S. Carey, of the significance of open work gravel (46).

One paper has been left for special mention and comment, this being a careful review of "The Silt Problem" by J. C. Stevens (86). This paper was a record of one of the first comprehensive studies to be made of the problem of silt accumulation in man-made reservoirs, a problem upon which engineering attention came to be focused, as never before, when the Hoover (Boulder) Dam was completed. Stevens' paper was the work of an engineer and approached the problem from an engineering point of view. Inevitably, however, geological considerations came into the review and this feature of civil engineering papers (especially those dealing in any way with foundation problems) has now become so regular that its absence, rather than its presence, will today elicit comment in discussion.

"The Silt Problem" is a paper of 43 pages of small type; it includes a good bibliography. In both these features, it is similar to most geological papers. It differs, however, as do most engineering papers, in that it is accompanied by 38 pages of intensive discussion, discussion which in this case (as in many other cases) is almost as valuable as the paper itself. This feature of professional engineering papers is in such striking contrast to geological publication practice that it seems appropriate to include this brief comment upon it in this review of the meeting place of the two disciplines. The tradition of informed and critical discussion is even more strongly rooted in Europe than in North America. To mention but one example, the papers published by the Institution of Civil Engineers, the oldest and senior of all engineering societies, are distinguished not only by their unusually high standard but by the discussions which they generate. Relatively few papers will be found, in the three hundred volumes which now contain the published records of the Institution, which deal solely with geology, even in its engineering applications. Few descriptive papers, however, are therein to be found (particularly in recent years) in which the geological background is not an integral part of the introductory material, so surely has geology come to take its place in the best practice of civil engineering. If the references which accompany this paper are to be limited to a reasonable and usable number, no attempt can be made to list even a typical selection of these British papers. Two examples only must suffice, the one a general paper of unusual value (74) and the other a more recent paper which, together with

its discussion, provides a singularly interesting record of the close interrelation between geology and soil mechanics (59).

Reference to this particular source of much useful, even if uncoded, information on engineering geology can serve as a useful reminder of the remarkably wide and diverse field from which such information is today to be gathered by the inquiring student. All the references noted up to this point have been taken from regular national publications on engineering or geology. A comparably impressive harvest of printed aids to the study of, and of records of progress in engineering geology can be garnered from more local and specialized publications. Regional geological surveys, for example, such as those of the individual States, have included in their own series of publications many helpful papers in this field of interest. Of significance is the fact that G. E. Ekblaw was able to take as the subject of his Presidential Address to the Illinois State Academy of Science "Twenty-Five Years of Engineering Geology in Illinois" (52). Publication of this stimulating review paper in the records of a regional scientific body may serve as a useful reminder of the valuable information on engineering geology, often of a local character, to be found in such volumes. Examples of such papers are the records published by the Boston Society of Civil Engineers of the test borings put down in the Greater Boston area, records thus cooperatively made available for general public use, records initially obtained for strictly utilitarian purposes but which can provide great assistance in local geological studies (44).

Correspondingly, in the case of the largest civil engineering structures, the records obtained may be so extensive as to warrant publication in individual volumes, by the responsible agency, when circumstances permit. An outstanding example is the volume published by the U. S. Bureau of Reclamation (which, it may be recalled, was once a part of the U. S. Geological Survey) dealing with the engineering geology of the Hoover (Boulder) Dam (96). In a similar manner, the Tennessee Valley Authority has published a series of volumes containing reasonably complete accounts of each of their major dam projects, the associated engineering geological work in every case receiving adequate recognition. (See 90 as an example.)

These and similar volumes come close to being text books and since text books in fields of applied science are so usually, and of necessity, a summary of current and past practices, no extended reference to them need be made in such a review as this. They are, however, essential tools for the practitioner and so must be briefly noticed if this record of the advance of engineering geology during the last half century is to be even reasonably complete. For many years, one text on engineering geology occupied an almost unique position. "Ries and Watson" was for long well and widely known and, although there may be honest differences of opinion as to the effect of the opening chapter (on Crystallography) upon the impressionable minds of engineering students, the fact remains that this book, in its successive editions and also in its abridged form, performed pioneer service to this relatively new field of applied geology (81). There are today an appreciable number of texts available, in English and other languages, their number having more

than doubled since 1939, a year which has already been seen to have been almost a turning point in the development of the subject under review, a year in which incidentally the writer published a volume devoted to a study of the engineering applications of geology (63).

Most of the recent books in English have been, in contrast, introductions to geology for engineers whereas European texts have in general also dealt with the applications of geology in the practice of civil engineering. The publication of new books is a good indication of the healthy state of any branch of science and, at once, a reflection of the current literature in the field. The developments which have already been described are a clear indication of the professional virility of the practitioners of this application of geology. As might be expected, therefore, there is a steadily mounting number of papers dealing with the many and varied aspects of engineering geology now to be found throughout almost the entire coverage of geological and civil engineering periodical literature, in all the main languages of publication. Unlike the case of most other fields of applied geology, publication of such papers in any number is a comparatively recent development. It is therefore yet too early properly to assess the relative value of many of these recent papers. A selection of representative papers will therefore be considered, arranged in relation to major branches of engineering work.

The papers to be mentioned have been selected, in general, from North American publications, one basis for selection being a desire to indicate the wide range of journals in which such papers do occasionally appear. European references, on the other hand, will be limited to textbooks, not only because they will usually be more readily available to American readers than individual European papers, but also because each of the books to be mentioned, by its nature, is itself a guide to the European literature of its specific subject. Two such European volumes which cover the entire field must first be noted, the pioneer work through which the name of Terzaghi first became known (80) and the more recent and more extensive publication of Bendel (36). There is also a periodical of a somewhat itinerant character, dealing with the entire field ("Geologie und Bauwesen"), now happily available from the well known Technische Hochschule of Vienna, edited by Josef Stini (88).

CONSTRUCTION MATERIALS

The use of natural mineral products in civil engineering operations has changed profoundly during the last half century. When ECONOMIC GEOLOGY first appeared, mass concrete was in its infancy and cut stone was still being used for large structures. Today, cut stone is a rarity on an engineering project except for special uses such as lock gate sills. Many older references to the geology of stone and stone quarrying could therefore be noticed but they would have little relevance to modern practice. Suffice it then to mention only that the most useful publications in this field appear to have come from England but the best known of these are now almost twenty years old.

Correspondingly, modern road construction was still a development of the future in 1905. It is indeed somewhat surprising to find that as late as

thirteen years after the start of this journal, Reinecke's paper (5) should be found still dealing with a macadam type of road construction that bears little relation to highway construction of today. As highway engineering has advanced on its phenomenal path of progress, the study of soils, alike in sub-grades and for use as road surfaces, has come to take pride of place in highway material investigations; it will doubtless be discussed fully in the companion paper to this which deals with Soil Mechanics. Bituminous materials and concrete share the task of providing wearing surfaces for main roads, their geological aspects being very little different from those which have to be considered in relation to other uses of concrete, upon which attention may therefore be concentrated.

Despite all the progress that has been made in the study of concrete as an engineering material, there remain many problems in connection with its use. Not a few of these are essentially geological in character, notably in connection with the natural materials used as aggregate. The American Society for Testing Materials held a special meeting on the subject of mineral aggregates in 1948, the published record of which is a singularly comprehensive review (32). Indicative of the literature now available on this one aspect of the general subject is the bibliography published by the Highway Research Board in 1949, extending through 89 pages and listing 467 items (53).

To make a general selection from this extensive and specialized collection of papers is clearly impossible. One detailed problem may be used to illustrate the attention which geology is now receiving in connection with this important engineering material, this being the deleterious reaction which has been found to take place between portland cement and certain natural mineral aggregates. One of the earliest papers on this problem was presented by T. E. Stanton to the American Society of Civil Engineers in 1942, a paper notable for the prolonged discussion which it provoked (85). Other papers on the same subject have been published by the same Society and several by the American Concrete Institute, of which that by Blanks and Meissner was one of the earliest (43), although long preceded by a paper by Loughlin in 1923 which must have been thought at the time to have been "ahead of its time" (66). Geologists have shared the interest of engineers in this subject, papers in the *American Mineralogist* by McConnell and Irwin (76) and in the *Bulletin of the Geological Society of America* by Mielenz (73), in 1945 and 1946 respectively, testifying to the widespread attack being made on the problem.

Papers on the geological aspect of portland and other cements are to be expected, but the non-engineering student of the application of geology to engineering may be surprised to find the attention which engineers have given, in recent years, to replacement materials which can also be used in concrete, notably the pozzolans. An interesting reversion to the *pulvis Puteolanus* of the Romans, the modern use of pozzolanic materials has become so important that another special meeting of the A. S. T. M., was devoted to it, this one in 1951. Again, the "Special Publication" of this Society re-

cording the papers and discussion at the meeting is a most useful and informative review (33).

Ceramic building materials must be briefly mentioned although again there has been not only a great change in their use in civil engineering operations but also a significant reorientation in clay technology with the advent of X-ray diffraction and differential thermal methods of analysis. A vast and highly specialized literature on modern clay investigations has quickly developed. Just as the well known book by Heinrich Reis (82) provided such a useful guide to the earlier literature on clays and clay technology, so will the new volume by Ralph E. Grim on Clay Mineralogy provide an excellent introduction to the clay technology of today, a branch of scientific inquiry which links many practical branches for soil study (60).

Finally, there is available from Europe a comprehensive volume by von Moos and de Quervain which deals generally with rocks as they are used in engineering. Although concentrating upon the mineralogical aspects of rocks, the book serves also as a useful introduction to other modern techniques used in the study of rocks and so forms a useful link between books on geology and those dealing with soil mechanics. It contains also a useful bibliography (100).

TUNNELS AND DAM FOUNDATIONS

The most obvious applications of geology in civil engineering practice are in connection with the construction of tunnels and the founding of dams upon their natural foundation beds. This is clearly reflected by the references which have already been cited and is confirmed by the fact that in each of these branches of engineering geology there is available, again from Europe, a useful volume. It is now over twenty years since Dr. M. Lugeon published his masterly review of Swiss geological experience with dam foundations but it remains a most useful and illuminating record (67). It gives a general overall view of the possible complexities of this apparently simple application of geology in a way that no study of individual papers will readily yield.

It is from Austria that a correspondingly comprehensive treatment of the application of geology to tunnel design and construction has come, its publication in 1950 being a welcome indication of the resumption of European book publication in the field of geology which has so distinguished a record. The book is by Dr. Josef Stini whose interest in engineering geology is well known. It is a very complete résumé of the whole practice of tunnel construction, together with a remarkably comprehensive collection of examples of unusual geological features (87). In view of the unique importance, both in engineering and geology, of the long tunnels through the Alps, reference should be made also to the publication of a new edition of Andrae's volume on these tunnels (34). It is of some interest that the new edition is in French whereas the book was published originally, in 1926, in German. It may almost be classed as a "standard" reference whenever deep tunnelling has to be studied.

So well established has the application of geology in tunnelling now become that rarely does one find an engineering paper describing the construction of a tunnel which does not include some reference, and usually a complete section, dealing with the relevant geology. Accordingly, there are few papers which deal exclusively with tunnel geology in any useful way. One or two have been mentioned. Another particularly helpful example, appearing in one of the less well known technical journals, is Fluhr's account of the geology of the Lincoln tunnel, New York (55).

It must be admitted that the records of geological applications in tunnelling are not as complete as are the records in corresponding fields. This may be because if, as a result of careful preliminary geological study, the construction of a tunnel is completed without difficulty, the full significance of the contribution made by geology may be overlooked. If, on the other hand, difficulties are encountered, then it is only natural that when professional papers are written they should tend to concentrate upon the engineering measures used to overcome the difficulties, geology again taking a place of subsidiary importance. For this reason alone, it is pleasing to be able to include in this review a reference to an excellent relevant commercial publication (79). Produced by the Commercial Shearing and Stamping Company (of Youngstown, Ohio) quite frankly in connection with the sale of their steel tunnel supports, the volume entitled "Rock Tunnelling with Steel Supports" yet includes admirable information on geology in relation to tunnelling, notably a paper by Dr. K. Terzaghi. Tribute should also be paid to the many other commercial publications produced by companies producing equipment and supplies for tunnel work, in which geology is at least recognized (sometimes handsomely so); detailed reference is impossible although practically all recent commercial technical publications related to rock drilling (such as "The Compressed Air Magazine") will be found to be quite useful.

The geology of the natural rock beds upon which a dam has to be founded is so obviously of importance to the safety of the structure that, once the idea of utilizing geology in civil engineering work came to be accepted, the geology of dam foundations began to receive attention in authoritative publications. As early as 1929,* the American Institute of Mining and Metallurgy issued as a special publication a collection of useful papers on various aspects of this branch of engineering geology (31). In the same year, Kirk Bryan's well known paper on the same subject was published by the U. S. Geological Survey (45). Subsequent publications have provided a steadily mounting volume of corroborative evidence, derived from actual construction experience, to support the general principles suggested in these earlier publications.

Reference has already been made to some of these, but a few more may usefully be noted in order to demonstrate the relevant information which is now available. Another of the notable volumes issued by the Tennessee Valley Authority, for example, brings together in concise and convenient form the geological experiences of the professional staff of the Authority,

* For the significance of this date see p. 538.

naturally being related chiefly to dam foundations (89). The U. S. Corps of Engineers has similarly made generally available a vast amount of useful information derived from the far-flung civilian activities of the Corps. One of the most useful of these is the record of the Conference held at Kansas City, Mo., in 1949 on Foundations and Embankment Construction, which may properly be noted here since the proceedings went far beyond the ordinarily recognized boundaries of soil mechanics (97). Another official publication of the Corps of Engineers deals with the serious slides which occurred during the construction of the Fort Peck Dam (98). A paper on this accident was presented to the American Society of Civil Engineers and the keen discussion which it provoked showed clearly the close inter-relation of geology and soil mechanics especially when foundations are involved (72).

This paper followed in the best of engineering traditions by describing what could be called a failure, bringing it, so to speak, to the bar of informed engineering opinion for constructive discussion. All too often this is not done, due frequently to the timidity of owners unaccustomed to the impartiality of professional traditions. There are fortunately, however, a number of such papers available in this and related fields, one of singular interest being another of the local publications to which reference has already been made. Mackin has presented in a bulletin of the University of Washington a geological interpretation of the failure of the Cedar Reservoir in this western state (68).

Finally, it is in connection with dam foundations that the possibility of seismic action assumes an importance which warrants the closest attention. Publications reflect this urgency (see 65 as an example) and bring engineers, geologists and seismologists together into a synthesis which has served usefully to advance the boundaries of scientific inquiry in this vital branch of the earth sciences. The links between engineering and seismology are now so many and so varied that even an outline treatment would be extensive. This passing reference must suffice to direct attention to yet another of what may properly be called branches of engineering geology.

OTHER ENGINEERING WORKS

Although almost all of the works of the civil engineer have some relation to geology, either directly or indirectly, works other than dams and tunnels may not be so obviously dependent upon local geological conditions. The dependence is always there, however, even if unrecognized. The frequent utilization of soil as a bearing medium, rather than bedrock, may possibly have contributed to this situation in view of the relative emphasis placed, at least in North America up to very recent years, upon "hard-rock geology" and the study of Pleistocene deposits. As already noted, engineers have been led into their own studies of soils, the subject of soil mechanics now providing another meeting place for the two disciplines.

It is therefore somewhat difficult to review the progress made in the application of geology to other civil engineering works without encroaching upon the field of soil mechanics. The foundations for buildings, for example,

rarely give rise to any serious problems if on solid rock with the result that there are few useful papers in this part of the field. Fluhr, however, as a part of his studies of the engineering geology of the city of New York, has recorded (with J. J. Murphy) a valuable summary of foundation conditions on the island of Manhattan, excellent detailed records of which are filed conveniently in the Borough offices (75). The corresponding record of local foundation conditions for the city of Boston has already been mentioned (44). An increasing number of cities are following this practice, either through public officials or by private groups, and not only in North America. van Moos, for example, has published a summary for the city of Zurich (101) and (101) and Bendel a similar record for the city of Lausanne (both in Switzerland) (37).

Excavation work, other than that for tunnels, is usually incidental to other civil engineering operations and, in general, gives rise to serious problems again only when soils are involved. There is fortunately available a good guide to the type of problem which large excavation work in rock and soil can create in a paper presented to the American Society of Civil Engineers, as a part of a symposium dealing with the proposed sea-level canal at Panama (42). The fact that the discussion of this paper occupies as many pages as the paper itself is a good indication of the complexity of slope stability problems and a salutary reminder of the frequent inadequacy of purely geological solutions to such problems, solutions which are occasionally suggested when geologists write on the engineering applications of their work.

It is when the works of the engineer interfere with the ordinary processes of nature that some of the most interesting and, at the same time, the most complex problems in engineering geology are created. Shore and beach erosion, for example, is an inevitable part of the cycle of nature. When, because of the value of the land being eroded, the engineer has to interfere with this process, he faces problems of design which are themselves geological and so indeterminate to a degree. Records of previous experience can here be an invaluable guide. In Europe, such records have been accumulated over the centuries, starting in Roman times, but in North America—possibly because the economic value of developed land is of relatively recent origin—there is a conspicuous lack of information until the last decade. The establishment of the Beach Erosion Board, operated under the U. S. Corps of Engineers, has resulted in the appearance of a collection of valuable records of regional studies of erosion, and of papers dealing with some of the fundamentals of this unusual branch of engineering (see 95 for a useful introduction to the publications of the Beach Erosion Board).

So serious has the problem of shore erosion become in some localities that a variety of modern techniques has been applied to its study, including the interpretation of series of aerial photographs. This procedure is now so well accepted, and has proved to be so powerful a tool in so many branches of terrain study that it demands at least brief notice in this review, even though its use as an aid to engineering geology is in no way unique. As an example, and as a good guide to its use in studies of beach erosion, a paper by Dietz may be noted, especially as this appeared in a specialist journal

which is a useful source of information upon photo-interpretation in general (49).

Erosion of shorelines is a natural process; so also is much of the erosion caused by the flow of streams and rivers. The training works developed by engineers for the control of rivers and of their eroding power therefore provide another link between geology and engineering. The long history of the steadily increasing control exercised on the Mississippi River has made available to engineers on this continent a wealth of valuable information, information which includes due reference to the geology of the great valley. Fisk has provided, in his paper to the A. S. C. E., a good general review of the inter-relation of the valley geology and river control (54). Matthes has written a similarly useful review of the progress made in the deliberate formation of cut-offs as a part of the control measures (69). And throughout the years, a steady stream of papers and reports, mainly of a factual character, has issued from the U. S. Corps of Engineers, through the Waterways Experiment Station at Vicksburg for the last quarter of a century in the case of the Mississippi. An early example which has not lost anything of its value since publication is the Vicksburg Report of 1935 on the movement of material in a stream bed (99). It must be emphasized that the Corps of Engineers has issued many reports on rivers other than those dealing with the Mississippi, many of them in the form of House Documents published directly by Congress.

The problems surrounding the movement of solid material in stream beds has long been under study, Gilbert's investigations having achieved almost classic stature (58). The U. S. Geological Survey, as early as 1937, issued a 91-page bibliography on erosion and silt movement and the volume of relevant literature has steadily increased since that time (103). It has been the work of engineers which has introduced a new element into the familiar problem, this being the "artificial" erosion (if it may be so designated) of river beds below dams, when the building of a dam has caused a basic change in the river regime. One of the earliest American papers on this subject was that by Lane, published in 1934 in *Engineering News-Record* (62). (Although the character of this long established periodical has changed materially during recent years, it warrants special mention in this review, since it still continues to be the "news-paper" of civil engineering in North America and so enables those interested to keep in touch with current developments in this field.)

In view of these obviously close associations of engineering work and sedimentation processes, it is not surprising to find frequent engineering references in the several volumes on this interesting geological topic which have appeared in recent years, such as that by Twenhofel (93). Some measure of the increase in engineering interest in, and contributions to the study of sedimentation as a geological process may be gained by a comparison of the engineering contributions to the two well-known symposia on the subject, the one published in 1932 (94) and the other in 1950 (92).

A FINAL NOTE

It will be fitting to bring this review to a close following this quite logical and appropriate reference to the contributions which engineers and engineering have made to a geological compendium. The wheel has indeed turned full circle for engineering geology, at least in the minds of the well informed, to permit of the possibility of scientific value stemming from engineering work being not only acknowledged by geologists but cordially welcomed by them. Too much emphasis must not be placed upon this eminently desirable goal of full and mutual cooperation, but the fact that such cooperation is now no isolated phenomenon, dependent upon close personal associations, may fittingly sound a closing note to this review.

Almost exactly at the half way mark of the half century covered by this review, the work of engineers in building a tunnel through the Lorrettoburg in the ancient German city of Freiburg provided an essential clue to the interpretation of the Rhine Graben, an incident happily recorded in the recently published autobiography of one of the responsible geologists, Hans Cloos (47). In the twenty-five years which have elapsed since that incident, engineering works have been the means of providing geologists with an increasing amount of otherwise unobtainable information which has been put to good scientific use. Today, there are clear indications that engineers themselves, working in close association with geologists, are beginning to make their own contribution to man's knowledge of the earth.

Contributions in *Applied Sedimentation* are not the only indicators of this trend. Reference was made earlier to a paper by Rominger and Rutledge (83) which is equally significant and suggestive. It records the results of the application of some of the regular tests of soil mechanics to samples of the sediments from Lake Agassiz and it shows how the use of these "engineering data" may provide a powerful means of geological correlation. A somewhat similar study of glacial drift along the north shore of Lake Erie differs only in that it was carried out by geologists who acknowledge their indebtedness to the techniques of soil mechanics (50). Current engineering investigations of permafrost in the northern part of this continent, and in Europe, and studies of soil temperature variations in many locations for strictly utilitarian purposes are but two more of the ways in which the work of engineers may itself be expected to contribute to geological knowledge generally, to a steadily increasing degree.

But a start only has been made in this direction. There are still far too many engineers to whom geology is a closed book, its potential contributions to their work unknown and unsuspected. There may still be geologists to whom the idea of applying their scientific knowledge to aid the construction of utilitarian engineering works is an anathema. There are still construction operations conducted not only in disregard of geological principles but even in violation of them. Excavations are still carried out and covered up without the geology which they reveal being appreciated or recorded.

Let all this be admitted. The fact remains that the record presented in this review shows that, despite a very slow start, good progress is being

made in the application of geology to civil engineering work of every major type. This advance is reflected in, and encouraged by the publication of technical papers and books such as those to which this review is but an introduction. Throughout its first fifty years of service, ECONOMIC GEOLOGY has steadily progressed in the publication of its own contributions in this branch of its own special field. There is every indication that this progress will continue, so that the next half century may confidently be expected to witness the publication in its pages of a steadily unfolding and enlarging picture of the joint and mutual efforts of engineers and geologists working together, the engineer using the opportunities provided by his work for enlarging the scientific knowledge of the geologist, as some return for all that the skillful application of geology can mean in assisting him with his task of directing and controlling the great forces in nature for the use and convenience of his fellow men.

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NOTE

It is a measure of the maturity of engineering geology that its first bibliographies are appearing. In *Géotechnique*, vol. 1, p. 40-48, 1948, appears a paper by A. von Moos, "Engineering Geology in Switzerland: a Review of the Literature." The Engineering Geology Division of the Geological Society of America is sponsoring a Selected Reading List on Engineering Geology, under the guidance of S. C. Happ. The writer is indebted to an advance copy of this list for a most useful check on some of his own references.