Geotechnical Site Investigations for Underground Projects: Volume 1

DETAILS

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Geotechnical Site Investigations for Underground Projects

Volume 1
Overview of Practice and Legal Issues, Evaluation of Cases, Conclusions and Recommendations

Subcommittee on Geotechnical Site Investigations
U.S. National Committee on Tunneling Technology
Commission on Engineering and Technical Systems
National Research Council

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Preface

The high costs of underground construction are a major concern of both the general public and the agencies (federal, state, and local) that build or provide funds for a variety of projects. The U.S. National Committee on Tunneling Technology (1974; 1978) has issued recommendations addressing certain aspects of underground construction that contribute to its high risk and high cost. However, underground construction continues to be expensive, with project costs rising rapidly and often significantly exceeding the preconstruction estimate.

At a time when the desirability of constructing underground rather than surface facilities is becoming increasingly apparent, this escalation in costs detracts from the most advantageous use of the subsurface. The emphasis on underground construction for various purposes is growing in proportion to a variety of needs: to conserve surface space as our population grows; to conserve energy required for heating and cooling; to provide refuge from, and mitigate the effects of, both natural and man-made hazards; to permit economical storage of food, water, and strategic goods; to provide for safe disposal of toxic and radioactive wastes; and to make possible subsurface energy-production projects. Improvements in cost-effectiveness, however, will be required to spur the growth of underground construction.

Considering the advantages of using underground space, it is desirable to find ways to improve the economic feasibility of underground construction. One promising avenue is examination of the geotechnical site investigation process for proposed construction sites. Of all large construction efforts, underground projects are among the most complicated. They are particularly sensitive to geotechnical considerations

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U.S. National Committee on Tunneling Technology. 1974. **Better Contracting for Underground Construction.** Washington, D.C.: National Academy of Sciences.

U.S. National Committee on Tunneling Technology. 1978. **Better Management of Major Underground Construction Projects.** Washington, D.C.: National Academy of Sciences.

because the construction environment both affects and responds to the design and construction processes as well as, ultimately, the operation of the completed facility. Therefore, an adequate and reliable determination of subsurface conditions is essential to every phase of the project and, as a consequence, is a significant factor in the final cost.

The basic objective of this study is to discover improvements in practice and procedures that will enable planning and conducting more effective geotechnical site investigation programs. In turn, the results of the study are expected to contribute to a series of wider objectives: advancements in underground construction technology, improvements in controlling or moderating construction costs, and reductions in the incidence and degree of construction hazards or failures.

METHODOLOGY

The approach adopted for this study was to examine completed projects for which the results of the preconstruction site investigation could be related to the construction history. The procedure was designed to permit in-depth study of a large number of these projects, their respective site investigation programs, and the construction problems and unanticipated costs (or lack thereof), as a means of determining the nature and significance of the relationship between investigation programs and project problems and costs.

The method for carrying out this study proved to be quite complex, requiring extensive input by members of the subcommittee and the underground construction community (see Appendixes A, B, and C). In addition to a three-day writing workshop, six meetings of the subcommittee or small working groups were held, and many specific tasks were assigned to individual subcommittee members. The subcommittee was assisted by a senior consultant and two subcontractors, one for engineering data and one for computer programming.

Essentially the study consisted of four main tasks:

- A list of underground projects completed in the last 20 years was developed, from which 100 projects were selected as suitable for case history study.
- A case history data form was developed to permit correlation of the types and extent of the site investigations conducted prior to design and construction, as-built geological conditions, differing site conditions claims, cost overruns, and delays encountered during construction.
- The data therefrom and additional information derived from the personal experiences of subcommittee members were evaluated and conclusions drawn, keeping in mind the rapidly advancing state-of-the-art in design and in construction equipment and methods.
- A computer program was developed to receive and store for future retrieval the pertinent site investigation and construction case history data.

The first meetings were spent outlining the study schedule, compiling a list of projects that appeared most desirable as sources of data, devising a detailed data recording document, and preparing letters of request to be sent to owners and contractors involved with the selected, completed projects. Charles W. Daugherty was engaged as the senior consultant for the project, to directly supervise the effort and coordinate incoming data, the field review, assignments subcontracted to Schnabel Engineering Associates (SEA), and the computer programming and processing undertaken by G. Wayne Clough at Virginia Polytechnic Institute and State University (VPI).

As a first step, the selected project owners were requested to send in a complete set of bidding and construction documents. These documents were then given to SEA, which extracted the bidding data for compilation onto the data form. Once the initial data compilation was accomplished, assignments were made to the consultants, members of the Schnabel staff, and members of the subcommittee to contact and interview owners, designers, and contractors in order to complete the data forms. This was the most difficult and time-consuming task. At the same time, a special working group devised a system of selecting, recording, and collating incoming data into a form suitable for computer programming and for subsequent overall analysis.

The last few meetings of the subcommittee and working groups were devoted to a writing workshop, selecting projects for detailed discussion as case studies, preparing a format for abstracting the case histories, reviewing and interpreting the data, revising the initial draft report prepared at the workshop, and developing conclusions and recommendations.

As the study progressed, it became apparent that although there exist a large number of projects from which to choose, obtaining complete data on any project is extremely difficult. No one source had available all the data on any project, and a surprising amount of information had been lost or thrown away. Also, much of the data was found to be proprietary or was simply not available due to unresolved claims litigation. Due to these constraints, 87 of the original 100 case histories were deemed sufficiently complete to be included in the final compilation of data presented herein. The conclusions drawn, therefore, are based on the predominant data obtained and do not necessarily reflect every case history examined.

DATA COLLECTION AND COMPILATION

The subcommittee's methods of collecting and compiling mined tunnel data are covered in considerable detail in Appendix C. This information is included in the report for two reasons: the data presented are varied, complex, and subject to more than one interpretation; and the approach and methods may be of some interest to researchers contemplating similar studies. Briefly, the collection and compilation process incorporated the following steps:

- Obtaining data packages from the owner; these consisted of contract drawings, specifications, geotechnical reports, bid abstracts or tabulations, and other documents.
- Extracting information for transfer to the basic 15-page data form (compilation to approximately the 40 percent stage).
- Interviewing owners, contractors, and others affiliated with the project for answers to the remaining questions on the data form (compilation to approximately the 90 percent stage).
- Combining the information obtained from the data packages and the interviews to prepare a final version of the data form (compilation to 100 percent).
- Reviewing the final data form for consistency and clarifying any ambiguities through follow-up discussions with individuals who were original sources of information.
- Reducing the 15-page data form to a 2-page abstract of the project.

It should be recognized that the brevity that is necessary in any printed form has the potential to produce distortion, in that a short answer may not explain the shadings or nuances of a particular situation. This was generally compensated for in the 15-page data forms (see Appendix C) by adding explanations in parentheses and footnotes. This form became the basic record of all data collected for each project studied, and provided the information extracted for the data matrixes (provided separately as Plates 1 and 2), case history abstracts (see Volume 2), and computer retrieval system (Volume 2).

The reader should understand that for general knowledge of the 87 projects reported as case histories, a study of the data summary matrixes will suffice for quick correlation. For a more thorough understanding of particular projects, it will be necessary to research the abstracts, which are themselves more general than the original data forms.

Acknowledgments

This study was conducted with the assistance of the underground construction community. Many individuals--owners, designers, contractors, construction managers, engineers, geologists, geotechnical engineers--provided documents and information, expert opinion, suggestions, and constructive criticism. Without their contributions, a study of this complexity would have been impossible. Additionally, other individuals listed in Appendix A participated with the subcommittee in a three-day writing workshop. The owners listed in Appendix B supplied contract drawings, specifications, geotechnical reports, bid abstracts or tabulations, and construction history reports for numerous projects.

The study was supported through the Transportation Systems Center by eight agencies: Defense Nuclear Agency, Department of Energy, Nuclear Regulatory Commission, U.S. Army Corps of Engineers, U.S. Bureau of Mines, U.S. Bureau of Reclamation, U.S. Geological Survey, and Urban Mass Transportation Administration. Their representatives provided encouragement and suggestions throughout the study.

The subcommittee was assisted by two consultants, Charles W. Daugherty and William Pease. Mr. Daugherty served as senior consultant and was responsible for putting into practice the methodology adopted for the study, supervising the work of the engineering and data processing subcontractors, scheduling interviews and assigning interviewers for case projects, reviewing all data forms for consistency and accuracy throughout various stages of completion, managing reduction of the data to abstract form, verifying tabulations of data prepared by the subcommittee, participating in the meetings and writing workshop, and attending to countless details. Mr. Daugherty devoted many long, and often tedious, hours of effort to these responsibilities; his dedication, vigilance, and intense personal interest in every aspect of the study were vital to successful completion. Mr. Pease played an important role in the early stages of the project; during approximately the first year, he assisted the subcommittee in refining the study concept, developing procedures and plans, and initiating contacts with owners and contractors.

Schnabel Engineering Associates (SEA), Bethesda, Maryland, served as the engineering subcontractor for data extraction. Brian W. Beard led the SEA effort with great competence; he was assisted by Thaddeus R. Bergling. Virginia Polytechnic Institute and State University (VPI), at Blacksburg, was the computer programming and processing subcontractor.

G. Wayne Clough directed the work at VPI and designed the computer format for managing the case history data. His combined knowledge of underground construction and computers was a substantial benefit throughout the lengthy process of data collection and compilation.

Several individuals provided special assistance during the course of the study. James S. Redpath and Charles K. Presley contributed their considerable expertises on shafts, each graciously donating time and effort to participate actively in writing sessions conducted by the subcommittee. Ronald E. Smith, of Woodward-Clyde Consultants in Rockville, Maryland, attended to innumerable details and arranged for staff members Douglas T. Detman and Frederick W. Meyer to assist in reviewing and checking the information presented in the data summary matrix. Subcommittee members Don C. Rose and Howard J. Handewith undertook the arduous tasks of designing and compiling the data summary matrix and preparing charts and graphs illustrating various aspects of each project. Another subcommittee member, Edward L. Waddell, was instrumental in obtaining detailed information on the several projects needed to test the suitability of the data form.

The subcommittee expresses its sincere appreciation to all of the contributors, participants and sponsors for their interest in and support of the study project.

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INTRODUCTION

In the construction of recent subsurface projects, particularly transit systems, it has been apparent that costs were often greater than first expected. Although there are a number of reasons for this, including periods of high inflation, one particular phase of the process of design and construction of underground structures has become the target of serious questions. This target is the exploration phase, specifically subsurface geology and site investigations. Essentially, geologic conditions constitute the greatest source of unknowns prior to actual construction of a project. These unknowns usually exist in inverse proportion to the amount, nature, and quality of the geotechnical investigations. Moreover, data indicate that differing site conditions are the alleged basis for many costly construction changes and claims*.

In order to evaluate the relationship between geology and construction costs, the U.S. National Committee on Tunneling Technology formed a special subcommittee to study geotechnical site investigations for underground design and construction. It was decided at the outset that the subcommittee should not prepare a manual on site investigations, because such manuals already exist. Moreover, manuals tend to become increasingly out of date as the state-of-the-art of design and construction progresses. Instead, therefore, a decision was made to collect data from completed projects and have the data examined by a body of experienced engineers, geologists, contractors, designers, owners, and attorneys. The product of the study would then be an accessible repository of pertinent case history data and a statement or written discussion of the subcommittee's interpretation of the case histories.

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*In this report, "claim" is a shorthand expression that may encompass not only an assertion of differing site conditions but also any extra payment made as a result of an unexpected subsurface situation. For example, some owners may settle all subsurface-related overruns as "contract modifications" and, therefore, the word "claims" would not appear in their records. We use the word to cover <u>all</u> geotechnically related requests for extras.

The two volumes resulting from the study are intended for a broad and disparate audience in terms of perspectives, needs, and goals. Therefore, Volume 1 begins with overview chapters presenting the basic rationale and legal considerations for exploration programs. It becomes increasingly specific with chapters discussing particular problems and projects, and then proceeds to evaluation of selected cases and interpretation of case histories. The final chapter reports the conclusions and recommendations, both analytical and judgmental, developed throughout the course of the study. For the convenience of readers desiring additional information, Volume 1 also includes suggested formats for Geotechnical Design Reports, a Selected Bibliography, and a Glossary. Volume 2, supplemented by the data matrixes provided separately as Plates 1 and 2, presents raw data in abstract form for 87 projects reported as case histories and a computer program for managing the data to suit several purposes.

The subcommittee believes that the information presented in these volumes will result in improvements in the planning of site investigations and in the securing of geotechnical data that are specifically needed by a variety of users. These potential users include: owners developing new projects and related cost estimates; designers of new structures; contractors estimating project costs and selecting construction methods and equipment; and equipment manufacturers seeking to produce tools and machines which are more efficient and less costly to operate. The ultimate result should be improvements in the economics, efficiency, and effectiveness of underground construction, thereby benefiting projects for which it is the only alternative as well as those where it may prove an advantageous alternative to surface construction.

EXECUTIVE SUMMARY

The geotechnical site investigation must provide data to foster a safe and economical design; to assist the contractor in analyzing the feasibility, costs, procedures, and equipment for construction; to enable the owner to prepare contract and bid documents that accurately reflect and provide equitable methods for resolution of potential areas of contingent costs (which are a function of the known and unknown geotechnical information and data). The geotechnical site investigation must answer, or assist in answering, the designer's question of the loads for which the structure must be designed; the contractor's questions of what type of ground is to be excavated, how it will behave during construction, what method is suitable to build the structure, and how much it will cost; and the owner's questions of whether the budget is adequate and the schedule can be met.

The ultimate goal of the geotechnical investigation must be an understanding of the behavior of the soil and rock. Elucidating those behavioral characteristics is the essence of the geotechnical investigation; raw data and the identification and classification of materials are not enough. The analysis and recommendations of specialists experienced in the acquisition, interpretation, and presentation of the data are vital to the successful design and construction of underground projects.

The geotechnical site investigation is not an isolated part of the design and construction processes; nor is it only an early part of basic feasibility decision making. Rather, it must and should serve as a continuous resource throughout the design/construct/operation processes. The format and content of the geotechnical site investigation must be oriented toward the owner, designer, and contractor.

Conclusions

- It is in the owner's best interests to conduct an effective and thorough site investigation and then to make a complete disclosure of it to bidders.
- Disclaimers in contract documents are generally ineffective as a matter of law, as well as being inequitable and inexcusable in most circumstances.
- Contracting documents and procedures can provide for resolution of uncertain or unknowable geological processes or conditions before and during construction, rather than afterwards.
- On major projects especially, it is important that (a) the owner employ a multi-disciplined team including engineering geologists, engineers, and a construction specialist to develop subsurface data and evaluate their impact on design and construction; (b) designers and geologists possess a thorough working knowledge of construction methods and equipment so that the proper geotechnical data are secured and design is consistent with construction systems; and (c) contractors employ geologists experienced in underground work to evaluate and interpret the data provided at the time of bidding, thus ensuring that all the information obtained is fully considered in preparing bids.
- Site investigations have to proceed through, but should not always end with, completion of the feasibility/alignment setting/final design programs.
- Procedures for logging, documenting, and preserving samples from boreholes require improvement.
- Geophysical methods can be used to advantage, especially in coordination with boreholes.
- Groundwater and its effects on the subsurface materials merit greater attention in exploration programs.
- Laboratory testing of the subsurface materials generally needs to be increased.
- Exploratory adits and shafts are generally justified only when absolutely essential to obtain critical design data or when a substantial benefit to construction is indicated.
- Maintenance of technical data obtained during design and construction of underground projects often is not pursued by owners or demanded of their consultants and contractors.

Recommendations

- Expenditures for geotechnical site exploration should be increased to an average of 3.0 percent of estimated project cost, for better overall results.
- The level of exploratory borings should be increased to an average of 1.5 linear ft of borehole per route ft of tunnel alignment, for better overall results.
- The owner should make all his geotechnical information available to bidders, while at the same time eliminating disclaimers regarding the accuracy of the data or the interpretations.
- All geologic reports should be incorporated as part of the contract documents.
- Designers of mined tunnels should compile a "Geotechnical Design Report," which should be bound into the specifications and be available for use by bidders, the eventual contractor, and the resident engineer.
- Monitoring of ambient conditions prior to construction should be undertaken to establish a baseline of information for comparison during and after construction.
- Pre-bid conferences and site tours should be conducted to ensure that all bidders have access to the maximum amount of project information.
- Geologic information from preconstruction explorations and as-built tunnel mapping and construction procedures should be compiled in a report detailing project completion.
- Investigation methods and predictions should be improved for three specific conditions: in-situ stress, stand-up time, and groundwater.
- Improved horizontal drilling techniques should be developed that can recover rock core and penetrate long distances without wandering from line and grade.
- Research and development should be conducted to expand the capabilities of geophysical or other remote sensing methods for obtaining geotechnical data between boreholes and from the surface down to depths too great for boreholes.

2.
Geotechnical Site Investigations

Once, an "adequate" tunnel exploration program consisted of a boring at each portal and another boring halfway down the tunnel line. In many cases this was an adequate program because the tunneling design methods were very conservative and the construction methods were easily adapted to a variety of ground conditions. However, in some cases serious problems developed, and ultimately the costs of providing a contingency for every possible situation became excessive.

The development of rock tunnel boring machines in the late 1950s was the precursor of numerous faster, more efficient, and less labor-intensive tunnel construction techniques. A similar development has occurred in tunnel design, bringing, for example, more sophisticated tunnel liner/ground interactive analysis which permits the use of thinner, stronger, and safer lining systems. These developments, however, have not been without their price. As tunnel engineering has become more exact, it has demanded more exact prediction of ground conditions to make the improved techniques work.

In many cases the parties responsible for the exploration of underground excavations--including shafts, tunnels, chambers, and underground mines--have risen to meet the need for better predictions. However, the number of disputes arising from unanticipated adverse effects of ground behavior on a contractor's operations has also risen. It is also true that the development of new tunnel concepts, designs, and construction techniques is continuing and that the demand for accurate data about the ground to be excavated will increase. For example, the safe operation of a proposed underground nuclear-waste storage facility must be predicated on a total understanding of geologic and hydrologic regimes at the site.

Field and laboratory techniques to be used for developing the required site investigation data are not addressed in this chapter. These techniques are described in a number of publications, some of which are listed in the Selected Bibliography that accompanies this report. Those publications provide guidance to the factors that must be considered in underground site investigations, such as the types and methods of exploration, the number of explorations and their locations, and the kinds of tests. Descriptions of specific underground projects and their particular problems are provided in later chapters of this report.

This chapter evaluates the advantages and liabilities associated with site investigations, discusses the use of site investigation data and the basis for providing data to potential users, considers the content of the geotechnical report, and notes the effects of geology on the cost of construction. Understanding the general rationale for geotechnical site investigations is essential to the case history analysis that constitutes the primary thrust of this study. This chapter is intended to set forth an overview of the concept and functions of the site investigation process. The overview, in turn, serves as a link between the data and the conclusions developed from interpretation of the case histories.

ADVANTAGES, RISKS, AND LIABILITIES

A technically sound and thorough geotechnical site investigation program is an essential ingredient in obtaining the lowest fair cost for underground construction. To accomplish that end, the program must not only be optimal in design for the particular conditions at the site, but must also be sensitive to needed refinements in the scope of traditional data, data reporting, and interpretation in order to take full advantage of new cost-reducing construction methods, equipment, and concepts in project design. Along with fairer tunneling cost, other advantages that will result include greater project suitability, longevity, and safety.

The adequacy of a site investigation program cannot be measured by cost alone, because the cost, however large or small, is not always a valid indication of effectiveness. The ultimate goal--which is to determine with reasonable accuracy the nature of subsurface formations and how they will react or behave during tunneling--comes at highly variable costs, depending on the state of prior (or equivalent) tunneling knowledge in the area, as well as on the geologic complexity of the proposed site.

The knowledge and skills necessary to achieve a sound and thorough geotechnical investigation are not possessed by all investigators. Therefore, the user (owner, designer, contractor) of the geotechnical data should be responsible for evaluating the investigator's capability to conduct an effective exploration program, and to know when special skills or additional knowledge may be needed. As a case in point, knowledge of construction methods and equipment is essential to the investigator's capability to plan and manage an effective site investigation. Moreover, such knowledge could be critical where specialized tunneling equipment or methods are being considered.

There will always be significant physical and financial risks associated with tunnel construction. The use of new, specialized equipment and techniques may actually increase those risks. To consistently reduce the risk potential, the emphasis of future geotechnical investigations must be directed toward optimizing the scope of investigation and data reports for each site. Critical attention must be given to the prospective use of new tunneling equipment and techniques, and to the ability of the investigator to provide an exploration program and evaluation suited to the equipment and techniques.

However, it must be recognized that geotechnical investigation for underground structures is not an exact science; not all problem areas can be predicted. Owners must recognize this circumstance and provide a contractual method for defining and clearly allocating the risk and associated costs. Experience has shown that the best way to define and allocate the risk is by establishing a baseline of geotechnical data, interpreting the data using the best possible talent, and presenting the interpretations to all the bidding contractors. If, after exposure in the tunnel, the geotechnical conditions encountered vary materially, then an equitable change in the contract should be recognized, and a cost adjustment should be made.

Establishing these geotechnical and contractual parameters will lead to more realistic cost estimates by both designers and contractors, allow more competitive bidding, and eliminate the need for most contingencies in the event of adverse conditions. The result should be a reduction in the incidence and degree of cost overruns.

PHASING OF GEOTECHNICAL EXPLORATIONS

Site investigation is an iterative process. Early in the first phase of project investigations (during the planning stage, for example) maximum use should be made of existing data, including past local experience, available literature, and field examination of all of the potential sites. The aim is to gather as much information as possible at the lowest cost, since the viability of the project is still unknown. The emphasis should be on defining regional geotechnical aspects and conditions.

If the project is continued, the second phase of the geotechnical investigation should build on the knowledge gained in the previous phase to begin establishing the specific site characteristics. For example, an air photo analysis of the site should be conducted, geologic field mapping accomplished, and a boring plan developed identifying the general characteristics of the soil and/or rock and the geologic structure. Borings are usually widely spaced, and laboratory tests on recovered samples emphasize the basic properties of the materials. Data should be examined as they are produced to evaluate their validity, then plotted to establish the materials through which the project will be excavated. A preliminary design is often developed on the basis of second phase exploration. In this manner, the design engineer can identify those areas for which there may not be sufficiently detailed geotechnical data to permit the design to be developed.

Ideally, prior to proceeding with the third phase of the investigation, the accumulated data should be gathered and thoroughly analyzed by experienced geologists, design engineers, and construction engineers. The primary concern of this interdisciplinary team should be to identify unexplored potential geotechnical problems that could affect the design and/or construction. If the geology is simple, all of the potential problems may have been identified and there will be no need for additional explorations. However, any potential problems should be thoroughly evaluated prior to final design.

Thus, the need for a third phase of explorations depends on whether questionable areas are identified by analysis of the earlier phases of exploration. This phase should be planned carefully. It is often during the third phase that specific features to be encountered by the project are explored, such as fault zones, lithologic contacts, hydrologic conditions, and in-situ stress. The most important element of this phase is input of the design engineer; this phase should provide answers to specific questions regarding the alignment.

Although this third phase normally concludes the preconstruction explorations, in special cases additional explorations may continue if the data required are slated for use by the bidding contractors. For example, it may not be necessary for the design engineer to know specifically the bounds and volume of an aggregate source or muck disposal area to be used on a project. However, those data may be critical to the contractor bidding the job.

One important aspect of the geotechnical investigation that is often overlooked is monitoring of conditions prior to construction. Monitoring establishes a baseline of information for comparison during and after construction. The process can range from visual inspection of existing facilities or structures within a zone of vibration or subsidence to long-term measurement of groundwater levels. Records of specific data can be useful in preventing or settling disputes related to construction conditions or effects, as well as in protecting both owner and contractor from frivolous claims.

USES OF GEOTECHNICAL DATA

The needs for geotechnical data were once relatively unsophisticated, and were keyed primarily to site selection and design. Hence the methods of investigation were simple as well, because construction techniques were readily adaptable to adverse conditions. Current and developing underground construction methods are not so forgiving; they demand greater attention to the collection of geologic information to permit their efficient and economic use as an integral part of modern and future practice. When we find that tunneling costs escalate because of unexpected conditions that geologic studies have overlooked, it becomes clear that we must reevaluate our exploration programs and interpretation techniques so as to improve the detection of adverse conditions, or else be forever plagued by cost overruns.

Site Selection

Geotechnical evaluation should play a more significant role in the siting of an underground structure. In the past, tunnel site selection was often based principally on geographic or solely on engineering considerations; occasionally, portal locations might be changed slightly to minimize adverse geologic conditions. Now, in many instances, geologic considerations together with engineering considerations are entering into the planning and site selection processes. For example, the location of a major interstate highway tunnel may be abandoned and a longer route around a mountain adopted due to the prediction of difficult tunneling conditions, or the elevation of a water transmission tunnel may be changed drastically because of difficult geology at depth.

The cost of excavation is the most significant part of many projects and may be a critical factor, especially if geologic conditions are adverse. Controlling or reducing the cost by improving site selection is highly desirable. In addition to the economic benefits, an appropriate site selection process will provide important contributions toward accomplishing project goals and objectives for the owner, designer, contractor, and ultimately the user.

Design

The traditional approach to data collection is to answer questions or determine the parameters that the designer needs for the project. Prior to beginning final design, the designer should be provided with all data collected, so that the need for and type of supplemental information to be developed are decided according to the designer's specified interests. It behooves geologists and geotechnical engineers to understand how the data they collect and interpret are used. The following is a list of some design uses of geotechnical data:

- Rock/soil classification and rock mass characterization
- Tunnel configuration selection (horseshoe, circular)
- Overbreak prediction (in rock tunnels)
- Wall/face stability analysis (e.g., wedge failures, slaking, squeezing)
- Support system selection and requirements (e.g., loading values)
- Shaft and station location and layout
- Groundwater prediction and control
- Lining requirements (need for and/or type)
- Grouting requirements (e.g., location, materials)
- Subsidence prediction and control
- Portal location, configuration, and stability
- Alignment and invert elevation adjustments
- Operations and maintenance

The traditional approach to geologic interpretation should be constantly updated, modified, and expanded through the use of advanced techniques. This can be accomplished by review of available techniques and by continuing research. Constant attention to the application of developing techniques will lead to cost-effective exploration programs (cost-effective in the sense that the programs should be iterative and able to identify and interpret anticipated underground conditions, rather than to simply produce borehole logs). For example, a study of jointing in a granitic batholith at a tunnel location may show that the two major petrographic facies have different joint orientation maxima because of different cooling conditions (stress history). However, when individual joint orientation diagrams include measurements from both facies, the different maxima are superimposed and effectively disguised. A stress history, indicated in regional studies, should alert the geologist and geotechnical engineer as to the need to determine the values of stress in the rocks by a specific test program. Results can verify or eliminate that concern for design--clearly a cost-effective procedure. Gaps in stratigraphic sequence along a tunnel alignment may cause significant construction problems if they are not discovered in the exploration program. Cost-effective programs would insist that pump-out hydrologic tests be carried to equilibrium, a necessary condition for proper interpretation. Even inspecting different sets of aerial photographs may identify important features that viewing only one set would fail to disclose.

Bidding and Construction

The particular construction methods best suited to the project will normally be selected by each bidder according to the description of the rock/soil character and behavior, hydrologic conditions, and site location provided in the contract documents. Field data as reported from borings (clarified by visual inspection), laboratory and field tests, geophysical surveys, and geologic reports from the project and any neighboring structures have an important status. These data will assist the contractor in identifying the best methods of excavation, choosing the size and type of equipment needed, estimating rates of advance, selecting methods and stages of temporary support systems, calculating anticipated rock overbreak, establishing groundwater control measures, developing the contingencies which should be available for control of fluids or gases, and determining the possible uses of excavated materials. In addition to selection of methods and equipment, the geotechnical data will be important to the contractor in determining the price and contingencies to be added. Hence, geotechnical data are equally important to the owner.

During construction, the contractor should be able to use the geotechnical data and interpretations to predict the limits of each method of temporary support and loading and to anticipate the need for any special equipment. This helps to avoid delays in job progress and to reduce safety problems for the workers and equipment. The methods and procedures selected during the design and bidding stages may then be maintained or revised slightly to meet the conditions as excavation proceeds.

Post-Construction

The geotechnical information obtained prior to and during construction does not cease to be useful on completion of the project; rather, it should serve several purposes that benefit the owner. Unquestionably, such data are important to effective and efficient operations, as well as maintenance, of the completed facility. The availability of this data assumes even greater importance considering the increasing emphasis on repair, rehabilitation, and expansion of existing projects. In addition, the owner should be able to incorporate the information into an evaluation of the project, particularly exploration, design, contracting, and construction management techniques.

REPORTS OF GEOTECHNICAL DATA

Geotechnical Report

A geotechnical report should be produced prior to construction; specifically, it should be compiled prior to or during design, and should be included in the contract documents. The designer should be able to use the report in developing the design concept; the contractor should be able to use it as a basis for bidding. The report should include collected data, interpretations of data, predictions of ground behavior, and recommendations to the designer. (Note: Construction contract documents should include a statement to those other than the designer that, if recommendations or other information in the report conflict with the designer's statements in the specifications, then the specification's statements shall take precedence.)

The geotechnical report should contain data collected in the field, test results from the laboratory, information on regional geology, and historical data regarding previous and existing work in the area. Such data should include only observations and facts, and should be clearly distinguished from the interpretation portion of the report. The degree of confidence in or opinions as to the validity of the individual extrapolations and interpretations should be made explicit.

Field data include borehole logs, geologic surface maps, geophysical data, water levels in wells, occurrences of springs, gases, chemicals, etc. Field observations should note all unusual features or conditions that the field personnel believe may have some effect on design or construction. Laboratory data should include standard properties of the tunneling medium (rock or soil) and petrographic analyses, including representative silica content in rock. Tests should be made that help both the designer and contractor. The report should include an overview of regional geology, including tectonic history, and regional seismic conditions. This information will be useful in estimating the potential for residual or in-situ stress. Historical data should include maps and other information on previously constructed tunnels, mines, shafts, highway cuts, quarries, and earlier geological/engineering investigations in the area. Researchers of the above data should strive to seek both the standard "textbook" information and any other special data that may assist the designer or contractor.

The geotechnical report should include interpretation of in-situ tests, evaluation of in-situ stress conditions, and geological profiles. Estimates of stand-up time and support requirements as calculated by established empirical methods should also be included, along with a listing of possible trouble zones. The anticipated groundwater inflow zones and rates should be discussed, and the basis for their selection provided. The level of confidence should be presented candidly, with recognition by the owners, designers, and contractors that this is among the most difficult aspects of subsurface investigations.

Recommendations in the geotechnical report should cover estimated loadings, applicable geotechnical properties, sizes of the zones of influence, and suggested tunneling methods. Such recommendations should be considered from a geotechnical point of view, yet be aimed at the designer. It is the designer's responsibility to study these recommendations and other information in the geotechnical report, combine it with information from all other aspects of the job, and then make appropriate recommendations or statements in the specifications for the benefit of bidding contractors.

Geotechnical Design Report*

Depending on the philosophy of the owner and subsurface specialist, the geotechnical report (also known as a geologic report or subsurface investigation report) might or might not make predictions about construction conditions and might or might not be made available to contractors. However, whatever the label, all such reports have one thing in common: Due to the time frame of their compilation they may include recommendations on geotechnical design parameters, but they cannot present the "last word," as the designer may modify the preliminary design concept and try other alternatives for final design after the reports have been completed.

In underground construction, the potential for critical situations is high and changes are costly. The contractor has a right to know precisely how the anticipated subsurface conditions affected the final design and what the owner and/or designer thought about subsurface effects on, and behavior during, construction. The designer is in a unique position to provide explanations by writing a report that develops parallel with the design. Such a report might be called a "Geotechnical Design Report." It should be based on (without repeating verbatim) the information contained in earlier geotechnical reports compiled by the investigator responsible for the exploration program. The report should be bound into the contract specifications, thereby making it easily available and confirming its status as an actual contract document.

Appendix D presents general outlines of both rock and earth tunnel geotechnical design reports used by the Washington Metropolitan Area Transit Authority. These reports have served well for at least nine years, proving to be more suitable than previous means of apprising bidders of the geotechnical ramifications for design and construction. Although the outlines would have to be modified for different geographical

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*"Geotechnical Design Report" is terminology adopted from the Washington Metropolitan Area Transit Authority and is WMATA's shortened version of their formal title, "Geotechnical Basis of Design and Construction Specifications." Many agencies issue this type of document under a different title, such as "Design Rationale Report."

areas and tunnel types, the basic idea is worthy of adoption. In addition, it may be useful to expand the content of such reports by including one of the systems for rock classification, such as the Rock Structure Rating or RSR concept (Wickham and Tiedemann, 1974), the Rock Mass Rating or RMR system (Bieniawski, 1974), the Q-system (Barton et al., 1977), or the Terzaghi classification (Proctor and White, 1968). However, these systems are not suited to use by inexperienced personnel; to ensure proper application, the purposes and limitations of these systems must be thoroughly understood.

Geotechnical "As-Built" Report

Geologic information obtained during preconstruction explorations and recorded in the log of job progress, including as-built geotechnical tunnel mapping, should be compiled in a project completion report. Ideally, for consistency the constructed project should be mapped by the same group that conducted the original explorations. As an absolute minimum, the geotechnical conditions encountered should be reviewed by the original exploration group to see how and where their techniques and interpretations could be improved.

Knowledge of actual construction conditions can assist in identifying the cause of and proper method of correcting problems encountered during the operational life of a tunnel. The existence and availability of an as-built report would prove invaluable if another project were to be constructed in the same area. Such a report would also be useful in transferring experience to projects in other areas with similar geotechnical considerations. For example, as-built geotechnical data are required as part of safety analysis reports submitted in accordance with licensing procedures for nuclear power facilities.

Barton, N., R. Lien, and J. Lunde. 1977. "Estimation of Support Requirements for Underground Excavation," **Design Methods in Rock Mechanics** (Proceedings of the 16th U.S. Symposium on Rock Mechanics). New York, New York: American Society of Civil Engineers.

Bieniawski, Z.T. 1974. "Geomechanics Classification of Rock Masses and its Application in Tunneling," **Advances in Rock Mechanics, Volume IIA** (Proceedings, 3rd Congress of the International Society for Rock Mechanics). Washington, D.C.: National Academy of Sciences.

Proctor, R.V., and T.L. White, eds. 1968. "Introduction to Tunnel Geology," **Rock Tunneling with Steel Supports** (revised edition). Youngstown, Ohio: Commercial Shearing and Stamping Company.

Wickham, G.E., and H.R. Tiedemann. 1974. **Ground Support Prediction Model (RSR Concept)** (Report for the U.S. Bureau of Mines under Contract HO 220075, ARPA Program). Springfield, Virginia: National Technical Information Service.

EFFECT OF GEOLOGIC FACTORS ON COSTS

In the bidding phase of a project, a method of accomplishing the work is determined by the contractor. Specific manpower, equipment, and material requirements are calculated and then costed. Finally, margin or fee (with contingencies) is added to produce a total cost to the owner. The adopted methods will be either conservative, middle-of-the-road, or optimistic, depending on the perceived importance of various factors. For an underground project the factors are usually manifold. They may include such considerations as availability and quality of labor, project location, geology, how well the project lends itself to the application of various types of equipment, the general rate of economic inflation, and the reputation of the owner. Contingency may or may not be an element of estimated cost, depending on how many uncertainties exist. As the project moves into the execution phase, costs will vary with conditions encountered. In this respect, geologic conditions are the most significant factor for every underground project.

With regard to geology, during the bidding or estimating phase the contractor either has no knowledge (the rare case), or a little, or a reasonable amount. When nothing is known, the chosen method often will be conservative and costs will be high; there will be a number of unknowns, so a contingency will probably be added, increasing costs even more. Moreover, it is likely that no innovative equipment will be assumed in the bid preparation, because high capital costs would result with no reasonably assured benefit. Production will usually be set low because there is no reason to set it high, and support requirements will be literally guessed. All in all, the owner will be penalized greatly for failure to provide an adequate rationale for bidding. Bids may be significantly higher than the estimate; in the extreme, bids may not be submitted at all.

When only a little of the geology is known and conditions look difficult, the owner will still pay, for the same reasons noted above. Similarly, when a little is known and conditions look favorable, the owner might well reap benefits in the form of lower bids but pay later in claims. However, most competent contractors will tend to discount the importance of what is known when it is based on a small sampling. The result will be reflected in the bids in the form of reduced production, non-innovative equipment, conservative support, and probably contingency as well.

The pre-bid condition to strive for is that in which a reasonable amount of raw data and interpretation is available. Then (and only then) does the contractor have a rational basis for preparing a bid and the owner have a rational basis for evaluating bids. If the data look promising, then the owner will properly reap the benefits of good, solid, competitive bids with almost no contingency (assuming the existence of a changed conditions clause). If the data look unfavorable, then the cost will properly reflect the conditions; bids will be neither overly pessimistic nor overly optimistic.

Just as knowledge of predicted geologic conditions is reflected in cost during the bidding stage, so too are geologic facts reflected in actual costs during construction of the project. As the geologic facts come in, they may present welcome or unwelcome surprises, or no surprises, when compared to pre-bid predictions. Unwelcome surprises are the most usual. Cases of excessive water inflow, heavily fractured ground, and too-hard ground are commonplace in the industry.

It is worth noting a few of the generally overlooked effects of such surprises. First, management and supervisory personnel may have been selected for a project because particular conditions were assumed to exist. In the underground business there are "good ground" specialists and "bad ground" specialists, and it is usually wise to keep them within their respective areas of expertise. A manager accustomed to working slowly in the face of adverse ground conditions may slow down needlessly in favorable conditions because of training and habit. Conversely, a "good ground" manager usually is able to proceed much more rapidly, and this can be disastrous when in adverse ground. Thus, in the case of unexpected ground conditions--particularly adverse conditions--a mismatch of management talent may be expensive for the owner or the contractor.

Second, if favorable conditions are assumed at bid time, highly specialized, high-production equipment might well be selected. By its nature, specialized equipment requires a particular type of ground in order to be effective. The lack thereof will usually render the equipment ineffective, many times to the point of complete change. Thus, the cost of the initial equipment selection is lost, and the additional cost of new equipment has to be incurred. Again, either the owner or contractor bears the expense.

Last, schedule slippage resulting from adverse and unexpected geologic conditions delays commencement of service life of the structure. This will cost the public, as well as the owner and contractor.

As it is, even welcome geologic surprises can be of no value. For example, in the case of equipment, the use of a tunnel boring machine (TBM) may have been eliminated based on assumed adverse geology. When the ground is found to be much better than expected 25 percent of the way through the job, it is usually too late to secure a TBM. Someone pays the penalty of lost opportunity in terms of production rates.

Sometimes no affordable amount of investigation will forecast adverse conditions. However, only when an adequate amount of pre-bid geologic investigation is undertaken are surprises usually eliminated. In most instances, no surprises are the only "good" surprises.

3.
Legal Aspects of Site Investigations

Unexpected subsurface conditions are the primary cause of disputes and litigation arising from contracts for underground construction. The risk of unknown subsurface conditions is a primary concern of contractors in the pricing of such contracts. Given these pragmatic circumstances, the contractual or legal allocation of these risks is vitally important. More important, effective preconstruction contract investigation of the geotechnical conditions is important not only to allocate risks but also to reduce them.

Lacking specific contract terms, owner representations, or unusual circumstances, in a fixed-price contract the risk of difficult and disruptive subsurface conditions is imposed on the construction contractor. In most recent circumstances involving major underground construction, however, a preconstruction geotechnical investigation of the subsurface materials is conducted, and some or all of the resulting information becomes a part of the contractual transaction. In these situations, the contractual documents frequently change the risk allocation through specific "Differing Site Conditions" or "Changed Conditions" clauses, explicit or implied warranties, or other terms which tend to place the burden of these risks on the owner.

Where the contract terms are not explicit, the owner may unknowingly assume the risk by failing to disclose or misrepresenting factual information yielded by the preconstruction geotechnical investigation. In either event, the investigation becomes a central element in the definition and allocation of risk when difficult subsurface conditions are encountered during performance of the work.

There are strong economic and engineering reasons, presented elsewhere in this report, for reducing uncertainty as to subsurface risks and the allocation of those risks. Preconstruction contract uncertainty as to risk and post-contract uncertainty as to risk allocation are ready catalysts for disputes and litigation. In part, this explains the policy adopted in the federal sector. In the nonfederal sector and certainly in the commercial world, a range of choices remains open to owners as to the contract terms.

RISK ALLOCATION POLICY OF DIFFERING SITE CONDITIONS CLAUSES

It is the policy of most government agencies and many owners to bear the majority of risk due to subsurface uncertainties (and thus avoid significant contingencies in pricing by contractors) through specific terms known as either Differing Site Conditions or Changed Conditions clauses.

These relatively standard clauses permit the contractor an adjustment in contract price where the subsurface conditions actually encountered in performance differ materially from those "indicated by the contract documents." Although the drawings and specifications themselves may provide indications within the meaning of these clauses, the "indications" most directly in point lie in the data yielded by the owner's prior geotechnical investigation.

The standard clauses also provide for an adjustment where the subsurface conditions differ materially from those "ordinarily encountered" and "generally recognized as inhering" in the contract work. This less precise standard is more difficult for the contractor to meet and has a less direct relationship to the prior geotechnical investigation. Nevertheless, disclosure of the pre-bid investigation may protect the government or owner by broadening the concept of what is ordinarily encountered in the type of work called for by the contract.

This basic contracting policy is made mandatory in the Federal Acquisition Regulations (FAR), and thus is operative as a matter of law. It is perhaps best expressed in the landmark decision of the United States Court of Claims in <u>Foster Construction, et al. v. United States</u>, 435 F.2d 873, 887 (Ct. Cl. 1970):

> Whenever dependable information on the subsurface is unavailable, bidders will make their own borings or, more likely, include in their bids a contingency element to cover the risk. Either alternative inflates the costs to the Government. The Government therefore often makes such borings and provides them for the use of the bidders, as part of a contract containing the standard changed conditions clause.
>
> Bidders are thereby given information on which they may rely in making their bids, and are at the same time promised an equitable adjustment under the changed conditions clause, if subsurface conditions turn out to be materially different than those indicated in the logs. The two elements work together; the presence of the changed conditions clause works to reassure bidder[s] that they may confidently rely on the logs and need not include a contingency element in their bids. Reliance is affirmatively desired by the Government, for if bidders feel they cannot rely, they will revert to the practice of increasing their bids.
>
> The purpose of the changed conditions clause is thus to take at least some of the gamble on subsurface conditions out of bidding. Bidders need not weigh the cost and ease of making their own borings against the

> risk of encountering an adverse subsurface, and they need not consider how large a contingency should be added to the bid to cover the risk. They will have no windfalls and no disasters. The Government benefits from more accurate bidding, without inflation for risks which may not eventuate. It pays for difficult subsurface work only when it is encountered and was not indicated in the logs.
>
> All this is long-standing, deliberately adopted procurement policy, expressed in the standard mandatory changed conditions clause and enforced by the courts and the administrative authorities on many occasions.

The U.S. National Committee on Tunneling Technology (1974) has recommended this policy for adoption by all owners. Obviously, the effectiveness of the Differing Site Conditions clause in achieving the purposes outlined in <u>Foster Construction</u> is heavily dependent on the adequacy of the prior geotechnical subsurface investigation.

OWNER'S DUTY TO CONDUCT INVESTIGATIONS

The owner has no legal duty to make a geotechnical investigation of the subsurface. In the absence of such an investigation, the burden falls on the contractor to make his own investigation or to assume the risks of the lack of an investigation.

However, owners usually do conduct investigations. This customary practice is dictated by the owner's need for geotechnical data for design purposes. Such information has obvious relevance to construction as well as design, and is subject to a duty of disclosure, as described in the paragraphs that follow. Moreover, the failure to conduct an investigation and to provide its results to the contractor would substantially defeat the purpose of the Differing Site Conditions clause by denying the contractor indications of the subsurface conditions through the contract documents.

OWNER'S DUTY TO DISCLOSE

Where the owner has, through a specific preconstruction geotechnical investigation related to the project or other relevant prior experience, obtained information indicating the nature of the subsurface conditions,

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U.S. National Committee on Tunneling Technology. 1974. pp. 20-21 in **Better Contracting for Underground Construction**. Washington, D.C.: National Academy of Sciences.

the question arises whether there is a duty of disclosure to bidders. Unfortunately, this question is frequently addressed in the post-construction litigation circumstance, rather than at the time of contract formulation.

The rule, based on the common-law concepts of misrepresentation and fraudulent inducements, is that the owner has an obligation to disclose material information. The rule is clear where the owner is a public entity. The judicial precedents arising from commercial construction are not as well developed, but the legal principles have obvious applications.

If a public entity (federal, state, or local) possesses information about geotechnical conditions which it knows the contractor does not possess or have access to, and which is material to the cost or method of performance, then the public entity must disclose such information. [*See generally* Annotation, Duty of Public Authority to Disclose Information Affecting Cost or Feasibility of Performing Contract, 86 A.L.R. 3d 182, SS 8-12.] A government agency may not knowingly allow a contractor to follow a "ruinous course" by withholding superior knowledge. [See *Helene Curtis Indus., Inc. v. United States*, 312 F.2d 774 (1963).] This rule was recently stated by a federal board of contract appeals as follows:

> The government has an implied duty to help, rather than hinder, performance and is obligated to provide contractors with special knowledge in its possession which might aid the contractor in formulating his cost estimates and his bid.
>
> The courts and boards have taken an increasingly stringent attitude toward the withholding of such information. [*Flores Drilling*, AGBCA No. 82-204-3, 83-1 BCA, 16,200 at 80,486 (1982).]

This duty to disclose covers all material information about the site that the government possesses, even if not discovered specifically in preparation of the bid materials. [See *Raymond International, Inc. v. Baltimore County*, 412 A.2d 1296 (Md. Ct. Spec. App.) *cert. denied*, 449 U.S. 1013 (1980).] Failure to disclose can constitute misrepresentation when some, but not all, facts are disclosed. If the owner chooses to reveal any information from test borings, it has an obligation to disclose the information "fully and accurately." [See *Robert E. Lee & Co., Inc. v. Comm'n of Public Works*, 149 S.E.2d 55, 58-59 (S.C. 1966).] In *Michigan Wisconsin Pipeline Co. v. Williams-McWilliams Co.*, 551 F.2d 945, 951-53 (5th Cir. 1977), the Corps of Engineers' failure to represent a subsurface pipeline in bid drawings, contrary to its usual practice, constituted an affirmative representation that the pipeline was not there, rather than a mere omission.

However, the owner does not have a duty to disclose judgments and conclusions which it draws from factual data, as opposed to the raw factual information itself. [See *S&M Constructors v. City of Columbus*, 70 Ohio St. 2d 69, 434 N.E.2d 1349 (1982).]

Nor is the government liable for nondisclosure of information to which the contractor has equal access through its own experience, through cursory inspection, or through industry data. In *Morrison-Knudsen Co.*

v. Alaska, 519 P.2d 834 (Alaska 1974), 86 A.L.R. 3d 164, the state was not required to disclose information it received from other bidders since this same information obviously could have been acquired by the present bidder if it had made a reasonable effort. Furthermore, a contractor will be held responsible for making reasonable inferences about site conditions from information that the owner does disclose. [See Luke Construction Co., ASBCA No. 24889, 81-1 BCA, 15,023 (1981).]

Where the owner discloses data as a part of the contract documents, the contractor is entitled to rely on such data. Indeed, the contractor cannot ignore the data. Where the owner discloses information without incorporating it as a contractual matter, the rights of the parties become less clear. Where the contract documents only call attention to the information, it is arguable that the contractor cannot ignore it and, thus, as a matter of fairness, that he is entitled to rely on it. [See United Contractors v. United States, 177 Ct. Cl. 151, 368 F.2d 585 (1966): "neglect" not to consider data; "illogical" to fault contractor for having relied on data.] On the other hand, it has been held that the contractor is not bound by and not entitled to rely on this type of information. [See Dravo Corp., ENG BCA No. 3901, 80-2 BCA (14,757), and American Structures, Inc., ENG BCA No. 3408, 75-1 BCA (11,283).] Where the owner provides information by a process not explicitly or implicitly related to the contract, the contractor does not appear to be entitled to rely on the data as a "contract indication" within the meaning of the Differing Site Conditions clause. At the same time, he may not be required to rely on it.

LIABILITY FOR SUBSURFACE INFORMATION DISCLOSED BY OWNER

Where the contract contains a Differing Site Conditions clause, the owner assumes the risk of material differences between the actual conditions and those indicated by the geotechnical information which the owner discloses. Indeed, as noted previously, this is one of the basic mechanisms for fulfilling the risk allocation policy underlying the Differing Site Conditions clause. [See generally Annotation, Effect of "Changed Conditions" Clauses in Public Contracts, 85 A.L.R. 2d 211, 217-20.]

A more difficult question arises where the owner furnishes information which turns out to be materially discrepant from the actual conditions, but there is no Differing Site Conditions clause. The contractor, not having obtained an explicit contractual promise that the price would be equitably adjusted in such event, is forced to depend on more general and speculative legal theories. There is no implied right to extra compensation as a result of changed conditions. Thus, the contractor discovering geotechnical subsurface conditions that materially differ from data furnished by the owner must rely on allegations of implied warranty and fraud or misrepresentation on the part of the owner. [See Mobile Turnkey Housing, Inc. v. Ceafco, Inc., 321 So. 2d 186, 191 (Ala. 1975).] Such theories are speculative because they depend on detailed facts of the particular transaction. Contractor recovery on such theories, and the attendant thrusting of the risk on the owner, is nonetheless possible.

DISCLAIMERS OF SUBSURFACE INVESTIGATION DATA

It is a common practice of owners to disclaim, in varying ways, responsibility for the geotechnical information which they provide to bidders prior to contract. This is a practice that has been criticized (see, for example, **Better Contracting for Underground Construction**, above). It is widely assumed by contractors that such disclaimers are ineffective as a matter of law: in most (but not all) circumstances, they are.

Where there is a Differing Site Conditions clause, the disclaimer is usually seen as being in conflict with the clause's language allocating the risk based on what is "indicated by the contract documents." Where the Differing Site Conditions clause is required by law, as in federal government construction, conflict between the mandatory clause and the disclaimer has been resolved in favor of the mandatory clause, and the disclaimers are adjudged ineffective. Thus, a general disclaimer of the government's responsibility for geotechnical subsurface information is not enforceable to overcome a Differing Site Conditions clause in a federal contract. [See, for example, Foster Construction, et al. v. United States, above.]

Even in the context of public procurement, however, the owner may be able to avoid responsibility for the results of the geotechnical site investigation in certain circumstances. For example, the disclaimer may be so specific that it will be deemed not materially inconsistent with the standard clause. Or, in nonfederal procurement, the standard Differing Site Conditions clause may not be required by law or general policy and thus the disclaimer may be acceptable even where there is a Differing Site Conditions clause in the contract. [See McHugh Construction Co., ENG BCA No. 4600, 82-1 BCA, 15,682 at 77,530 (1982).]

Obviously, a disclaimer does not confront the same hurdles when there is no Differing Site Conditions clause in the contract. In such circumstances, the exculpatory language will be upheld, unless the contractor can show fraud or bad faith. [See S&M Constructors v. City of Columbus, 70 Ohio St. 69, 434 N.E.2d 1349 (1982).] Thus, courts will seek a way to prevent an owner from making a representation, explicit or implied, but disclaiming responsibility for it. Exculpatory clauses are not per se invalid; they can be enforced when the court finds that the owner did not make a representation that was later found to be materially incorrect. [See Miami-Dade Water and Sewer Auth. v. Inman, Inc., 402 So. 2d 1277, 1278 n.2 (Fla. App. 1981).]

In sum, the use of disclaimers introduces an ambiguity as to risk allocation which tends to promote expensive disputes and litigation. In most circumstances, their use is considered to be inequitable and unenforceable.

4.

Geologic Problems and Consequences in Construction

In the most general and simplified sense, the major problem during construction is "ground" (i.e. rock or soil) behaving differently than anticipated. The nature of the ground has significantly different implications for hand mining, drill-and-blast, and shield and/or tunnel boring machine operations. Equally important to the basic identification of "hard" or "soft" ground is the determination of the zone of transition from "hard" to "soft" or vice versa, as well as the potential for both extremes to exist in the same place, i.e. "mixed face." In identifying characteristics important for construction, consideration must also be given to factors that can affect ground behavior, such as the presence of water or the construction process itself.

Classifications and predictions based on inaccurate or insufficient information can easily result in a partial to total difference between expected and encountered conditions. Especially from the construction point of view, the geotechnical site investigation should provide the basis for anticipating in a reliable and specific way the behavior of the ground.

Using the abbreviated list of "problems encountered" appearing in the project abstracts (Volume 2), Table 4.1 was prepared to identify some of the construction consequences. The conditions noted became construction problems, or escalated to greater and more troublesome importance, mostly because the contractor was not prepared for them.

This circumstance raises the question of whether these problems could have been avoided, or their impacts minimized, with a more thorough or different preconstruction geotechnical site investigation. It is possible that some problems could have been eliminated by making soil or rock borings at closer spacings, and/or by utilizing geophysical seismic surveys to gain information, or by applying other investigative techniques. Still, it is essential to note that not all of the problems could have been anticipated by additional investigation.

TABLE 4.1 Effect of Geologic Conditions on Construction

Major Problem Areas	Consequences/Requirements
Ground behavior	
blocky or slabby	excavation method, special equipment, immediate support
running	time loss, special method of control
flowing	time loss, special method of control
squeezing	immediate support
swelling	intermediate support
spalling (bursts)	progress shut-down, safety
stand-up time	immediate support
rock loads	extra steel, long-term support
in-situ stress	cave-ins, time loss, special procedures
Groundwater	
operating nuisance	inefficiencies, slow-downs, extra pumping
large quantity	progress shut-down, handling procedures
high pressure	progress shut-down, handling procedures
corrosive or insoluble salts	damage to excavation equipment, temporary supports, concrete
Existing conditions	
noxious wastes	safety, inefficiencies, time loss
utilities and structures	progress shut-down
obstructions (boulders, piles, concrete, etc.)	progress shut-down, equipment damage
gas	safety, progress shut-down
mixed face	special procedures, techniques, equipment
Mechanical problems in rock	
hard, abrasive	progress rate, tool life
mucking	downtime
soft bottom	progress rate, grade and alignment, special design
face fall-out	progress shut-down
gripper instability (TBMs)	progress rate, alignment
roof slabbing	cave-ins, progress shut-down, additional support
drilling and blasting necessary for line drilling	progress rate
pressure binding	progress shut-down, immediate support
Soft-ground problems in machine mining	
surface subsidence	damage at surface
face instability	progress slow- or shut-down, immediate support or compaction grouting
water inflow (significant)	progress slow- or shut-down
material hardness	machine binding, progress shut-down
steering	time loss, grade and alignment correction
high rock or intrusions	machine damage, blasting, excavation method
Compressed air	
blowouts	safety, progress shut-down
fire	safety, progress shut-down
other safety restrictions	productivity
contingency dewatering and grouting	progress rate, safety

MAJOR PROBLEMS FOR CONSTRUCTION

The project case histories developed during this study probed the nature of the geotechnical site investigations and subsequent conditions encountered during construction. The discussion that follows centers on the conditions and resulting problems which, based on the case histories and on the experience of the subcommittee, have been shown to be important either because of frequency of occurrence or magnitude of impact.

Stand-Up Time

A stand-up time problem occurs when the ground (rock or soft earth) will not support itself for a time sufficient to accommodate the construction. Stand-up time affects five major areas of concern: type of ground support; equipment selection (e.g., shield); manpower requirements; production and schedule; and cost.

Construction Impact

Stand-up time, particularly in blocky ground, dictates in large part whether ground support systems such as rock bolts and mesh are required, or other systems such as steel supports or shotcrete. In extreme cases, a combined system of rock bolts, steel sets, and shotcrete may be required.

Stand-up time, or lack thereof, dictates when ground support must be installed, which in turn may have a pronounced effect on rate of progress and costs. The type and timing of ground support installation will affect progress either directly or indirectly. In the case of the requirements to install ground support immediately after blasting or mechanical excavation, the work involved will be "in the cycle," and thus will directly extend the round time and the schedule. The work involved is "unit" production and no short-cuts can be taken.

The method and timing of ground support installation will dictate the type of equipment required to accomplish the work effectively. The equipment selected must permit rapid and proper installation of the support elements and yet not be so cumbersome as to delay other operations that must be accomplished in the tunnel. Highly specialized equipment that is capable of installing only a specific ground support system will be totally costed against the project in question, as opposed to partial amortization.

As stand-up time strongly influences the type of ground support system to be used--and consequently the equipment necessary to install it--manpower will also be affected. Some types of ground support systems are more labor intensive than others. For example, a simple system of widely spaced rock bolts will no doubt require much less labor than a very elaborate system of rock bolts, steel sets, and shotcrete.

Because significant elements of the construction plan are dictated by the assessment of stand-up time, an unanticipated adverse condition is disruptive--and sometimes dramatically so. Delayed performance, implementation of a different ground support plan, and increased cost are the results.

Data (and Interpretations) Available Prior to Bid

There is no known specific laboratory or field test that can be conducted prior to construction that will accurately predict stand-up time. However, the use of RQD and core recovery, close inspection of the joint conditions, consideration of depth of overburden, and observed behavior of the ground in road cuts, outcrops, or any existing projects adjacent to the one contemplated, may provide valuable insight into the stand-up time to be expected. To be useful, collections of observed behavior need to be accurately and completely described. For example, the amount of induced ground vibration caused by blasting should be addressed, along with factors which relate to slaking or squeezing, such as circulating air, water saturation, and water flow.

In cohesive soil, stand-up time is fairly well indicated by the relation of overburden load to undrained shear strength (sometimes called the "overburden factor"). If the overburden factor is 5 or 6, the soil is only marginally stable. However, if the factor is 3 or 4, stand-up time will be good.

In cohesionless soil, the stand-up time is less easy to quantify. The acting water pressure, gradation, and relative density are important. For example, marginal stability and short stand-up time with a tendency to running conditions would be indicated by a cohesionless soil having a uniformity coefficient of less than 3, with less than 5 percent fines (passing a No. 200 sieve) and a relative density of less than 40 to 50 percent.

To be constructive in terms of potential stand-up time problems, the geotechnical investigation should include as relevant information surveys of adjacent projects or projects in similar ground conditions, in addition to site specific data. Complete and accurate logging of rock core and description of joint spacing, orientation, and roughness would be useful.

In-Situ Stresses

In-situ stresses in rock are induced by geologic loading, such as may have occurred during glaciation, or by tectonic activity. The excavation of a tunnel opening creates a change in stress condition that can result in excess movement and, possibly, local failures of the rock surface created by the tunnel.

Construction Impact

The ratio of the in-situ stress to the strength of the rock determines the scope and degree of deformation or failure that can occur. If the stress is much higher than the strength, local to large failures can occur; in the extreme, the rock may behave in a plastic manner, or in a way similar to soil.

The excavation cycle can be adversely affected by local failure, such as fall-out at the heading, popping or squeezing rock, and other movements of rock that directly interfere with the excavation process and necessitate the installation of special supports. Support through rock reinforcement (e.g., rock bolts and spiles or sets) increases the excavation cycle time. The selected equipment may then be inappropriate.

Data (and Interpretations) Available Prior to Bid

The geotechnical site investigation must be structured toward identification of zones of high stress, especially in known areas of high preload or tectonic activity. Overcoring and/or hydraulic fracturing at greater depths are methods useful for investigating the in-situ stresses.

Swelling and Squeezing Ground

Swelling occurs when the ground expands in volume by absorbing or adsorbing water and then tends to move into an available opening or to exert pressure. Squeezing occurs when weak material (generally clayey) behaves plastically under the weight of overlying ground and slowly advances inward without perceptible volume increase. Either condition can be serious, mainly affecting support requirements and excavation equipment, particularly shields.

Construction Impact

Steel sets and lagging can become distorted and out-of-shape with appreciable swelling or squeezing pressures. Distortion may be great enough to preclude the placement of permanent support, such as concrete lining.

Excavation can be affected if swelling or squeezing ground impedes equipment. In (admittedly) the most dramatic case, the skin of a shield may seize due to friction that cannot be overcome by the hydraulic thrust system. Also, a heaving bottom can ruin tramming equipment and mucking procedures by inducing severe shock loads.

Data (and Interpretations) Available Prior to Bid

The geotechnical investigation should include analyses both for clay minerals indicative of swelling (i.e., montmorillonite) and for wet conditions that could induce physical swelling. The boring program should be structured to provide appropriate samples for laboratory tests and analyses.

Groundwater

A groundwater problem is the presence in higher volumes than predicted--or worse, the unanticipated presence--of water during tunneling. The presence and movement of water strongly influences ground behavior, creates a requirement for handling, and affects labor and equipment productivity, and thus cost.

Construction Impact

In the case of rock, as water moves throughout the medium, particularly in areas having fault and gouge zones, the water may carry loosened particles of material into the excavated opening. As this material migrates out of the host medium, voids are created and the matrix becomes loosened, in turn causing instability in the rock mass.

Water can change physical properties of the ground such as cohesion, plasticity, and tendency to swell. In the case of soft ground, water under pressure (even low pressure) may bring smaller particles with it as it moves into the opening, thus creating voids. As these voids are created, the ground will move inward, often resulting in subsidence above or adjacent to the excavation. Subsidence in soft-ground excavations may be particularly critical in urban areas because of the potential for damage to adjacent structures.

Water also creates requirements for handling. The primary handling necessitates the use of collecting pumps, conveyance lines, and in many cases a centralized pumping system. The installation and maintenance of this primary handling system may adversely affect production and schedule. Moreover, a secondary handling system may be required to satisfy environmental concerns. Features of a secondary system may include elaborate settling basins and chemical treatment equipment. In addition, effluent testing is a likely requirement.

The presence of groundwater raises problems with respect to labor and equipment productivity. In the case of labor-intensive operations that are to be accomplished in a wet environment, human effectiveness will be reduced by these less-than-optimal conditions. This reduction of effectiveness translates directly into production losses. However, less labor-intensive operations are also subject to the effects of water. For instance, when excavated material must be trammed over long distances, abrasion of rotating parts occurs as the equipment travels through rock slurry covering the floor of the tunnel. In addition, saline water can be detrimental to mechanical equipment because of its corrosive effects on electrical components. TBMs are particularly susceptible to corrosion; however, the problem usually occurs only when a project is located under a saltwater body.

Problems and resulting costs are magnified when the groundwater volumes and pressure are not anticipated. The result is that the primary and secondary handling systems, ground support systems, excavation equipment, and general method of attack are usually inadequate. This impedes production and increases costs.

Data (and Interpretations) Available Prior to Bid

Pump tests to determine groundwater levels and behavior should be performed, because groundwater will often be the key element in the contractor's work plans. Multiple piezometers to measure perched water tables should be installed and monitored over a considerable period of time. These measurements will enable the contractor to evaluate methods of handling excess groundwater.

In a fractured rock medium, pump tests are often advantageous. In the case of soft ground, chemical analyses and testing for effects of exposure to air should be performed, in addition to standard pumping tests taken to equilibrium and drawdown studies.

For rock, there are no highly reliable groundwater prediction mechanisms which can be used and still maintain cost-effective construction. Nevertheless, a statement concerning estimated volumes and pressures, based on engineering judgments, should be presented. Particular attention should be given to the jointing system and its degree of openness. Finally, data from any adjacent projects should be canvassed carefully for pertinent information. (Note: A variety of techniques exist that can be combined for reliability, but the cost is usually far beyond the resources of general underground construction.)

Existing Structures

Existing surface and underground structures can be sensitive to the construction operations of dewatering, excavation, and support as well as to blasting and equipment vibration. If construction operations are undertaken without adequate forewarning or preparation, these structures can be damaged. In addition, performance of the contract may be disrupted while emergency protection measures are instituted.

Construction Impact

In earth tunnels, if the soils are compressible, dewatering can cause subsidence and damage to adjacent surface structures. To correct these problems requires underpinning of structures, recharging, continuous sheeting or slurry wall, or combinations of these construction procedures. Depending on the permeability and gradation of the soil, compaction grouting may also be used.

Settlements caused by "loss of ground" at the tunnel face and supported perimeter, as well as elastic yielding into the excavated space, may be the determining factors in selecting the methods of excavation and support, as well as the support plans for structures within the area of influence.

Data (and Interpretations) Available Prior to Bid

Data relevant to the presence and physical condition of existing structures should be obtained and provided. Site investigation methods and laboratory tests should be planned to provide clear information and conclusions regarding (a) the behavior of the water table and (b) the compressibility, permeability and gradation (important in recharge and grouting considerations), density, and strength of the soil. Preconstruction monitoring of area elevations and detailed inspection of preexisting structure distress is desirable. In a rock profile where drill-and-blast procedures are applicable and sensitive structures exist at the site or nearby, preconstruction blast/vibration/noise/sensitivity measurements should be made for comparison with later construction effects and for use in establishing a public relations program.

Gases

Gases encountered underground can be noxious, toxic, and hazardous, posing significant problems in construction. If unanticipated, such gases can obviously be dangerous; if anticipated and planned for, the danger may be reduced or eliminated.

Construction Impact

When gas is encountered, its properties as well as its chemical and physical reactions to moisture, air (chemical constituents), high temperature, pressure, etc., must be evaluated. The gas and/or its products must be studied for effect on personnel, corrosive action on material and equipment, and potential for explosion. In addition, the potential for release of gas from groundwater should be investigated.

The tunneling equipment may have to be "spark-proofed" if explosive gases are contemplated. A special ventilation and absorption system may have to be installed for noxious and corrosive gases. Personnel may need training in the detection and handling of unexpected gases, and safety equipment may have to be specified or issued. Moreover, the entire excavation procedure may have to be controlled by strict mining standards.

Data (and Interpretations) Available Prior to Bid
Adjacent soil and rock should be evaluated as potential sources of explosive gases and other noxious or corrosive gases. Chemical testing should be conducted according to strict standards, especially in suspected problem areas. Groundwater samples must be checked as a source of gas as well as for reaction with gas. All exploratory boreholes should be checked for the presence of gas, and it may be advisable to install special probes within some boreholes to permit recurring checks of gas type, concentration, and pressure.

Rock Hardness and Strength*

Problems can occur when the rock to be excavated is (a) harder and more difficult to penetrate than anticipated, or (b) less competent than anticipated. Information about rock hardness and strength is important, and may be critical, to the success of the tunneling operation.

Construction Impact
Rock hardness and strength affect drill or cutter penetration rates and equipment wear. At least to some degree, strength affects stand-up time. The contractor's excavation method, equipment selection, labor estimates, and round-cycle times are based on the preconstruction assessment of rock hardness and strength. Inadequate information on these factors introduces risks which may lead to undesirable contingency pricing or to later disputes. Construction will be significantly affected when rock hardness and strength turn out to be materially different from those anticipated. A revised excavation approach and changes in equipment are required, leading to delays and attendant cost increases.

The adequacy of available information on these parameters affects the bidder's ability to determine the competency of the rock to be self-supporting. For TBM operations it is important in determining advance rates, cutter costs, and types of cutters to use; for drill-and-blast operations it affects round cycle time and costs of labor and equipment.

Data (and Interpretations) Available Prior to Bid
In any one type of rock formation the strengths may vary by several thousand psi, or even tens of thousands of psi. Hence, although unconfined compressive strength provides excellent data overall with respect

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In this report the term "rock strength" generally refers to the unconfined compressive strength of intact rock cores.

to a single sample of rock, it has been found that a minimum of 50 to 60 samples per lithologic unit at tunnel depth are needed to obtain a good statistical average or range of strength for making judgments as to equipment and methods of excavation.

For example, compressive strength has been used for at least 28 years by a major machine manufacturer to predict TBM performance. Within a given rock type, compressive strength is useful (although perhaps not definitive) for predicting TBM progress. When the rock cutter's normal force load exceeds the compressive strength of the intact rock, TBM performance is good.

There is no agreed test for abrasiveness, but the percentage of minerals with Mohs hardness of 5.5 or greater is commonly reviewed to estimate cutter wear. Silica (quartz) is among the most abrasive minerals. Percentage by volume of silica in rocks is best determined by thin sections, but in practice an approximation based on standard petrology textbooks is often used. Indications are that, at present, an insufficient number of silicate content determinations are being made of the material to be excavated (e.g., granite and sandstone). Knowledge of silica content permits more realistic estimates of the abrasion to which excavation equipment will be subjected.

The subsurface exploration program, therefore, should be set up to obtain a level of information that enables the bidder to make reasonable assumptions in regard to strength and silica content, thereby reducing uncertainties and lowering project costs.

Deviations in Rock or Soil Elevation

When bed rock is unexpectedly found to protrude to a point within the excavation limits of an underground opening, or when soft ground intrudes into a rock tunnel, it is usually a serious problem. The adverse effects of high rock in a soft-ground tunnel will vary in degree depending on the extent of the rock, on the elevation of the top of rock, and also on whether or not what results is a mixed hard-rock/soft-rock face. For a mixed-face tunnel from inception, the height or top of rock above the invert will affect both the top heading and bench operations.

Construction Impact

In the case where the rock is higher than expected, the top heading or the steel support will not have the proper configuration to fit the tunnel and will have to be modified. Also, the excavation and mucking equipment may well prove to be too large for efficient use. Conversely, in the bench operation the drilling equipment may have booms which are too high to accommodate vertical drilling. Thus, a change to horizontal drilling may be required. Because the volume of material to be moved will be larger than anticipated, the original muckers may be too small.

In a situation where the rock is lower than expected, the top heading steel will be "too short" and will require expensive splice welding. If the top-of-rock variance is large enough, multiple top drifting may be required. In a case of lower top of rock, however, the bench operation may escape without major adverse impact.

In the case of a full-face soft ground tunnel from inception, a rock intrusion, particularly if continuous over any distance, may be disastrous. The shield will have been designed to excavate soft ground, not rock. Blasting will be required and the shield skin, doors, and hydraulics may be subject to critical damage because blast-proofing may not have been incorporated in the design of the shield. Additionally, the excavating tool, or "digger," may be too light to excavate even loosened rock on a sustained basis. In the extreme case of high rock, the shield may have to be abandoned, necessitating a top heading and bench operation.

The scheduling impact of a change in construction method may be great because it will have been unexpected; support steel and other top heading excavation equipment will not be readily available. A similar problem will exist with regard to equipment needed for the benching operation.

Data (and Interpretations) Available Prior to Bid

Core boring is the most reliable indicator of top of rock and of the weathered transition zone between top of rock and overlying soil. However, uncertainty will persist for the area between borings because that area is unexplored; only inferences can be drawn from borings. Seismic surveys may yield more continuous data, although the quality of those data is inferior to that gained by coring.

Both core borings and seismic data should be obtained for use in locating the top of rock. In the case where rock is thought to be close to an otherwise full-face soft-ground tunnel, or where soft-ground is thought to be close to an otherwise full-face rock tunnel, extra data should be collected in order to rule out the (potentially disastrous) possibility of a significant intrusion.

Compressed Air

Compressed-air techniques are confined mainly to earth tunnels driven through pervious, water-bearing soils or driven under or adjacent to bodies of water. In shallow tunnels, such as those frequently found in or near urban centers, excessive water inflow is generally the primary concern, with face instability being an exacerbating factor. The use of compressed air to combat face instability alone is more often encountered in tunnels at great depth or in very weak soils. Compressed air may be the most reliable or only feasible construction technique for completing a length of tunnel in certain soils below the water table, especially when water inflow or face instability, or both, are expected to be severe.

Construction Impact

Compressed-air techniques are expensive and can impose risks to construction and to personnel that are not encountered otherwise. Therefore, serious effort should be devoted to finding an alternative alignment. If that process fails, the second most desirable approach is for the owner to undertake a sufficiently detailed investigation program to permit dictating procedures. If compressed air is not specified, then the low bidder may be the one who is gambling on success with a less conservative (hence, less expensive) technique. That type of risk-taking can have serious consequences; failure of the construction method will shut down and delay not only the particular tunnel section involved but also (usually) the entire system. The third approach is to select the alignment according to a comprehensive subsurface exploration, within the siting constraints for the project.

The decision to use compressed air is not one to be made lightly; although the technique overcomes some potentially serious construction problems, it introduces unique problems of its own. Any compressed-air operation requires the mobilization of expensive equipment in the form of compressors and air locks. Personnel costs rise because workers must be medically certified for fitness to work in the environment, and medical personnel must be available to handle emergencies. In addition, operational complications and slow-downs are introduced, the most obvious being that personnel, equipment, and muck must all use air locks to enter or exit the compressed-air working environment.

At moderate levels of pressure (generally 12 psig or less), the penalty for compressed-air tunneling is not significant in comparison with more conventional methods. For example, compressor size and capacity are relatively modest and working shifts are shortened only slightly. With increasing pressure, compressor expenses mount, but the largest cost increase is caused by shortening shifts to protect worker health. When working shifts are limited to one-half or one-third the length of the usual eight hours, several crews may be required to perform work normally accomplished by one. Moreover, increasing pressures require additional time for gradual compression and decompression to protect against the bends. Thus, the contractor is paying full salary to personnel who must spend hours of the shift in relatively unproductive work while confined to the air locks.

In addition to inconvenience and expense, compressed-air tunneling is subject to unique and self-induced hazards, especially at higher pressures. For example, the sudden loss of air (i.e., a blow-out) through an anomaly such as unexpectedly thin overburden can result in crippling decompression or extensive flooding. Fire is also a major concern, because a blaze that would be minor in free air can be a conflagration in a compressed-air environment. This consideration requires cautious construction procedures, eliminating the use of many common materials such as wood lagging for initial support. Certainly it should severely limit the use of compressed air in gassy ground where explosions are already a potential hazard.

Data (and Interpretations) Available Prior to Bid

In evaluating the feasibility of using compressed air, it is essential to determine the density and shear strength of the soil, the grain size distribution, the cohesion, and the hydrostatic and overburden pressures. Applied air pressure must be given careful analysis because it affects the safety of crews, adjacent structures, and equipment.

Groundwater levels, flow rates, soil classifications, and soil properties (particularly density and permeability) are data that must be determined to arrive at a decision about the need for compressed air to control hydraulic pressure and water inflow. Hydrostatic pressure, porosity, and shear strength must be well defined in order to permit a reasonable analysis of required air pressure, and thus of production and cost.

When compressed air is being contemplated for a project, consideration should be given to offsetting the exploratory borings from the tunnel alignment to minimize piercing of the tunnel opening. Special care should always be exercised in sealing exploratory borings in soil and rock.

Geologic and hydrologic investigations may reveal that the proposed tunnel will encounter a poorly graded gravel, rock, or old timbers as well as high head and low shear strength, etc. If so, the use of compressed-air methods could be severely restricted or inappropriate. As an alternative in such cases, pipe jacking or preconstructed tubes sunk in place in pre-excavated underwater trenches may be solutions.

COST CONSEQUENCES

An important consideration in devising an exploration program is the need to correlate the actual investigations to the problem areas of construction, as well as to provide the basis for design assumptions and engineering cost estimates. The investigation data and interpretations should be available to the designers during the design stage, as well as to the bidders who need answers for the problem areas, or an opinion, or a statement that "we do not know." The design assumptions and criteria for temporary structures should be clearly stated, with explanations and qualifications included. Possible or alternative solutions to problems identified as a result of the investigations should be detailed in the contract documents, with provisions for approval of procedures and payment (which should be accomplished in a prompt and ongoing manner during prosecution of the contract). In addition, if the data are presented with "unknowns," an equitable solution should be offered in the contract documents for the possible costs due to lack of information. The equitable solution should be a clear statement of the assumed expected behavior of the soil and/or rock with regard to the anticipated construction. Thus, bids can be appropriately prepared as a function of production estimates based on a common anticipation of support criteria, soil/rock behavior, and acceptance of risk by owner and contractor.

Common to all of the problem areas identified in Table 1 at the beginning of this chapter is the fact that had they been identified prior to construction, the disruption of construction caused by the unexpected would have been eliminated. If disruptions do not occur, the nonproductive cost of delays and inefficiencies can be avoided.

Performance of effective geotechnical investigations can minimize these costs by giving both designers and contractors a better understanding of the conditions to be encountered. If problem areas have been detected and the possible consequences recognized at an early stage in the design/construct process, all necessary design and construction activities can be geared to overcome them. In a sense, then, they are no longer "problem" areas. The cost of overcoming these conditions will have been included in the project budget, rather than appearing later as cost overruns, magnified in amount by disruption costs and, too often, litigation costs as well.

However, subsurface investigation is something less than an exact science, and not all problems can be predicted. Therefore, provision should be made for clear definition and allocation of risk and associated cost. Establishing a baseline of information and assumptions concerning subsurface conditions will benefit both owner and contractor. The owner will receive a reliable cost estimate from the designer, and the contractor can be accorded appropriate adjustments in the contract and price for conditions varying materially from those assumed.

5.
Special Purpose Projects

In recent years there has been an increase in the number of underground projects carried out for special purposes that were previously less common. Case histories of such projects as underwater taps, steep inclines, and deep underground chambers are so few and the data so limited that they were not collected for this study; by the same token, limited data were obtained for shafts. However, the geotechnical factors are equally important to site selection, design, and construction of these projects.

Construction methods have been changing in recent years, and there is now a distinct trend to mechanizing the excavation process. The use of mechanized excavators requires data that may not have been needed for older excavation processes. Mechanized construction requires a large capital investment by a contractor, and delays become costly. Thus, avoiding delays by means of a site investigation can easily recoup the cost of the investigation.

It must be recognized that the specific parameters to be investigated vary with both site and use. It must also be recognized that a project comprises several phases--site selection, facility design, construction, and operation and maintenance--and appropriate data should be collected and analyzed to support the requirements of each of the individual phases.

DEEP UNDERGROUND CHAMBERS AND SHAFTS

These two categories are jointly discussed for two reasons. The first is that most underground chambers, as later defined, require some type of shaft for access to them; the second is that (as just noted) very little of the case history data obtained by the subcommittee deals with either deep shafts or deep underground chambers, despite vigorous efforts to obtain such data. Consequently, most of the conclusions and recommendations are extrapolations from data obtained on shallower excavations, tempered by the personal knowledge of the subcommittee members.

In general it may be stated that the geological, geotechnical, and hydrological information that can be obtained with existing techniques in the course of siting a deep underground chamber will be sufficient for the supporting shafts. However, that information must be used properly to achieve effective design, appropriate bidding, and successful construction of the supporting shafts.

Deep Underground Chambers

Deep underground projects that require large chambers usually serve one or more of the following purposes: to extract a resource, to store a resource, to dispose of waste, to house equipment, or to protect against hazards. Whether the principal use for the excavation is civil, military, or commercial, there will be a requirement to optimize its location in light of the intended use and required performance. Site selection is controlled by the required performance and use, with limited latitude available to the user for other considerations.

Factors in Site Selection

Chambers excavated for resource recovery are sited on the basis of exploration that has defined the dimensions of the resource body and the hazards and exigencies associated with extraction. Chambers excavated for resource storage or waste disposal are sited, insofar as possible, to maximize their ability to provide containment and isolation and to avoid or minimize conditions adverse to safe performance. Chambers for protection are usually sited according to the nature of the threat and what is to be protected.

Waste disposal in particular has required the development, still evolving at present, of a closely constrained siting process. This process favors explicit delineation of disqualifying conditions, adverse conditions, and favorable conditions, each of which is defined in terms of the user's ability to demonstrate the likelihood of safe performance as mandated by regulatory agencies. A waste-disposal chamber must meet the containment and isolation stipulations during both its operational (i.e., filling) and functional (i.e., disposal) lifetimes. Given the long-term toxicity of many of the wastes produced by our society, the ability to site, design, and construct facilities that must perform safely for many generations poses a significant challenge.

Chambers excavated to house equipment derive their site selection criteria from the operational conditions. Some chambers must withstand vibration alone; some, vibration and heat; others, vibration and moisture.

Uniform (predictable) rock bodies and groundwater systems, long-term tectonic stability, and a benign geochemical environment are important considerations for all storage cavities. In all three categories, the disqualifying criteria must be specified prior to exploration activities so that the drilling and logging activities may be planned properly. Exploration activities must also provide information required for design and construction, allowing input to updated designs which incorporate realistic cost and schedule estimates.

Site-Specific Considerations

After choice of a site, for which the controlling criteria should be influenced by geotechnical data, the specific considerations that must be addressed in a chamber for resource recovery are similar to those for shafts (see next section). The exploration phase for a storage chamber is somewhat different.

For a storage chamber, the information acquired must confirm the use of a volume of rock-surrounded space for containment; yet the exploration activities to obtain that information must not significantly reduce that containment capability. Storage caverns must not encounter faults, breccia pipes, clastic dikes, or karst features that can permit the transmission of contained material within or near their confines. Consequently, the exploratory drilling program for a storage chamber must thoroughly evaluate the candidate site(s) without creating migration pathways that cannot be properly sealed. The lithology of the rock mass surrounding a storage cavern must be compatible with the material to be stored. The geochemistry of the host rock must be such that the rock does not interact adversely with the material to be stored under the conditions of storage. The strength of the host rock must be sufficient to withstand the maximum potential adverse conditions. Such adverse conditions include the potential maximum stresses caused by seismic activity, thermal load, hydrogeologic differential, in-situ stresses, and stress differential. As a part of the geologic site investigation, all of these conditions must be evaluated through careful laboratory and in-situ tests prior to actual emplacement. Depending on the depth and geologic complexity of the proposed facility, an exploratory shaft and test chamber may be the only practical method of obtaining the quality of in-situ data needed for final design.

Storage chambers for a single-phase, nontoxic material that generates no heat require relatively simple preliminary test programs.

Chambers for the emplacement of equipment involve similar site-specific considerations as those that apply to sinking shafts. These chambers may also serve as underground civil or military structures and, as a result, their design and support measures tend to be conservative compared to those used solely in mining practice. This is because the chambers are intended for both continuous and "permanent" use rather than the more limited periods of use customary in mining.

Geology and Construction

The methods of construction for an underground chamber must be chosen so as to yield a functional product while being compatible with the material properties of the host rock. Depending on the material to be excavated, a chamber can be mined either by conventional drill-and-blast methods or by mechanical mining, or both. The excavation can proceed in either an axial or radial direction, or in stages in which the two directions interchange or alternate. Because of the large size and shape of most chambers, excavation usually proceeds from the top down in several stages. For the purpose of economy, the handling of broken or fragmented material should be minimized. Both drill-and-blast and mechanical methods of mining should take care not to produce a combination of natural and induced fractures yielding unstable roof conditions in the host rock. Blasting operations must be strictly evaluated to ensure that structural integrity and isolation capability are not adversely affected.

Shafts

Shafts may be either vertical or inclined from the vertical. The degree of inclination is, by definition, generally steeper than 45 degrees from the horizontal. (Slopes of less than 45 degrees define the "steep incline," discussed in the next section.) Cross sections may be rectangular or circular, or variations thereof; the vertical length is great compared to the cross-sectional dimension. Shafts may be lined with a variety of materials or left unlined in highly competent ground.

Shafts may be constructed for access or egress, material hoisting or lowering, ventilation, mucking, or water conveyance. Many shafts fulfill a combination of several purposes; design is governed by projected end use(s) and geotechnical considerations.

Factors in Site Selection

In most cases, geotechnical factors dictate the location of an underground facility such as a nuclear-waste repository or a powerhouse. However, shaft site may be prescribed by the position of such an accompanying underground facility, rather than from an optimum geotechnical standpoint. Nevertheless, every attempt should be made to site the shaft so as to reduce the impact of undesirable geotechnical features, within the constraints imposed by the location of the accompanying facility.

As noted in the previous section, the voluminous data essential to proper siting of a large underground chamber (or repository complex) are generally adequate for appropriate shaft design and construction, if properly used. In cases where the shaft location is essentially predetermined by the accompanying facility, there may be no low-cost approach. For example, the data may reveal the presence of a number of obstructions to low-cost shaft sinking and may dictate approaches such as blind shaft drilling or raise boring (vs "conventional" sinking). However, the geologic, hydrologic, and geotechnical data should be defined well enough so that unknowns are minimized, if not totally avoided.

When the end use of a shaft is not specific to a chamber or repository, as in the case of resource recovery, the required design and construction data are less likely to be available. In those cases the trial site selection should be made after an analysis of geotechnical, environmental, legal, economic, and utility factors. Where geotechnical knowledge is lacking, surface mapping, seismic surveys, and data from boreholes should be employed to pinpoint the trial site.

Site-Specific Considerations

At the point that verification of the trial site commences, the geotechnical (including hydrologic) considerations become paramount. The scope of the geotechnical investigation is determined by several factors:

- End use of the shaft
- Type(s) of geology anticipated
- Water condition(s) anticipated
- Nature and depth of overburden
- Shaft depth
- Sinking method (and alternatives) under consideration
- Information available from other nearby boreholes or openings.

In order of priority, the most important data to be obtained pertain to the water conditions that will be encountered, and to the characteristics of the soil and rock that the shaft must penetrate. This is because water, or water in combination with unconsolidated ground, has historically presented the greatest impediment to conventional shaft sinking. The shaft exploration should include, as a minimum, a cored borehole or holes near the shaft site or within its area,, because geologic and hydrologic conditions may vary considerably over a short distance, even in flat-lying sedimentary formations or strata.

With nonhorizontal geologic features, and especially in areas where potentially near-vertical features occur, more than a vertical hole is required. It is also important to drill an angled hole or holes (depending on depth) in an effort to detect unfavorable features such as parallel faults, dikes, or shear zones.

Deep shaft exploratory holes drilled without directional techniques may eventually deviate from the vertical enough to make their information ambiguous, and hence less relevant. Although this may not be a problem in uncomplicated geologic settings, it is recommended that straight-hole drilling techniques be used where difficult conditions are expected and specific data are required.

In all cases, the core should be carefully logged and a geologic section prepared. (Electric logging may be helpful in preparing useful information.) Tests to be conducted are tailored to the specific situation, but some of the more essential determinations are the following:

- Potential water inflow and groutability (or freezability) at various elevations, when drilling fluid is lost or water is suspected.
- Swelling ground, when the potential is expected.
- Standing water level (which should be recorded).
- Chemical composition and pH of the water.
- Orientation of the exploratory holes.
- Rock and water temperatures, in deep shafts or in shafts where freezing or extra ventilation may be required (or where personnel may subsequently have to work).

When the foregoing have been determined (and their importance cannot be overemphasized), it may appear time- and cost-effective to change the approach from a "conventionally" sunk (drill-and-blast) shaft to a drilled shaft or shafts. One example of an environment where a drilled shaft presents an attractive alternative is in the more heavily water-bearing areas of the Grants (New Mexico) uranium belt.

Geology and Construction

A thorough and systematic geologic/hydrologic/geotechnical investigation is fundamental to time- and cost-effective shaft construction. Proper exploration will predefine the problems and will permit an engineer's estimate to accurately reflect the actual construction costs.

The determinations noted above will confirm whether certain alternatives may work. Additional tests should then be made, depending on the desired or anticipated construction methods. For example, if dewatering or depressurization is contemplated, additional borehole(s) and related tests should be carried out. The relationship between appropriate geological information and selection of shaft construction methods is amplified in the following discussion of freezing, grouting, ventilation, mechanical mining, and drilling.

When freezing is contemplated, groundwater velocity and direction of movement and in-situ water content are important; laboratory tests to determine the properties of the frozen material should be conducted. Gas content and the potential weakening of a freeze wall by dissolution of gas should be addressed. In cases where freezing is to be used, ultrasonic readings should be taken between freeze holes before ground freezing starts, in order to provide a comparative background for later ultrasonic testing to detect windows in the freeze wall.

When grouting is anticipated, laboratory tests should be conducted to determine the ground characteristics related to grout-curtain design and grout selection, such as grain size and distribution, porosity, and permeability. The feasibility of pregrouting should also be studied. Pregrouting is becoming increasingly important as down-the-hole mining machines become more commonly employed in shaft sinking, considering the relatively greater capital cost involved in stand-by time.

In exploration for deep shafts, temperature measurements are essential to the selection of mining method, need for and design of freeze walls, and design of ventilation during both construction and operation.

When mining by mechanical methods is considered, physical specimens should be tested to provide data for estimating rates of penetration and cutter costs. Ground having a potential for balling of the bit or cutters should be characterized carefully in cases where surface-based or down-the-hole boring is contemplated.

When drilling in the form of raise bore and slash or full face is employed, the angles of formation intersection and behavior of the core holes will indicate potential accuracy problems. For drilling, the ability to control potential sloughing or wall failure with mud becomes important. The ability to provide appropriate control should be addressed at the geotechnical investigation stage in consultation with mud experts. The potential for sloughing in a raise bore should be assessed geologically, because the raise bore and slash method can be very adversely affected by sloughing.

The potential for high in-situ stress in the rock should be evaluated for effect on construction methods. In extreme cases, prestressing and benching may be indicated instead of full-face blasting.

STEEP INCLINES

A steep incline is a tunnel or shaft constructed on a slope; roughly defined, it includes angles between about 15 degrees and 45 degrees from the horizontal. The method of construction is almost always drill-and-blast, although the use of TBMs is becoming more common. The actual construction can proceed either upward ("positive angle") or downward ("negative angle"). Incline is an acceptable term for both, but downward construction is sometimes referred to as a decline.

As is true for shaft sinking by drill-and-blast, inclines are among the most difficult, hazardous, and costly underground excavations. Geological conditions will affect water handling, roof support, and the shape of the opening. Particular attention to roof conditions is required, as inclines frequently intersect the bedding planes of a stratified rock formation at low angles, which creates a situation prone to roof falls. In weakly bonded sediments, a rectangular opening may be more desirable than a circular cross section because a circular configuration may encourage the cusps, or corners, to fall out.

Water inflows create difficult problems for incline construction, and efforts to stem flows by grouting, freezing, or pumping down the water table are frequently required. However, if construction proceeds upward, some inflow of water may be considered an advantage if it can be employed to remove the muck.

Factors in Site Selection

An incline has inherent advantages and disadvantages in site selection that are similar to those that affect a tunnel. During site investigations there is usually some discretion permitted in routing the incline to avoid the worst ground conditions. A thorough geological profile of the immediate area is therefore warranted. Particular attention to water flow and the dip of the strata will minimize two of the major hazards of slope construction.

Site-Specific Considerations

In most cases, once the course of an incline has been determined from general site geological studies, a limited site-specific study has been the normal approach. Coring of additional, closely spaced boreholes along the specific route is unusual, unless perhaps a particularly critical zone is suspected. Boring an inclined hole along the proposed axis of the incline is a highly desirable procedure, once the location and bearing have been determined. Such a boring eliminates the need for probe holes during construction. The feasibility of this approach, however, is limited by the length of the incline.

A more usual approach is to prepare contingency clauses in the construction contract and handle special problems if and when they arise. Without an inclined exploratory boring, the progress of the incline can be delayed as the excavation approaches an anticipated fault zone. In this case, a probe drill can be bored ahead of the face to determine the exact nature of the zone; then grouting and/or stabilization methods can be employed if necessary.

Roof support methods are probably the most frequent deviation from the construction specifications. The bonding of formations is perhaps the most critical rock characteristic in determining proper roof support in an incline. This characteristic is also one of the more difficult to predict on the basis of core samples. As construction progresses, instrumentation to assess roof and rib creep or floor heave is warranted, unless similar excavations have determined otherwise.

Geology and Construction

The direction, geology, purpose, and shape of the completed incline (or decline) influence the methods of construction. Methods include drill-and-blast, tunnel borers, road headers, raise drills, or box-hole drills. Each method has benefits and limitations.

On a relatively short incline, raise drills or box-hole drills may be considered. Although modern raise drills are capable of pulling raises as far as 3,000 ft, it becomes very difficult and hazardous to trip the reamer head at the slopes considered here (15 to 45 degrees from the horizontal). The raise drill is therefore limited to what can be achieved on a single pull. If machine boring or excavating is contemplated, site investigations require an assessment of both rock strength and abrasiveness.

A box-hole drill operates in the same excavation mode as a raise drill, except that the head is pushed up from below rather than pulled down from above. This process is slower and more costly than raise drilling, and is limited to a length of about 600 ft. It is, however, a mechanical method of achieving a steep, blind incline.

Tunnel boring machines have found limited use in downward construction but have been successful in upward construction. On a downward slope, these machines have difficulty removing the cuttings from the face. Full-face borers have been used in upward slopes, including one at 45 degrees. Muck can be removed by flushing with the aid of gravity in such cases. However, compared to traditional horizontal rates, progress of the machine is slow and costs are higher.

Drill-and-blast is still the most common method of incline construction. Because the rates of mechanized methods are slow, the lower capital investment of the drill-and-blast method is attractive. Muck removal is also simplified with free access to the face by loading equipment. Inclines driven by the drill-and-blast method typically use specialized suspended-track climbers which provide drilling and ground support installation platforms. Depending on the slope angle, the inclines can be self-mucking and are free-draining. Drill-and-blast also offers versatility in shape of the tunnel (i.e., the cross-sectional shape can vary with depth).

A method which in some cases competes with drill-and-blast is a roadheader. These mobile excavators offer the flexibility and access to the face equivalent to drill-and-blast techniques, while providing the safety and smooth surfaces of a mechanical excavation. The major weakness to date has been the inability of the roadheaders to economically cut hard or abrasive rocks. Recent developments in water-jet-enhanced picks and a mobile unit employing rolling cutters may increase the proportion of mechanically excavated inclines.

The purpose of the incline also affects the construction method and is similarly related to geological conditions. Tubular shapes are desirable for aqueducts, whereas a flat floor is required for operating vehicles. In certain applications, smooth walls and minimum disturbance of surrounding rock can be compelling requirements. Therefore, the geological studies of slope sites will also have a profound influence on the choice of construction method within the constraints imposed by end use.

UNDERWATER TAPS

An underwater tap is a subsurface connection between a body of water and an onshore installation. Taps may be required for either the withdrawal or discharge of water by the installation.

The applications for underwater taps are growing more numerous, and will continue to increase within the United States as water and power resources are developed. Hydroelectric power will be extracted with low-head generating technology from dams and sites previously ignored. Power plants require large quantities of water for cooling. The trend is for waste water from urban sources to be discharged into the sea by controlled diffusers rather than using only rivers or open drainage. Because of the expanding need and its implications for the future, site selection procedures and planning of underwater taps based on geological study are increasingly important.

Frequently the tap is constructed between a vertical, or steeply inclined shaft and a horizontal tunnel. A direct lateral tap into a body of water is avoided if possible because of the difficulty in judging the breakthrough cut. The final cut must be taken with utmost care because there is minimal opportunity to correct this tap after the workings are flooded. The tap should be made as nearly normal to the bottom of the water body as possible to assure uniform thickness of the final plug.

Factors in Site Selection

In a project involving an underwater tap, location of the tap must be considered in relation to the other project facilities. In some instances, such as an offshore intake or discharge, considerable latitude in location is possible. In others, such as a powerhouse intake, the tap location may be dictated largely by adjacent facilities.

In either case, as much geological data as possible should be obtained, including at least the use of overflights, photography, and a study of the surrounding formations. Cores should be taken and examined. Seismic examination may also be considered, as tap construction depth is generally shallow. A complete geological profile should be developed, with particular attention to faults, weathered rock, blocky ground, and parameters for determining water inflow (e.g., permeability, discontinuity spacing, and hydrostatic head). Usually a tap will involve drill-and-blast excavation; therefore, RQD, abrasiveness, and compressive strength are significant factors.

It is important to remember that construction of a tap often crosses two interfaces and involves two or three dissimilar construction methods. The geological interfaces are the water-sediment boundary and the sediment-underlying rock boundary. Construction through the water-sediment boundary may involve piling construction with excavation by dredge, pump, or clam. At the rock layer, a blind drill using reverse circulation for muck removal may be involved. From the opposite direction, a tunnel or incline construction is probable. Geological considerations will probably dictate the method and type of equipment selected for tap construction, and will probably affect its location as well.

Site-Specific Considerations

Once a specific site is selected, the complexities of design and construction of an underwater tap demand that a thorough site investigation be conducted prior to initiating final design or construction. The onshore site must be investigated by geological mapping, and core drilling is needed to eliminate as many uncertainties as possible. Thorough offshore studies are required as well. Cored boreholes are essential; cores can be drilled in the subsurface rock using barges or platforms. Inspection by divers, underwater photography, and soil sampling are useful for determining the water-sediment and sediment-rock interfaces.

It is particularly important to establish the occurrence and character of faults and intercepting joints or fractures that could conceivably conduct water. The strength of the rock and definition of the strata are needed to ensure structural integrity of the completed installation. Determination of the applicable rock properties will enhance the selection of construction equipment and control of its operating cost.

In the case of an underwater tap, a second opportunity for specific site investigation occurs when construction nears the point of breakthrough. Given the penalty for error if the crucial tap is performed carelessly, this opportunity should not be ignored. From a tunnel, probe drills, with packers or operating through a seal, can safely drill horizontally for about 200 ft or less. If a drilling operation is involved, a probe drill along the axis of the excavation is possible. Seismic and electromagnetic pulse examination should prove effective; density changes are among the most readily detectable characteristics recognized by seismic tests. Electromagnetic (radar) means are sometimes successfully used for identifying aquifers at close range. The objective of this final study is to accurately identify the rock boundaries and confirm evaluations of the integrity of the rock.

Geology and Construction

Consideration must be given to the methods of geological analysis and potential treatment in relation to the type of excavation to be employed. A fissure intersecting the floor of a water body may not be a deterrent to blind drilling, but it could be calamitous in a hand-excavated tunnel. Treatment such as grouting or ground stabilization must be compatible with the planned construction method.

Methods of creating the final tap vary with end use, but generally fall into four categories.

- The vertical structure is built on bed rock offshore. A caisson may be built to surface. Bed rock below the structure is drilled down to a point where it will intersect the approaching tunnel. This cut can be "wet" or "dry." If the offshore structure permits, the vertical column can be pumped out and the final cut is dry. The facility is then flooded by removing a portion of the vertical structure.
- A reverse procedure can be employed, in which the tunnel portion is completed first and the connection is made by drilling into it. An underwater caisson is built on bed rock above the tunnel and the connecting hole is drilled, sometimes through the caisson and into the tunnel. This procedure is used where a diffuser outflow or manifold tap is employed.

- The connection may be made by drilling upward from the tunnel. A raise drill can be employed from a drilling platform. Again, wet or dry connections are possible.
- The caisson built offshore on bed rock may contain a plug. After contact with the caisson is made from the tunnel, either below or horizontally, the plug is removed by explosives. Such a hydraulic bulkhead can even be dewatered by pumping so that a liquid explosive can be poured in and detonated remotely. When blasting the final plug wet, a sump or trap may be built downstream to catch and permanently store the rock from the final blast or spread it evenly along the floor of the tunnel.

6.
Selected Case Studies

The ten projects (nine mined tunnels and one shaft) presented in this section were selected because they represent problems or situations which the subcommittee feels it will be instructive to explore in detail. The case studies of the mined tunnel projects were chosen to match as many of the following criteria as possible:

- Taken together, the projects should represent the widest possible range of basic problems encountered, as reflected under that subheading in the project abstract. (In fact, most of the selected cases will illustrate two or three major problem groups and twice as many subgroups.)
- The nine cases should represent at least several different tunnel purposes, such as water conveyance, power generation, rapid transit, etc.
- Each case must be based on a thoroughly researched study project. This eliminated, for example, those projects for which a follow-up interview with the owner was not carried out.
- Each case must be based on a study project for which all construction has been completed.
- Each case must be based on a study project for which all litigation (if any) has been resolved.
- At least one of the cases should be based on a project with no significant construction problems and no subsurface-related cost overruns.

Although all of the 84 mined tunnel projects illustrated some problem or feature that might deserve discussion, the 9 cases selected best met the widest range of stated criteria. The projects represent only 6 of the 28 owners or agencies who provided information for the study. Thus, it might appear that those six were singled out for particular criticism, but that would be a misconception. It is purely coincidence, and not perceived flaws in philosophy of design or site investigation, that caused the selected case studies to represent so few of the owners or agencies. In any case, limiting the number of projects selected for special examination necessarily restricted the set of owners and agencies.

For the shaft case study, the choice was much more severely limited because only three deep shaft projects were studied. The subcommittee decided to use the Waste Isolation Pilot Plant (WIPP) project because it is comparable to the type of undertaking contemplated in the construction of waste repositories requiring a number of deep shafts for access to chambers designed for storage of radioactive and other hazardous substances. Neither the Loon Lake penstock shaft nor the Brunswick No. 3 mine shaft could yield the maximum amount of information to the parties involved in the planning for deep underground storage, because of their different needs and opportunities for subsurface investigations. Therefore, the WIPP project was selected as best meeting the criterion of applicability to user needs.

It should be noted that the costs presented in the case studies are as taken from bid tabulations and pay vouchers. The dollars represent values for the years in which they were obligated or paid, with no escalation factors applied.

CASE STUDY NO. 1

Name of Project: MBTA Red Line Extension, Porter Square Station

Purpose: Passenger station for subway system

Location: Massachusetts (Cambridge)

Construction Period: March 1980--June 1981

Site Investigation Period: 1976--1978

Size: Trainroom 490 ft long; 45 ft 7 in. high by 70 ft 6 in. wide.
Crossover 68 ft long; 37 ft 1 in. high by 44 ft 2 in. wide.

Project Cost: Estimated $36,969,138
Bid $43,887,900
As Completed $44,877,854 (includes all extra payments)

Mined Tunnel Construction Cost: Estimated $13,035,444
Bid $21,045,650
General Contract Mods -$701,598
Subsurface Related Overruns $0
As Completed $20,344,052

Subsurface Investigation Cost: $2,000,000 (plus or minus)

Summary of Site Geology: Predominantly fresh to slightly weathered, bedded argillite with a slight dip, and overlain by thin glacial till, marine clay, outwash sands, and miscellaneous surficial till. Minor intruded dikes of basalt and andesite. RQDs indicate generally fair to excellent quality, but two faults were identified in addition to frequent shears perpendicular to the station axis. Unconfined compressive strengths were 9,740 to 45,500 psi for argillite and 15,900 to 24,800 psi for igneous rocks. Joints and fractures, a source of stored water, were mostly tight but areas adjacent to intrusive dikes likely to be more pervious. Depth of overburden ranged from 64 to 82 ft above tunnel crown (30 to 47 ft of rock cover above crown). Static water table at 15 to 20 ft below surface; no water inflow predicted.

Design Criteria: Maximum total load of 8,800 psf for final lining; concentrated rock loads of 1,200 to 3,500 psf also used for other geometries. Water level at El. 123 (60 ft above crown in trainroom and 48 ft above crown in crossover chamber).

Contract Provisions:

Type: Unit price per cubic yard of excavation and per unit of lining components (support steel and shotcrete).

Stipulations:

Schedule and/or time of completion: Total contract to be completed by 9/11/82.

Definition of delay and suspension of work.

Liquidated damages: $2,500 per calendar day of delay.

Payment: Monthly; 5% retainage (may be eliminated after 50% completion).

Construction method: Drill-and-blast (4-stage scheme, modifiable by contractor).

Restrictions: Work not permitted on weekends or holidays without approval. Surface hauling not allowed between 11:00 p.m. and 7:00 a.m.; route and disposal site specified. Monitoring required for blasting. Strict noise level control.

Disputes resolution: Decision by owner's engineer. If agreement is reached, contractor reimbursed at cost plus 1%, 6%, or 10%, as determined by engineer. Recourse is appeal to director of construction, then a review board, then litigation.

Geotechnical data made part of contract documents: "Geotechnical Interpretive Report" (available for purchase), which included cross sections and test data. Boring logs and pilot tunnel maps included in contract drawings. Core samples available for inspection by appointment.

Disclaimers: None with respect to owner-furnished information on subsurface conditions.

Changed-conditions clause: Yes

Construction Method: Drill-and-blast, 3-stage excavation (top heading, intermediate heading, and lower bench). Primary support of steel ribs, rock bolts, and 3 stages of shotcrete. Permanent support the same as primary support plus 4th stage of shotcrete (minimum total thickness of 15 in.).

Conditions Encountered: Relatively good conditions, essentially as predicted and perhaps slightly better. The contract was modified to permit the contractor to change from a 4-stage to a 3-stage excavation scheme. Groundwater inflow of 42 gpm for two months, until underground reservoir drained.

Problems Encountered:

Construction: None of major consequence. There was a delay of perhaps three weeks when a fault was encountered in the portal. (This was early in the learning curve of perfecting the support system.)

Operations and Maintenance: Groundwater flowing through the bed rock has sufficient concentration of $CaCO_3$ to be considered calcareous. There is evidence that the carbonates may be precipitating in open air, enough to begin clogging drainage systems over a period

riod of time. At this writing, it is not known how serious the problem may become. (The problem is well documented on several sections of the Washington Metro system.)

Resolution of Assertions Re Subsurface Changes: No assertions were made with respect to subsurface changes.

Analysis/Opinion: When planning for the Porter Square site investigation was begun, just after the mid 1970s, there had been no previous experience with design and construction of a large shallow chamber in the argillites around Boston. The WMATA system in Washington, D.C., had been providing a record of experience since the late 1960s, but those shallow chambers were constructed in schists and gneisses of a completely different geological regime. The MBTA geotechnical engineer apparently decided that a very great deal of information about the rock in his local area would have to be developed before attempting such excavations and therefore took a very conservative approach to the site investigation. The resulting body of knowledge was quite impressive and was undoubtedly a major factor in the absence of cost overruns in the mined opening. Because the investigation seems to have been extremely successful in achieving its primary purpose, cost effectiveness is the only aspect of the program that is legitimately open to debate.

Shallow rock chambers are generally regarded as some of the more critical of the civil engineering projects because of the excavation spans involved, the probability of closely spaced discontinuities (and perhaps intense weathering) so near the bed rock surface, and the general looseness of rock blocks because gravity induced stresses are too low to keep them pressed firmly together. An absolute minimum site investigation for such construction would certainly include a generous number of boreholes with rock coring, lab testing to determine strength, hardness, etc., and borehole water level and permeability tests. Prudence would dictate the use of a few oriented core holes to determine rock structure attitude and maybe some overcoring tests for quantifying and orienting locked-in stresses. It would not be unreasonable to consider a small pilot tunnel for detailed mapping and later access by bidders. Perhaps in addition to or as a substitute for some of the above, one might consider pumping tests, blast vibration tests, or the construction of a test shaft.

The interesting thing about the Porter Square investigation is that it encompassed all of the above techniques of rock and soil exploration. Although some of the tabulated costs are estimates or bid prices rather than final recorded figures, it appears that the total amount spent for the complete program was in the neighborhood of $2 million. With the final cost of the mined station chamber being about $20.3 million, a best guess is that the owner's exploration costs were about 9.8 percent of the construction costs (ignoring the fact that exploration dollars had a mid-to-late 1970s value while construction dollars had an early 1980s value). Still another way of looking at the matter is to note that the owner originally estimated the cost of the mined opening at slightly more than $13 million. Hence, exploration costs were perhaps 15.3 percent of the presumed construction costs (again ignoring the effects of inflation).

It is logical to ask if the scope of the site investigation could not have been reduced without detracting too much from the data base developed for designers and bidders. Because the pilot tunnel (excavation bid price of $1,683,800) took the lion's share of the exploration budget, a closer look at its cost effectiveness seems warranted. Sized at 12 ft by 12 ft, this opening certainly did its job of providing an opportunity for measuring water infiltration, confirming rock joint patterns and conditions, and demonstrating how certain joint sets would control overbreak. It also was instrumental in locating two small faults and two minor igneous dikes that had been missed by core borings. However, water infiltration had already been measured with accuracy in an inspection shaft (excavation bid price of $69,070) that was 36 in. in diameter and 111.5 ft deep. Assuming the pilot tunnel was truly needed to confirm the other geologic features, it could have been done just as easily in a smaller tunnel, perhaps 6 ft wide by 8 ft high. The smaller size surely would have cut the cost of the opening and would not have provided so much opportunity for the rock in the crown to loosen prior to opening up the full station chamber. The argument that only a large pilot tunnel easily permits the early installation of rock dowels for station excavation support may be a case of circular reasoning because too large an opening can be the very cause for needing such dowels in the first place. Indeed, a small construction problem did develop at Porter Square because blasting for the pilot tunnel damaged the integrity of the rock enough to require shotcreting of the pilot tunnel roof ahead of the advancing station chamber top heading in order to keep down overbreak.

One may say that this is all quibbling and the only important fact is that the pilot tunnel (in conjunction with the other elements of the site investigation) obviously reassured bidders about conditions, minimized construction problems, and eliminated cost overruns, thereby paying for itself in the long run. The only easy way to make a tentative judgment on this is to look at the construction costs, which break down as follows:

	Mined Tunnel	Total Contract
Engineer's Estimate	$13,035,444	$36,969,138
Low Bid	21,045,650	43,887,900
Contract Modifications	-701,598	+989,954
Geology Related Claims	0	0
	$20,344,052	$44,877,854

It is true that if one compares the low bid amount with the final cost figures, there were no geology related overruns in the station chamber. There was even an apparent savings, the exact reason for which was never made clear to the subcommittee interviewer. However, the bottom line is that the low bid and the final costs came in at approximately $7 million more than the owner had expected to pay. In a competitive situation, the question to be asked is whether less subsurface information from a less expensive exploration program would have raised the bid price by any substantial percentage of the $2 million (plus or minus) that was spent. This leads to the question of whether a less informed contractor might have encountered enough construction surprises to raise the ultimate cost to any great degree. There is no way to produce any adequate proof when speculating on "what might have been," but cutting the cost of the site investigation in half would have netted the owner approximately $1 million in early money savings to balance against bidding contingencies and potential construction cost overruns.

In developing subsurface information, one must always ask: "At what expenditure level do exploration costs begin to exceed potential construction savings?" No amount of money spent on exploration can remove all construction uncertainty, so the owner and the geotechnical engineer must draw the line at some point. This project may be an example of one where a line was drawn slightly beyond the bounds of cost effectiveness.

CASE STUDY NO. 2

Name of Project: WMATA Section C-4, Huntington Route
(Contract 1C0041)

Purpose: Running tunnels for subway system

Location: Washington, D.C. (northwest quadrant and under the Potomac River)

Construction Period: November 1972--August 1973 (shield tunnels)

Site Investigation Period: September 1966--August 1969

Size: Soft Ground 2,740 ft long; 20 ft 6 in. diameter.
Mixed Face 1,069 ft long; 19 ft 8 in. diameter.
Rock 8,303 ft long; 19 ft 8 in. high by 19 ft 8 in. wide

Project Cost: Estimated $26,930,647
Bid $23,397,053
As Completed $32,009,752 (includes all extra payments)

Mined Tunnel Construction Cost: Estimated $18,230,267
Bid $15,649,372
General Contract Mods $99,788
Subsurface Related Overruns $9,217,999
As Completed $24,967,159

Subsurface Investigation Cost: $98,150 pre-bid

Summary of Site Geology: Recent alluvium and man-made fill overlying Pleistocene terrace deposits (fine and coarse grained sediments) overlying decomposed rock and schistose gneiss bed rock. Eastern portion of alignment in terrace sands and gravels with boulders near base of deposit and layers of clayey silt and silty clay throughout the upper reaches. A relatively thin layer of saprolitic decomposed rock separates the terrace deposits from the underlying bed rock. Most of tunnel beneath the Potomac River in quartz-mica schist-to-gneiss of the Wissahickon and Sykesville formations. Foliation not particularly pronounced but shear zones common. Rock quality highly variable, ranging from slightly to highly jointed, with talc coating on some joint surfaces. Slightly to highly weathered, with some weathering zones at depth beneath sound rock. Unconfined compressive strength varying between 560 psi (in weathered zones) and 15,860 psi. Overburden ranges from 12 to 80 ft above the crown; soil thickness ranges from 0 to 50 ft except much thicker (120 ft) in gorge on east side of the river. Median permeability was 4 x 10^5 in rock. Predicted water inflow of 7 gpm in rock.

Design Criteria: Water pressure (range) from 8 ft below the tunnel crown to 65 ft above the crown.

Contract Provisions:

Type: Unit price per linear ft of tunnel excavation as follows: 2,740 ft earth tunnel; 1,069 ft mixed face; 8,303 ft rock. (Total tunnel excavation length = 12,112 ft along 6,056 ft of alignment.) Unit prices for support items: shotcrete (cubic yard), ribs (each), steel (round). Estimated quantity variation limits set at 15%, without contract price adjustment.

Stipulations:

Schedule and/or time of completion: 730 days to complete tunnels. (Contractor to submit schedule, which then became the contract time.)

Definition of delay and suspension of work.

Liquidated damages: $1,500 per day of delay.

Payment: monthly; 10% retainage (after 50% completion, may be reduced at contracting officer's option).

Construction method: TBM or drill-and-blast for rock tunnel. Various liner options, including shotcrete, cast-in-place concrete, and liner plates. Also option for either steel ribs or shotcrete and ribs in rock tunnels.

Restrictions: Three shifts to be maintained when using a shield. Blasting not allowed from 10:30 p.m. to 7:00 a.m. in Washington, D.C., or Virginia, but no restrictions in tunnels under the Potomac River. Hauling subject to local jurisdictions.

Disputes resolution: Decision by owner's contracting officer. Decision can be appealed within 30 days to owner's board of directors; board decision final unless question is one of law that results in litigation.

Geotechnical data made part of contract documents: Boring logs (bound directly into the contract documents). Core samples available for inspection. (Subsurface investigation reports, including profiles and laboratory test data, available for inspection and copies could be obtained from the National Technical Information Service.)

Disclaimers: Yes; data presented for information only with disclaimer on accuracy, interpretations, and conclusions in reports.

Changed-conditions clause: Yes

Construction Method: Drill-and-blast (boom mounted 4-drill jumbo) for rock tunnels and some mixed face. Shield in earth tunnels and some mixed face where rock was below springline. Primary support of steel sets, some shotcrete (initial portion of rock tunnels), and some spiling (soil roof of mixed-face tunnel). Final lining of reinforced concrete (12 in.).

Conditions Encountered: In soft ground and mixed face, essentially as predicted, except elevation of rock line higher than expected. Blocky conditions and excessive overbreak in rock, but this is a controversial matter (conditions varying from poor to fairly good, and probably no worse than predicted by owner). Rock between tunnel crown and Potomac River bottom possibly sounder than expected; water pumped for the duration of the project was on the order of 50 million gallons, only 10 percent of the specified allowance.

Problems Encountered:

> **Construction:** In soft ground, runs into the heading caused ground settlements, including two surface slumps. In mixed face, a higher than anticipated rock line for part of the extent resulted in a change from shield excavation to heading and bench. In rock, blockiness and overbreak resulted in the use of steel ribs rather than the design support system of rock bolts and shotcrete.
>
> **Operations and Maintenance:** At present, problems caused by ground conditions are minimal. Groundwater leakage is minor and there is hardly any buildup of the calcium carbonate precipitates that have plagued many other Metro rock tunnels. Drains were flushed perhaps 8 months ago (counting from January 1983) and still appear to be in decent condition. There is a bit of silt buildup in the drains at the low point of the tunnels; it is not known whether the silt originates in construction debris or in joint fillings in the surrounding rock.
>
> There was a short-term maintenance problem that stemmed from a man-made condition. During construction, the tunnels penetrated soft ground saturated with a heavy, tar-like substance left from an old factory site. After tunnel completion the material continued to seep through the permanent concrete linings. Although not a fire hazard, it was messy and was carried by the drainage system to the pumping station beneath the Potomac River. When released into the river, the petrochemical was considered a minor environmental problem. The substance disappeared after a few years, possibly because the pocket was effectively drained.

Resolution of Assertions Re Subsurface Changes: The contractor asserted that he encountered higher rock than could be anticipated from the pre-bid data, primarily because the geologic profile contained a plotting error indicating a 1.5-ft higher top by scaling than by written dimension. The contractor had scaled dimensions from the profile to prepare the excavation bid estimate and maintained that the error had increased his excavation costs by a factor of four. The owner's consultants contended that the plotting error was minimal, that all other drawings were accurate, and the written dimensions should have taken precedence. In addition, the geotechnical report indicated that variations of 2 to 5 ft in rock elevation could normally be expected. A claim was filed but settled prior to hearing at a cost of $162,788 (part of a blanket settlement).

The contractor asserted that steel ribs on 2-ft centers had been required due to blocky ground and safety of excavation and personnel, maintaining essentially that the design support system of rock bolts and shotcrete was faulty and not sufficiently conservative. The owner disagreed, indicating (1) that the contractor had never attempted to construct the tunnel as designed or as bid, (2) that numerous ribs installed evidenced no blocking, no loading, and no deformation, and (3) that the design support system could have been used effectively. Claims pertaining to overrun in ribs were settled during performance for $2,503,815 by owner's final decision.

Claims made by the contractor totaled $12,768,374. Some were settled by owner decision without litigation; others were filed before the Corps of Engineers Board of Contract Appeals but settled before an actual hearing. The final amount awarded to the contractor was $9,217,999.

Analysis/Opinion: WMATA's C-4 contract provides examples of two completely different kinds of subsurface problems that led to complications during construction. The first, caused by a higher rock line than the contractor apparently had a right to expect, is extremely common wherever a mined tunnel impinges on top of bed rock. It was recognized that the tunnels would transition from soft ground to mixed face to rock, and the contractor laid plans to push with his shield to the point where the rising rock would force him to abandon this method. However, due to an owner plotting error on one contract drawing and some rather simplistic borehole-to-borehole rock line projections by the contractor, the top of rock rose to a higher than expected elevation in the soft ground tunnels and slowed progress considerably. Probably contributing to the problem was the somewhat less than desirable borehole coverage, with spacings on an average of perhaps 200 ft apart and staggered from one side of the alignment to another. WMATA's present practice in similar circumstances is to make borings or pairs of borings (one on each side of the alignment) on 50- to 150-ft centers, coverage that is three to four times as tight as that provided on Section C-4. This constitutes acknowledgment of the fact that an owner can seldom go too far in determining the rock line when its presence is likely to affect a mined tunnel.

In all fairness, however, it is difficult to say whether knowing the location of the top of rock with great precision would have made much difference in the ultimate cost of these particular tunnels. Section C-4 was not designed to skim the top of rock in order to avoid mixed face conditions; it had to traverse those conditions in order to dive into rock, and a knowledge of their limits would not have lessened their extent or severity. The contractor made a high rock claim of $1,187,200 and ended up collecting $162,788 for it. A very precise knowledge of rock elevations would presumably have driven his bid up by a similar amount, and therefore it may be that the only money really "lost" was some relatively minor amount caused by the surprise factor and whatever the situation may have contributed to litigation expenses.

By far the more serious of the C-4 problems was the one relating to rock conditions and how they affected tunnel support. The situation was quite complex, with many overlapping claims and counter claims which, had they been paid in full, would have netted the contractor extras worth +$12 million; however, they were finally settled for +$9 million. Though difficult to summarize without sacrificing accuracy, the basic problem appears to be that the contractor bid a construction option which he later decided was impossible to pursue. Passing up the chance to use a TBM, he chose drill-and-blast tunnels with a mostly rock bolt and shotcrete lining, but with a designed support system of steel ribs on 4-ft centers in known weathered areas and shear zones. He then proceeded to line the tunnels with steel ribs on 2-ft centers and supplemented them with large amounts of miscellaneous steel, saying that the rock was obviously too poor throughout to be supported by the owner's design lining. The installation of so much tunnel steel interfered with shotcrete placement and mandated a reversion to cast-in-place concrete, a change which contributed heavily to the overruns.

To an outsider, all indications are that the rock probably was no worse than envisioned by the owner all along; his site investigation had predicted conditions with relatively fair accuracy. We believe the basic problem lay with contracting procedures and the way design and geological information was passed along to bidders. The contract placed a great deal of responsibility for tunnel safety on the contractor and then presented him with a shotcrete and rock bolt support system with which few Americans had much experience in 1972 and which may have appeared to be on the outer limits of feasible technology. The fact is that, even then, tunnels were being supported by shotcrete in ground that was certainly no better than Section C-4. However, a mere design drawing probably constitutes little reassurance for a builder contemplating relatively new support techniques. The C-4 contractor never tried the owner's design lining (which made it difficult to finally determine whether the ground was as predicted or not), but he might have been more willing if there had been a mechanism for explaining it to him.

In the early 1970s, WMATA made its interpretive "subsurface investigation reports" available for reading by bidders, but disclaimed any responsibility for conclusions drawn therefrom. In spite of this disclaimer, the C-4 contractor did depend on the reports in putting together a bid and at least had access to an accurate assessment of actual ground conditions. Unfortunately, but of necessity, a subsurface investigation report is compiled during the early to mid stages of design. Therefore, it is often impossible for such a document to treat or comment on many important design and construction matters because they are not worked out until a later stage of development. This is especially true in the case of innovative ideas for design or construction. Hence, the C-4 contractor had no easy way of comprehending the rationale for a shotcrete and rock bolt support system in these particular tunnels, and this may have contributed to his unwillingness to give it a fair trial.

Since 1975, WMATA has had a mechanism for passing along such important information to bidders and construction managers for all mined tunnel projects. That mechanism is a report entitled "Geotechnical Basis of Design and Construction Specifications," or "Geotechnical Design Report" for short. This report is compiled by the tunnel designer and bound as an appendix into the construction specifications so there can be no doubt about its status as a contract document. The geotechnical design report sums up the important geologic information from the subsurface investigation reports and then explains how the geology affected design and how it is likely to affect construction operations. Thus, the contractor and the resident engineer are fully apprised of the designer's and the geotechnical engineer's intentions and advice and, as a result, the field work proceeds more smoothly than it otherwise would.

Had there been such a report in the C-4 contract documents, it seems likely that much misunderstanding and litigation would have been avoided.

Aside from high rock and general rock conditions, a third and very minor C-4 problem is worth mentioning because it is symptomatic of the kind of occurrence that has proven more significant on other projects. The tar-like substance encountered beneath an old factory site was not volatile enough to be a true construction hazard and its general messiness is no longer very troublesome now that the pool has apparently drained. Nevertheless, the presence of this substance should not have been overlooked in the site investigation. To miss such a relatively innocuous substance means that one with greater potential for harm could have been missed just as easily. Many urban areas are dotted with spills from gasoline stations, factories, and the like, and it is incumbent upon investigators to identify such areas before the tunneler arrives to discover them for himself.

CASE STUDY NO. 3

Name of Project: WMATA Section G-2 (Contract 1G0021)

Purpose: Running tunnels and station for subway system

Location: Washington, D.C. (northeast quadrant)

Construction Period: October 1975--June 1978

Site Investigation Period: April 1972--April 1975

Size: 13,700 ft long; 20 ft 11 in. diameter.

Project Cost: Estimated $49,587,227
Bid $42,266,620
As Completed $48,555,357 (includes all extra payments)

Mined Tunnel Construction Cost: Estimated $31,831,000
Bid $18,226,940
General Contract Mods $86,204
Subsurface Related Overruns $4,718,311
As Completed $23,031,455

Subsurface Investigation Cost: $49,775 pre-bid

Summary of Site Geology: Stiff to hard Cretaceous plastic clays and sandy clays and compact to very compact silty sands, with many intermixings and interlayerings of the three basic strata. Overlain by Pleistocene terrace deposits and man-made fill. Depth of overburden ranged from 27 ft to 96 ft. Water table at 15 to 45 ft above tunnel crown. Median permeability was 4 x 10^{-6} fpm; the highest measured 6 x 10^{-4} fpm. Tunneled soils stiff/compact due to preconsolidation. Silty sand often with less than 10 percent fines, making it unstable, especially where water difficult to draw down due to interfering clay lenses. Wettest material was the the clean sand lenses occurring in otherwise silty and clayey strata. Evidence of perched water due to pumping from household wells at depth while upper strata recharged by infiltration from the surface. Predominance of clayey materials hinders vertical movement of water.

Design Criteria: Between 6 and 13 kips overburden load at tunnel springline; 15 to 45 ft head of water above crown.

Contract Provisions:

> **Type:** Unit price per linear ft of earth tunnel and lining. Estimated quantity variation limit set at 15%, without price adjustment.

Stipulations:

Schedule and/or time of completion: 910 calendar days for the total contract. (The contractor was required to submit for approval a detailed Logic Network Analysis with estimated activity durations and milestones for various major features, including running tunnels estimated at 203 calendar days for mining.)

Definition of delay and suspension of work.

Liquidated damages: $2,500/day for certain specific features; $1,500/day for the total contract. Maximum assessment limited to $5,000/day.

Payment: Monthly; 10% retainage.

Construction method: Soft-ground shield with breasting facilities.

Restrictions: Hauling according to applicable county ordinances. Noise levels for equipment in various locations and hours of resident activities.

Disputes resolution: Decision by Owner's contracting officer. Decision can be appealed within 30 days to owner's board of directors; board decision final unless question is one of law.

Geotechnical data made part of contract documents: Boring logs (bound directly into the contract drawings). Core samples, specifically indicated as available for inspection on 24 hours notice. Geotechnical reports, with profiles and results of all field and laboratory testing on soil samples, boreholes, and observation wells. (The geotechnical reports were laid out for bidders' examination and copies could be obtained from the National Technical Information Service.)

Disclaimers: Apparently none with respect to owner-furnished information on subsurface conditions.

Changed-conditions clause: Yes

Construction Method: Soft-ground shields with excavator hoe, breasting doors, and articulation capabilities. Primary support of ribs and lagging. Permanent support of cast-in-place concrete.

Conditions Encountered: Water inflow of up to 50 gpm from clean sand lenses. Hard, cemented sand lenses and layers up to 4 ft thick for 1,000 ft. Alternating pervious/impervious layers. Wet, flowing single-size sand lenses for 1,200 ft of each tunnel. Unstable ground around existing sewer.

Problems Encountered:

Construction: Hard sandstone lenses and layers required installation of rock-breaking hoe rams in shields and resulted in very slow advance rates when the lenses and layers were encountered. Single-size flowing sand lenses were difficult to dewater because of intervening clay layers and resulted in runs, major voids and settlements, and bogging down of both shields so that progress averaged only 30 ft/week. Wet, sandy ground around existing sewer required grouting for stabilization, with the result that the shield was practically grouted in place and the hood buckled when shoving resumed.

Operations and Maintenance: Acid water resulted when the shields penetrated about 2,000 ft of ground rich in iron sulfide (FeS_2), which oxidized when exposed to air in the advancing dewatered tunnels and formed sulfuric acid. The pH values of the groundwater in the affected area ranged as low as 2.0, which raised concern about corrosive effects on the permanent concrete lining.

Initial studies indicated that the outside of the tunnels reacted with the acid and associated sulfate ions to create an impervious layer which effectively blocked further attack. Additional studies are being pursued to determine if this holds true and if the acid may be dissipating with time.

The permanent lining in the vicinity of the acid water problem was extremely leaky after completion of construction. Effects of water intrusion were made worse by masses of muddy, rust-colored ferrous and ferric hydroxide, $Fe(OH)_3$ [a by-product of the acid formation] which formed troublesome deposits on walls, inverts, and safety walks. Three overlapping programs of post-construction chemical grouting were necessary to dry up this stretch of tunnel and prevent the rusty intrusions.

Resolution of Assertions Re Subsurface Changes: The contractor asserted that hard sandstone lenses and layers had been encountered where only soil had been expected. The owner agreed that the hard sandstone was unexpected and paid the contractor extras as the lenses and layers were encountered during construction. The total payment was $940,848.

The contractor asserted that neither (a) the combination of single size flowing sand lenses and intervening clay layers, nor (b) the unstable ground around the sewer were expected to be encountered. The owner disagreed, maintaining that these conditions could be easily predicted from information in the contract documents. Litigation ensued, with the contractor claiming +$22 million, about 95 percent of which pertained to (a). Litigation before the Corps of Engineers Board of Contract Appeals proceeded through the pleading, discovery, and trial phases; the parties achieved settlement on their own before a final decision by the Board. It may be significant that the figure settled on after the start of litigation--$3,777,463 for claims (a) and (b)--was part of a three-contract closeout settlement in which the contractor recovered $7 million out of claims totaling $50 million.

Analysis/Opinion: The primary fact about WMATA's site investigations and their impact on construction is that when this project was let for bid, in 1975, the "subsurface investigation reports" (WMATA's term) were not made a part of the contract documents. The boring logs, which are presumably mostly factual, were bound into the contract drawings and the bidders were responsible for the information contained therein. However, the subsurface investigation reports contained much interpretive data for which the owner did not wish to be held completely responsible. The reports were made available for study during the bidding period and photocopies could be purchased from the National Technical Information Service; however, this really served to confirm their status as information documents rather than binding contract documents. The situation may have made it justifiable for the G-2 contractor to make the somewhat ambiguous statement that the reports were "studied, read, and respected, but could not be relied upon." The legitimacy of this argument might be disagreed, but it is difficult to dispute because the contractor was later able to assert successfully that he was not required to take into account the available geotechnical information in making his bid.

The owner's arms-length attitude about his own reports may have worked to his disadvantage because the reports seemed to document very nicely the wet, flowing sand conditions that turned out to be the greatest problem on the job. Although no pumping tests were performed, there was good borehole coverage, plenty of falling head tests, and more than enough lab testing to define the nature of the soils adequately. Although one might quarrel with the lack of pumping tests, the fact is that the owner's geotechnical engineer was able to use the available data to describe the wet, single-size sand lenses that would be difficult to dewater because of the intervening clay layers. Had the contractor relied on that information--which he might have done if the subsurface investigation reports were considered full-fledged contract documents--he might have based his bid on more stringent dewatering and/or a better breasting system, thereby avoiding some very costly delays from bogged down shields. The cost of a more conservative original dewatering plan and better breasting equipment would not have approached the $21 million (plus or minus) claimed for flowing ground, and would have been much less than the $3.6 million (plus or minus) finally settled on that claim.

In addition, if the contractor had heeded the predictions of flowing ground and not suffered such slow progress for 1,200 lin ft in each tunnel, a secondary problem might well have been avoided. The sulfuric acid that materialized in the ground where the shields were struggling was apparently caused by oxidation of minute crystals of pyrites (i.e., iron sulfide, FeS_2). This probably would not have occurred had the machines made normal progress, but the day-after-day exposure of soils in an aereated tunnel face subjected them to an oxidizing environment that normally would not be encountered except in an excavation completely open to the surface. The resulting acid condition was not a severe excavation problem and caused no claim, but the oozing by-products made it mandatory to provide for extra-thorough grout sealing of the completed tunnel, while at the same time interfering with the grout's effectiveness and causing it to be more expensive. The acid also caused several years of additional study expense and general unease before it was concluded that the acid would not harm the concrete lining and would dissipate before causing any environmental damage. WMATA has never been faulted for failing to recognize the acid-producing potential of the ground, because it is a rare condition heretofore known only to a few very specialized soil scientists who have documented the behavior of the so-called "cat clays" in road cuts and other excavations open to the surface. It is worth noting that the condition apparently has not occurred in other WMATA tunnels, but will probably have to be watched for in the future.

The other major subsurface-related construction problem lay in the hard, cemented sand lenses whose identity and difficulty of excavation were not suspected by the owner or his geotechnical engineer. Actually rock-like in consistency and up to several feet thick, these lenses were either penetrated by a tri-cone bit or punched through with a split spoon during the investigations. No samples were recovered, and the resulting high blow counts were assumed to indicate only the presence of cobbles or boulders. The contractor obviously made the same assessment because he was surprised when his shields kept hanging up on what were in essence small masses of sandstone. By quickly negotiating extras worth nearly $1 million, the owner admitted that his site investigation was deficient in its techniques of identifying hard materials. Interestingly, however, it is very possible that pre-bid identification of the cemented sands would have made little difference in the ultimate cost of the tunnel. If the contractor had been fully aware of the difficulty of excavation, he might theoretically have increased his bid price by about the same amount as was ultimately negotiated in the field anyway. And, of course, the owner kept the problem from escalating beyond its true value by admitting fault and negotiating rather than entering into expensive litigation.

As of this writing, the Washington Metro system is about 22 years beyond the date of its first feasibility site investigation, yet final design investigations for some sections are currently under way and many others are scheduled for the future. This creates an opportunity for the owner to use construction feedback to vary his site investigation philosophy in order to respond to newly perceived conditions, to learn from experience, and to not continue with faulty methods. The Section G-2 case history provides the following examples of how WMATA has instituted such changes:

- In the sampling of certain sedimentary materials, tri-cone bits and split spoons are withdrawn from the borehole at the first indication of hard drilling that might signal the presence of a cemented sand layer. Then a diamond bit core barrel is substituted and the entire thickness of the layer is recovered for proper logging and ultimate examination by bidders.
- When drilling in potentially acid-producing ground, WMATA geologists now watch carefully for the presence of fine crystals of sulfidic minerals (generally pyrite and marcasite), especially in dark colored soils that might indicate deposition under reducing conditions. A few soil samples from each drilling program are routinely lab-tested for "total sulfur" content to detect the presence of sulfide concentrations that might escape detection by eye. Any time there is doubt about a soil's acid-producing potential, a consulting specialist is called in to render an opinion on the subject.

Possibly more important than the above changes in site investigation techniques is WMATA's relatively recent decision to upgrade the subsurface investigation reports from their status of information documents to full-fledged contract documents. Of course, the change came about because of many episodes of litigation on many projects, but the G-2 case history of flowing sand is a perfect example of why such a change may have been needed. It will no longer be possible for a contractor to deny responsibility for knowing the contents of the reports; rather, it will be expected that the bid and construction planning are based on that knowledge. The decision to upgrade the status of the reports may make the owner more certainly liable for mistakes in interpretive information. However, it should also create much more consistency in the assumptions made by bidders and will definitely curtail much time-consuming argument over whether a contractor is to rely on all of the information provided.

CASE STUDY NO. 4

Name of Project: Bonneville 2nd Powerhouse Railroad Tunnel

Purpose: Railroad tunnel relocation

Location: Columbia River Basin, Washington and Oregon (42 miles east of Portland)

Construction Period: June 1976--September 1977

Site Investigation Period: November 1974--March 1976

Size: 1,338 ft long; 35.9 ft high by 24.3 ft wide.

Project Cost:
Estimated $8,636,558
Bid $10,410,610
As Completed $12,172,226 (includes all extra payments)

Mined Tunnel Construction Cost:
Estimated $5,834,261 (excluding profit)
Bid $7,246,650
Extra Support Contract Mods $1,279,674
Subsurface Related Overruns $0
As Completed $8,526,324

Subsurface Investigation Cost: $1,452,026 pre-bid (excluding professional services).

Summary of Site Geology: Unconsolidated Cascade landslide deposits consisting of igneous, pyroclastic, and sedimentary slide debris. A graded mixture of gravelly, silty sand surrounding some basalt boulders and slide blocks of Wiegle formation sandstone/siltstone/claystone/conglomerate/lava with bedding dips of no more than 25 degrees and occasional high angle shear zones. Blocks soft to moderately hard with unconfined compressive strengths of perhaps 1 to 3 ksi, generally weakened by their movements. Extremely variable materials defined in the contract as mixed face. Depth of overburden ranges from 28 to 190 ft surface to crown. The mass contains highly variable percolating water, perched water tables, trapped water, and flowing zones. Rainfall recharges these areas, and the primary aquifer located in a layer of alluvium well below tunnel invert is hydraulically connected to the Columbia River. Minimal tunnel inflow expected, however, because the groundwater table is below invert most of the year.

Design Criteria: Assumed vertical rock load of 35 ft (one tunnel height) for temporary support. Assumed water levels would be drained to below invert level before or during construction.

Contract Provisions:

Type: Unit price per cubic yd of excavation and unit prices for support items (steel sets, rock bolts, shotcrete). Estimated quantity variation limits not specified.

Stipulations:
Schedule and/or time of completion.
Liquidated damages: $4,285 per calendar day of delay.
Payment: Monthly; 10% retainage (may be reduced after 50% completion). Progress payments for support items.
Construction method: Not specified but subject to approval of contracting officer.
Restrictions: Blasting (minor).
Disputes resolution: Decision by owner's contracting officer concerning questions of fact arising under the contract. Only recourse was litigation.

Geotechnical data made part of contract documents: Detailed geotechnical report describing conditions in the pilot tunnel. Geologic profiles provided in the drawings; material classification maps provided in pilot tunnel section of contract. Mechanical analysis (gradation curves) provided in drawings of pilot tunnel samples.

Disclaimers: General Provision #41 stated contractor is responsible for estimating properly the cost and difficulty and that the government assumes no responsibility for available information.

Changed-conditions clause: Yes

Construction Method: Top heading and bench and drill-and-blast, with drilling jumbo, wheel muckers, rebar jumbo, and lining form. Primary support of steel sets, rock bolts, shotcrete, and concrete wall plate. Permanent support of cast-in-place reinforced concrete (21 in.) and miscellaneous steel.

Conditions Encountered: Essentially as predicted by owner information.

Problems Encountered:

Construction: Minor fault problems, squeezing and running ground. In some areas there was inward movement of high side walls, contained with tiebacks and invert struts. Some water inflow, but effectively controlled by dewatering and grouting (assisted by favorable drought conditions during the construction period).

Operations and Maintenance: None of any consequence identified.

Resolution of Assertions Re Subsurface Changes: No assertions made.

Analysis/Opinion: This tunnel is a good example of the effectiveness of a thorough and well-conceived geologic site investigation in keeping the costs of tunnel construction down. The site was known to be very risky, so this short (1,400 ft, plus or minus) tunnel had a geophysical study, thorough surface mapping, 54 boreholes of various types, and a pilot tunnel with a geologic report on the pilot tunnel. With this information, the contractor was prepared for any conditions and was able to complete on time and with no claims for differing site conditions. In this case, the site investigation cost was about 12 percent of the bid price, but without these investigations the bid certainly would have been higher and the final cost would have been much higher.

CASE STUDY NO. 5

Name of Project: Buckskin Mountains Tunnel (Spec. No. DC-7096)

Purpose: Water conveyance

Location: Arizona (20 miles northeast of Parker)

Construction Period: April 1976--May 1979

Site Investigation Period: 1967--1972

Size: 35,915 ft long; 23 ft 5 in. diameter.

Project Cost:	Estimated $53,804,499
	Bid $58,256,638
	As Completed $65,613,963

Mined Tunnel Construction Cost:	
Estimated	$49,627,190
Bid	$47,268,690
General Contract Mods	$1,000,367
Subsurface Related Overruns	$5,441,077
As Completed	$53,710,134

Subsurface Investigation Cost: $1,238,000 estimated pre-bid

Summary of Site Geology: Volcanic flows in mass landscape of the Buckskin Mountains are dominated by andesite interlayered with tuff and agglomerate, which have been intruded by andesite dikes and laccoliths. The andesite is hard, dense, and blocky; it is situated in rather flat-lying flows and ranges from 10 to 100 ft thick. Pyroclastic rock interflows are 5 to 50 ft thick. The andesite exhibited few weathered zones and is quite strong, with unconfined compressive strengths up to 43,500 psi. The tuff and agglomerate, poorly to well indurated, is cemented with gypsum and calcite; the unconfined compressive strength is 1,100 psi. One fault zone was identified on the surface near the outlet portal.

Design Criteria: Maximum rock load of 70 ft; hydrostatic head ranges from well below tunnel invert to 18 ft above crown.

Contract Provisions:

Type: Unit price per linear ft of tunnel excavation and unit prices for precast liner segments (per square ft) and installation (per linear ft).

Stipulations:

Schedule and/or time of completion: 30 months for tunnel excavation and support; 1,800 calendar days for the total contract.

Definition of delay and suspension of work.

Liquidated damages: $2,000 per day.
Payment: Monthly; 10% retainage (up to 50% completion).
Construction method: Contractor's option.
Restrictions: Environmental precautions caused by mating of Blue Heron.
Disputes resolution: Initial decision by contracting officer, with appeal possible to head of agency. Further appeal to Board of Contract Appeals, Department of the Interior.

Geotechnical data made part of contract documents: Preconstruction geologic report; surface geologic map, profile, and boring logs included in contract drawings. Gravity survey results available for inspection. Construction and foundation materials test report available as separate document, by request only. Cores available for inspection; samples (up to 30 in.) permitted for testing.

Disclaimers: Borings show conditions at locations drilled only. Any interpretations are strictly the contractor's responsibility.

Changed-conditions clause: Yes

Construction Method: Tunnel boring machine with flexible, articulated hood, side grippers, and 15-1/2 in. disc cutters. Permanent (and primary) support of 6- to 7-in. thick segmented rings (reinforced, precast concrete).

Conditions Encountered: Loose joint systems and blocky ground conditions in the hard andesite. Soft invert in the tuffs and agglomerates. Fault zones with running ground conditions and cave-ins.

Problems Encountered:

Construction: Loose joint systems in the andesite resulted in blocky rock, face fallout, and excessive overbreak conditions which obstructed the mucking system and damaged the cutterhead components, requiring complete redesign of the cutterhead. Widely spaced joint systems resulted in blocky rock and roof fallout conditions which greatly reduced and sometimes stalled TBM progress. Soft rock in the invert caused the TBM to dive and resulted in problems with alignment and grade. Fault zones resulted in a cave-in and raveling ground conditions (chimney) at two locations. Face fallout at two locations required grouting and concreting of cavities ahead of the TBM.

Operations and Maintenance: None

Resolution of Assertions Re Subsurface Changes: The contractor filed claims totaling $7,767,802 for the above cited construction problems encountered. The claims were denied by the owner for the most part, and then settled by the Department of Interior Board of Contract Appeals. The Board awarded the contractor $5,441,077, but $1,343,077 of that amount was interest on the settlement award of $4,098,000. The method of calculating the interest is a subject of dispute, still unresolved as of the interview date.

Analysis/Opinion: The Buckskin Mountains Tunnel was bid in January 1975. Contractors had three options. Schedule No. 1 called for drill-and-blast excavation with a horseshoe shaped tunnel using cast-in-place final lining. Schedule No. 2 was for machine boring combined with cast-in-place final lining. Schedule No. 3 was for machine boring and pre-cast concrete liners. (Schedule No. 4 was for non-tunnel items.) The low bid was on schedule No 3 and represented the first attempt in North America to use four-piece precast concrete rings.

The contractor ordered a special hard-rock tunnel boring machine. This TBM was designed to cut 40,000 psi andesite and supported a 360-degree shield that served as a form for the four 3-1/2 ton precast lining segments. Each tongue-and-grooved ring comprised 5 ft of the tunnel length. One hoist placed the invert segment on a bed of preshaped pea gravel. The side and crown segments were carried into position by a ring gear located inside the inner circumference of the tail shield. Once the segment was rotated to the proper elevation and the tongues and grooves aligned with the previously placed sections, rams were used to push the segment into place. Lining was then completed by sealing the joints with mastic, blowing pea gravel into the annular space outside the segments, and grouting the gravel. The invert was grouted twice a week and the rest of the ring was grouted at longer intervals. The TBM was advanced by a rib gripper system and the lining was not designed to react against the machine's forward thrust.

The preconstruction geotechnical investigation was felt to be thorough by both the contractor and tunnel owner. There was no pre-bid conference. All interested parties were encouraged to visit the tunnel site and view the rock cores. Up to 30 in. of core was made available to any plan holder wishing to conduct his own tests.

Two major geotechnical problems were encountered during construction. Small cave-ins tended to chimney upward placing heavy rock-weights on the shields. Second, at the face, the 15-1/2 in. diameter cutter discs projecting from the cutterhead along with the muck buckets (or scoops) tended to catch hold of the rock blocks and pluck them from the tunnel face before they could be broken into small enough pieces to be carried away by the muck handling system. In general, the problem only occurred with rock pieces larger than 6-in. cubes. These rock pieces resulted in considerable damage to the cutterhead components and mostly to the muck scoops. It is quite possible that a mechanical rock core log (i.e., discontinuity spacing determination, piece counts, etc.) of the drill holes could have provided a forewarning of this loose joint problem.

To relieve the problem with the rock pieces, a false face was built on the cutterhead. This reduced the projection of the 15-1/2 in. diameter cutters to 4 in. In addition, low profile muck scoops were placed on the cutterhead circumference. The space between the original cutterhead and the false face was filled with grout to provide mass for vibration dampening. To withstand the cave-ins and keep large rock fallout from binding the machine, the shield was changed from the original 1-in. thick plate to 1-1/2 in. thick plate and extra internal bracing was added. Modification of the machine required more than three months to complete.

Another problem was a soft tunnel invert which caused the TBM to sink below grade. Gypsum had been identified in the preconstruction site investigation; however, water was not considered a problem (average annual rainfall less than 10 in.) and the core holes were not backfilled with grout as practice should normally dictate. It could well be that the drill holes open to the surface helped precipitate some of the soft invert problems.

The preconstruction geologic study missed locating two fault zones encountered during excavation. The boring logs gave no indication of open joints or blocky rock conditions. Drill holes were generally spaced 3,000 ft apart on this 35,915 ft tunnel (only 500 ft apart near the portals).

All told, nearly six months of construction time were lost due to unforeseen geologic problems that caused a major rebuild of the TBM. The major claim was for the TBM rebuild to accommodate the loose, blocky and raveling ground conditions.

The ground conditions also affected the lining. The precast segment design was based on a 70 ft rock load and a maximum deflection of 0.5 percent of diameter. The concentration of blocky rock loads failed several rings and the ring sections were redesigned while the TBM was being overhauled.

Several important lessons vital to tunneling in potentially blocky rock were apparent on this project:

- Geologic problems can be interdependent with the selected excavation method and must be considered as a necessary part of the preconstruction site study. With such a study, the blocky rock conditions would not have caused the three-month delay for rebuilding the TBM.
- Detailed knowledge of the joint spacing, openness, roughness, and filling is necessary in any rock formation that could have blocky rock. Use of a mechanical drill core log and angled drill core perhaps could have relieved some of the problems.
- Even when water is not expected to be a problem, all core holes should be grouted bottom to top to prevent ingress of surface water.
- A properly conducted water make/loss study may have helped to identify the loose joint system.

In all this, the tunnel proved to be an outstanding demonstration of a good mining method. Once the TBM was refurbished, the average 24-hour production day was 70 ft of excavated and final lined tunnel.

CASE STUDY NO. 6

Name of Project: Hades and Rhodes Tunnels (Spec. No. DC-7421)

Purpose: Water conveyance

Location: Utah (40 miles northwest of Duchesne)

Construction Period: September 1980--November 1981

Site Investigation Period: June 1975--Summer 1978

Size: 26,259 ft long (Hades = 22,149 ft, Rhodes = 4,110 ft);
10 ft 5 in. diameter.

Project Cost: Estimated $35,494,430
Bid $34,681,703
As Completed $34,611,894 estimated

Mined Tunnel Construction Cost: Estimated $32,951,695
Bid $27,908,413
Subsurface Related Underruns $1,737,425
Subsurface Related Overruns $1,380,086
As Completed $27,551,074

Subsurface Investigation Cost: Not available

Summary of Site Geology: Alternating strata of limestone, sandstone, siltstone, and shale, dipping at 18 degrees in a regional homocline. Bedding ranging from thin to thick, with some of the limestone being massive. Closely to widely spaced joints. Overall quality varying widely: shales generally weak, sometimes squeezing and swelling; limestone often solutioned; sandstone generally hard and sound, but cementation somewhat variable. At least three faults identified. Maximum overburden (surface to crown) 2,200 ft at Hades and 590 ft at Rhodes. Except for the black shale, all strata water bearing and expected to produce tunnel inflows of 1,000 gpm at Rhodes (diminishing with time) and 3,000 to 4,000 gpm at Hades (for extended period) along with extensive groundwater reservoirs.

Design Criteria: Head ranges from -40 to +200 ft above crown according to borings. Range of ground loads not available.

Contract Provisions:

> **Type:** Unit price per linear ft of finished tunnel, except for pressure grouting. A second unit price was requested for quantities beyond a specified limit.

Stipulations:

Schedule and/or time of completion: 1,445 calendar days for total contract.

Definition of delay and suspension of work.

Liquidated damages: $2,000 per day.

Payment: Monthly, 10% retainage (may be reduced after 50% completion).

Construction method: Options were (1) drill-and-blast for horseshoe, (2) drill-and-blast for circular horseshoe, (3) TBM for circular, and (4) "tunnel excavating machine" for modified horseshoe with vertical sidewalls.

Restrictions: None indicated.

Disputes resolution: Decision by contracting officer. Subject to appeal to head of governmental agency whose decision is final unless question is one of law.

Geotechnical data made part of contract documents: Summary of the geological investigations from specifications; draft of preconstruction geologic memorandum available for inspection. Surface geology map and diagrammatic geologic sections for each tunnel. Photos of core samples in contract documents and cores available for inspection. Electrical resistivity logs and results of expansion and uplift tests on shale samples.

Disclaimers: Deductions, interpretations, and conclusions from factual information are sole responsibility of the contractor.

Changed-conditions clause: Yes

Construction Method: Tunnel boring machine with two grippers and 14- and 12-in. cutters. Primary support of steel ribs and rock bolts. Permanent support of unreinforced cast-in-place concrete (16 in.).

Conditions Encountered: The rock types were as predicted, with much of the shale exhibiting definite squeezing tendencies but with the solutioned limestone producing a much greater volume of water than expected. Poor ground stability in mud filled cavities in limestone. Running ground in sand for a 50-ft reach.

Problems Encountered:

Construction: Excessive overbreak and squeezing shales appear to have affected operations, but not sufficiently to drive the contractor's costs above the figure that was bid. The most serious problem lay in five areas of Hades where large quantities of groundwater flowed from mud filled solution cavities in the limestone. Total flow reached as high as 6,000 to 8,000 gpm for extended periods, at least twice the quantities predicted by bid documents. The occurrences resulted in a number of delays to allow the flows to dissipate and made necessary an upgrading of the pumping system and periods of hand mining.

Operations and Maintenance: No problems identified.

Resolution of Assertions Re Subsurface Changes: The contractor made a claim (amount unknown) for the excessive water pouring from the Hades solution cavities. While the work was in progress, the contracting officer acknowledged the claim's validity and negotiated extras worth $62.31 per lin ft of the entire tunnel. The changes to construction involved deletion of the pressure grouting intended to plug the cavities and payment of $1,380,086 ($62.31 x 22,149 lin ft) to deal with the large water inflows. Because the cost of the grouting would have been greater than the cost of water handling, this change resulted in a net reduction in the contract price for the tunnel itself.

Analysis/Opinion: The general nature of most potential problems could be estimated ahead of time, based on experience in similar geologic settings. However, the owner did not provide sufficient information to permit bidders to make reliable quantitative estimates of problems (e.g., water, squeeze). Hence, the bidders were forced to take a great element of risk. Due to the great depth of overburden, the ability to explore thoroughly with borings was severely limited. The owner did a reasonable job of defining general stratigraphy based on published literature but did not provide cores for the entire stratigraphic section. Also, the owner did not provide sufficient data from laboratory tests to enable reliable estimates of squeeze behavior of weak shales; bidders had to estimate behavior based on their previous experience. Detailed information on experience with two nearby tunnels (different formations but similar overall geologic setting) was available to the owner but not provided to bidders.

This project was successful, but not because of excellent and adequate geologic and geotechnical data. Rather, its success can be attributed to the following:

- The contractor developed efficient means of handling difficult ground conditions such as heavy water inflows, squeeze, and extensive overbreak/fallout.
- Some problems were less severe than possible (e.g., geologic conditions were present for potentially even greater water inflows).
- The owner was willing to negotiate changes with the contractor.

CASE STUDY NO. 7

Name of Project: Carley V. Porter Tunnel (No. 65-29)

Purpose: Water conveyance

Location: California (Kern and Los Angeles Counties)

Construction Period: April 1966--October 1969

Site Investigation Period: 1957--1965 (very intermittent)

Size: 25,075 ft long; 24 ft 4 in. diameter.

Project Cost: Estimated $42,321,830
Bid $33,788,800
As Completed $48,316,215

Mined Tunnel Construction Cost: Estimated $41,341,900
Bid $32,848,600
Extra Support Contract Mods $11,369,256
Subsurface Related Claims $2,500,000
As Completed $46,717,856

Subsurface Investigation Cost: $2,000,000 estimated pre-bid

Summary of Site Geology: Mostly highly fractured, locally altered, strongly crushed and sheared Tejon Lookout granite with roof pendants of metalimestone and hornfels. Rock quality extremely variable, but generally poor. Garlock fault crossed inlet portal; many subsidiary shears throughout alignment. Some lakebed deposits consisting of siltstone and claystone, poorly to moderately indurated. Heavy, locally squeezing and/or running ground expected. Water stored in fractures, shear and granular zones, generally occurring in sporadic pockets. Depth of overburden ranges from 0 to 1,800 ft surface to crown.

Design Criteria: Maximum ground load of 18,150 psf (calculated from load cell data in pilot tunnel); up to 1,520 ft head of water above crown.

Contract Provisions:

Type: Unit price per cubic yd of excavation and unit price (by weight and quantities used) for temporary and final lining components. Estimated quantity variation limits not specified.

Stipulations:
Schedule and/or time of completion: 1,330 calendar days for total contract.
Definition of delay and suspension of work.
Liquidated damages: $2,625 per day.

Payment: Monthly; 10% retainage (may be reduced after 50% completion).

Disputes resolution: Decision by owner's engineer. Decision can be appealed initially to division chief and then to contract appeals board.

Geotechnical data made part of contract documents: Geologic data report available on request, including a profile with stick logs, geologic maps of route and pilot tunnel. Geophysical logs, core samples, and test data available for inspection.

Disclaimers: Data provided for information only. Conclusions and interpretations are sole responsibility of the bidders.

Changed-conditions clause: Yes

Construction Method: Two hydraulic shields with pushing jacks and forepoling jacks; drill-and-blast used as necessary. Primary support of steel liner plates with steel sets and gunite as needed. Permanent support of unreinforced cast-in-place concrete (10 in. minimum).

Conditions Encountered: Highly fractured, locally sheared, altered and crushed Tejon Lookout granite with roof pendants of meta-limestone and hornfels. At outlet portal, soft Pliocene lake deposits consisting of flat bedded, poorly to moderately indurated siltstone and claystone. Local heavy, squeezing and running ground. Water apparently stored in fractures, shears and granular zones, occurring mostly in sporadic pockets. Conditions quite variable, but generally very poor due to crossing the major Garlock fault and its many subsidiary shears. Depth of overburden ranges from 0 to ±1,800 ft surface to crown.

Problems Encountered:

Construction: Running ground and blocky ground, which in one instance caused a tunnel collapse that trapped 17 men for 22 hours and caused a 5-month delay for remining. One zone of very high water pressure and squeezing ground caused pressure binding and structural collapse of the shield. There was overall difficulty in steering the shield so that it failed to maintain the specified alignment. There was general slow progress at 29 locations where faults, granular and clayey altered granitic materials, large water inflows, running ground, and heavy ground loads were encountered. Overall conditions were so difficult that the contractor mobilized a shield and substituted steel rib and steel liner plate for the steel rib and rock bolt initial support called for in the contract documents.

Operations and Maintenance: One low area caused by diving of the shield was found to be silting up when the tunnel was inspected about 10 years after completion.

Resolution of Assertions Re Subsurface Changes: The contractor filed two major claims, one for the collapsed, pressure bound shield (zone of high pressure water and running ground) and another for the generally slow progress at 29 locations, maintaining that the conditions were unusual, unknown, and more frequent and severe than anticipated. The two claims totaled $7,870,101.

The first claim was denied completely by the owner, stating that shield collapse was caused by contractor procedures and poor condition of the shield. The owner also filed a $300,000 counterclaim for failure to maintain the specified alignment as well as negotiating a support steel unit price reduction worth $2,626,300 to himself. The owner disagreed with the contractor's second claim, indicating that the conditions were known, less severe than predicted, and that contractor procedures had contributed to the problems. However, the contractor's second claim was settled at closeout (without litigation) for $2,500,000, which was 32 percent of the amount requested.

Analysis/Opinion: This project is a prime example of how difficult it can be to clarify the question of subsurface related cost overruns in judging the adequacy of the pre-bid site investigation. The simple tabulations indicate that the contractor asked for extras totaling $7,870,101 to cover the cost of a shield collapse and the encounter with unexpected difficult tunneling conditions at 29 locations. The owner negotiated extra payments of $2,500,000 for the difficult tunneling and the records show that amount of loss due to claims. However, this picture may be oversimplified because the tabulation also shows that an additional $11,369,256 in contract modifications was paid to cover the cost of extra tunnel support, most of which was steel used in continuous liner plate proposed by the contractor and approved (though hardly anticipated) by the owner. Because the added support seems attributable to geologic conditions, it is probably fair to say that true overruns really amount to more than 5-1/2 times the 7.6 percent that would be indicated by looking at the claims alone.

The subject tunnel traversed an extent of ground that can be described as extraordinarily bad, given the excavation and support methods available. The inlet portal was driven through part of the major Garlock fault; the entire tunnel was driven through a wedge of ground caught between the Garlock and the San Andreas faults so that it was extremely fractured, sheared, crushed, and altered. The general condition is summed up in the statement from the "as-built" geology report that faults were mapped at an average spacing of 11 ft along the entire tunnel length. The seriousness of the condition was highlighted early by the low bidder's opting for soft-ground shields and continuous steel liner plate in what was supposed to be a rock tunnel that could presumably be supported initially with steel ribs and rock bolts, according to the contract documents. Although the alignment was apparently set in the best available location after extensive study of alternatives, it was most certainly a case of choosing the lesser of known evils.

This ground obviously deserved the most thorough of site investigations. The owner approached it by relying mainly on a program comprising boreholes, a test adit, and a pilot tunnel. The 600-ft test adit and the 3,688-ft pilot tunnel cost well in excess of $1,350,000, more than four percent of the engineer's estimate of tunnel construction cost. They did help to indicate the frequency of poor rock zones that might be encountered and provided the opportunity for grouting program evaluation, water inflow observations, overbreak monitoring, and ground load cell installations. The 1,250-ft spacing for exploratory boreholes seems a bit wide considering the poor geology. The choice of spacing was most likely influenced by difficult access and some great penetration depths (up to 1,820 ft), factors which could have made the desirable number of borings cost-ineffective. In such variable geology, with so many zones of poor rock, it would require an extremely close borehole spacing to thoroughly delineate the ground conditions for the entire length of tunnel. It may not have been unreasonable for the owner to put more than two-thirds of his exploration budget into a test adit and pilot tunnel for thorough observation of the ground at least along those limited lengths. This statement assumes that the owner should then be able to extrapolate from those limited area conditions to judge the general condition of the main tunnel extent. The necessary extrapolation may not have been accurately carried through, but the responsible parties must at least be credited with a serious overall effort.

Indications are that the owner did a considerable amount of detailed geologic interpretation before deciding that Carley V. Porter could be initially supported in typical rock tunnel fashion, with steel ribs and rock bolts. The contracting system was flexible enough to compensate for a certain degree of underestimating because support items were unit priced and it would be easy to pay the contractor for adding jump sets, additional bolts, etc. Yet the owner must have realized early that his assumptions had been very optimistic because he quickly accepted the low bidder's plan to drag soft-ground shields through what should have been rock, supporting it with a system normally associated with earth. He may have been very surprised later by the ultimate project cost because much of the money above and beyond the bid price went for an extensive number of unit priced steel ribs in addition to the agreed upon heavy steel liner plate. Nevertheless, the quick admission that previously presumed hard ground deserved some soft-ground treatment indicates that the owner had doubts about either his subsurface data or his interpretation of them.

Regardless of whatever doubts the owner may have had about his own geologic interpretations, he should have disclosed them to the bidders. This was not done, however. The contract geologic data consisted mostly of nondetailed stick boring logs, with no geologic profiles and almost no interpretive information. Working with this limited body of knowledge, the low bidder was apparently able to perceive the nature of the ground, at least in a general way, more accurately than the owner. Had the bidder been able to examine the detailed, interpretive information with a construction attuned eye, even more of the problem would possibly have been apparent earlier in the game, which then might have led to better overall planning. The owner may have sought protection by withholding pertinent knowledge in the belief that he then could not be held strictly accountable for possible misinformation. However, the bottom line is that the project overruns directly attributable to ground conditions amounted to 33.5 percent of the engineer's estimate and to 42.2 percent of the low bid. The owner gained little from the restrictive disclosure policy and may have actually lost money by employing it.

CASE STUDY NO. 8

Name of Project: Red Hook Interceptor Sewer (Contract 1A)

Purpose: Sewage conveyance

Location: New York (Brooklyn)

Construction Period: April 1978--May 1980

Site Investigation Period: Early mid 1969--June 1970

Size: 8,600 ft long; 10 ft 5 in. diameter.

Project Cost: Estimated $55,733,229
Bid $61,862,009

Mined Tunnel Construction Cost: Estimated $50,242,060
Bid $52,283,285
General Contract Mods $ -80,168
Subsurface Related Overruns $935,999
As Completed $53,139,116

Site Investigation Cost: $74,000 pre-bid (post award costs not available).

Summary of Site Geology: Mostly granular, miscellaneous fill overlying clean, horizontally bedded fine to medium glacial outwash sands with some gravel. Frequent channels, pockets, and lenses of bouldery till and peaty clay. Some obstructions expected in the form of timber piles, bulkheads, and piers. Sands generally compact to very compact, but some loose spots. Permeability of sands and amount of available water great enough to require compressed air or slurry shield for control. Depth of overburden ranges from 12 to 70 ft surface to crown.

Design Criteria: 2 to 10 ft head of water above crown.

Contract Provisions:

Type: Unit price per linear ft of completed tunnel and unit prices for grout and removal of boulders. Estimated quantity variation limits not specified.

Stipulations:
Schedule and/or time of completion: 1,100 calendar days for total contract.
Definition of delay and suspension of work.
Liquidated damages: $2,000 per calendar day.
Payment: Monthly; 7.5% retainage (until 5% of total contract retained).
Construction method: Slurry shield or shield with compressed air.

Restrictions: Blasting subject to engineer's approval. Dewatering not allowed near anchorage of Brooklyn Bridge; elsewhere it was limited to a maximum 6-ft lowering of the water table.

Disputes resolution: Decision, which is "final," by Commissioner of Water Resources. Appeal possible to commissioner; only other recourse is litigation in court.

Geotechnical data made part of contract documents: Report of soil investigation for proposed tunnel section, dated June 1970. General profile included in soil investigation report.

Disclaimers: Data furnished for information only and not a substitute for personal investigation.

Changed-conditions clause: Yes

Construction Method: Full breasting, soft-ground shield with hydraulic excavator and using 18 psi compressed air. Primary support of heavy steel liner plate. Permanent support of cast-in-place concrete.

Conditions Encountered: Essentially as predicted by owner information, except that boulders and timber obstructions were far more numerous. (The selected contractor suspected this possibility during the bidding period because he performed his own subsurface investigation.) In addition, natural gas (methane) and man-made toxic wastes were encountered.

Problems Encountered:

Construction: Running ground was severe enough to require full breasting in spite of the compressed-air operation. Air losses in many places and one fire. There were steering problems in the many tight curves. Methane gas a minor problem, but an encounter with toxic waste in both headings caused a 9-day shutdown. Shields were slowed by an almost continuous deposit of boulders in one 386-ft long section. Progress was slowed further by unexpected encounters with wood cribbing obstructions and timber piles of abandoned piers.

Operations and Maintenance: No problems were identified.

Resolution of Assertions Re Subsurface Changes: The contractor filed four claims for a total of $1,503,000. The claims covered extras for the toxic waste problem, the 386 ft of large boulders, the wood cribbing obstruction, and the timber pile obstruction. The owner accepted the contention that the conditions could not have been anticipated and reimbursed the contractor by negotiating change orders amounting to $935,999.

Analysis/Opinion: Many miles of soft-ground interceptor sewer tunnels have been constructed by the owner, with substantially the same bidding format as the Red Hook tunnel. For this project the owner provided "boring logs" and a "geological report" which could be inspected or purchased by prospective bidders.

The geologic report described the various soil strata identified in the boring logs, such as "fine sand-compact, till, possible boulders, etc.," with very little analysis or discussion of the effect of the varying geology on engineering and construction procedures and problems. It was not a "Geotechnical Engineering Report."

The soils were, in general, reworked glacial soils and the project ran parallel and in close proximity to a terminal moraine. There is considerable information available on the local geology and history as well as on numerous construction projects in the area, including 10 subway tunnels which crossed the line of the sewer tunnel. None of this was discussed in the report and few conclusions were drawn or evaluations made.

The soil samples available for inspection were about 10 years old and of little help to the bidders.

The major problems of a geologic nature that affected construction of the tunnel were as follows:

- An excessive number of large boulders, many more than indicated by the boring logs, and sometimes occurring as large pockets with little or no fines. In one 400-ft length of tunnel, 166 large boulders were encountered and mined through. The largest boulder extended 13 ft along the axis of the tunnel.
- Rock filled timber cribs (some noted on the geology report).
- Pile foundations (not indicated on the borings).
- Toxic chemicals and gases (not indicated on the borings or the geology report).
- An area of very low cover under a heavily traveled industrial street, with major utilities and running sand.

The construction problems encountered were severe, and delays were very costly as the tunnel was built in compressed air with six four-hour shifts per day. Fortunately, there was excellent cooperation with the owner and his contract manager, all with the attitude of how best to solve the problems and get the job done to the owner's specifications and requirements.

Despite many substantial disagreements in negotiating claims for changed conditions, all disputes were settled during the course of the work through negotiated change orders and no claims were filed for litigation by the contractor. The major change orders relating to geological conditions totaled about $936,000 whereas the contractor had requested $1,503,000. (There was another major change order of $574,000 relating to special requirements of the Transit Authority while mining adjacent to more than five pairs of subway tunnels, but this is not related to the purpose of this analysis.)

A more complete "Geotechnical Engineering Report" would have provided the contractors with more information for bidding purposes as well as for evaluating construction procedures. It might have predicted the incidence of boulders much more accurately (as a private report did).

However, better data may or may not have resulted in a greater overall project cost to the owner; the size of the change orders were very nominal for the gravity of the problems, and in a competitive bidding situation the original bids might not have differed greatly. Contractors looking for work are notoriously (but not always wisely) optimistic about solving "field" problems. Sometimes they succeed and occasionally they do not. A difficult project like this could have become a catastrophe, greatly increasing the cost both to the contractor and the owner. It is neither fair to the contractor nor prudent for the owner not to provide all relevant information that can be obtained without excessive costs, including the geotechnical evaluation of the data as they impinge on design and construction of the project.

CASE STUDY NO. 9

Name of Project: Edward Hyatt Powerhouse (formerly Oroville Power Plant)

Purpose: Underground chamber for hydroelectric power production

Location: California (on the Feather River, 5 miles northwest of Oroville)

Construction Period: March 1964--June 1966

Site Investigation Period: December 1959--October 1962

Size: 550 ft long; 139 ft high by 71 ft wide (average).

Project Cost: Estimated $20,592,461
Bid $18,366,780
As Completed $42,414,628

Mined Tunnel Construction Cost: Estimated $7,166,097
Bid $5,990,163
General Contract Mods $998,977
Subsurface Related Overruns $16,300,000
As Completed $23,289,140

Subsurface Investigation Cost: Not available

Summary of Site Geology: Generally fresh, hard and massive amphibolite with some granitic gneissic zones. Three predominant joint sets with fractures, moderately to widely spaced. Many shear zones and schistose zones from 1 to 6 in. wide, containing crushed rock and clay gouge, dipping steeply and spaced 5 to 20 ft apart. Weathering along these zones, but not extending to powerhouse depth. Depth of overburden approximately 300 ft surface to crown. Water movement expected within fractures, joints, and weathered shear zones.

Design Criteria: Modulus of deformation of rock mass = 1.5×10^6 psi; in situ rock stress determined to be isostatic at about 5,000 psi. Designed for relief of hydrostatic pressure (envelope grouting around the powerhouse with decreased injection pressures nearer the structure, combined with a system of gravity drains to relieve pressures on the structure).

Contract Provisions:

> **Type** Unit price per cubic yd for excavation and concrete, per linear ft for rock bolts, and per pound for reinforcing steel. Estimated quantity variation limits not specified.

Stipulations

Schedule and/or time of completion: 1,096 days for total contract.

Definition of delay and suspension of work.

Liquidated damages: $1,000 to $3,000 per day of delay and $100 per cubic yd for excavation outside the B line.

Payment: Monthly; 10% retainage (optional after 50% completion).

Construction method: Drill-and-blast; full face in three separate headings in upper portion and quarry method in lower portion.

Restrictions: None

Disputes resolution: Decision by owner's engineer. If the contractor disagrees, he may file a notice of potential claim; the formal claim must be submitted within 60 days. The engineer decides all claims and his decision is final. The only further recourse may be litigation.

Geotechnical data made part of contract documents: Project geology report available on request, including summary boring logs and mappings in exploration tunnels, but no interpretation. Core samples available for inspection on application.

Disclaimers: Owner completely disclaims responsibility for, and accuracy of, subsurface data.

Changed-conditions clause: Yes

Construction Method: Drill-and-blast using truck-mounted drill jumbos (two platforms with six drills on truck bodies). Primary support of rock bolts and shotcrete with wire mesh.

Conditions Encountered: As predicted by owner information.

Problems Encountered:

Construction: Extensive overbreak during excavation of benches near where adjacent tunnels enter the powerhouse. This required large quantities of rock bolts, steel ribs, and concrete backfill for stabilization. Rock movement in some areas and partial cave-ins of access tunnels.

Operations and Maintenance: No problems identified.

Resolution of Assertions Re Subsurface Changes: The contractor filed a $14,073,427 claim for the bench instability, contending that the complex design shapes were almost impossible to achieve in light of the extensive network of shear and schistose zones. The owner denied the claim, maintaining that the joint patterns and frequency could be observed in the rock exposed in the powerhouse excavation and that the broken condition of the rock was due to poor blasting control and heavy blasting in adjacent tunnels. The owner forced the claim into litigation. The Superior Court of California found in the contractor's favor within 6 months, but the $16,300,000 award (the amount claimed plus escalation and interest) was delayed by appeals until nine years after start of litigation.

Analysis/Opinion: For a project in which the awarded amount from changed-condition claims was equal to 272 percent of the bid amount, the Edward Hyatt Powerhouse location was unusually well explored. Although the cost of the subsurface investigation is not available, the scope of the program appears impressive considering the extent of boring and seismic work, the amount of field and laboratory testing, the footage of exploratory drifts, and the peg model which was constructed. The investigation indicated that construction would be generally within fresh, hard and massive amphibolite with relatively small amounts of granitic and gneissic rock. However, shear zones and some schistose rock were also identified; it was predicted that between these two sources of incompetent materials there would be steeply dipping zones of crushed and/or highly fractured rock every 15 to 20 ft along the chamber axis.

Such zones did indeed occur, and the areas of poor rock caused severe shattering and overbreak in bench areas near intersections between the chamber and adjacent tunnels. The condition required unexpectedly large amounts of concrete backfill as well as additional rock bolts and steel sets for support of the excavation. The contractor contended that the fractured and sheared condition of the rock at the foot of the powerhouse walls was inherently unstable and that the complex shapes required in the large chamber were not possible to construct within the B Line. We must assume this contention to be factual because the courts eventually (after nine years) awarded the contractor the amount asked, plus considerable interest.

The question then becomes: If the geologic site investigation was adequate to define ground conditions accurately, how did an almost unconstructible chamber configuration get into the contract documents? The answer would seem to be that the proper **interpretation** of geologic conditions as related to construction feasibility was not made by the geotechnical engineer or the designer. The effect of incompetent rock zones on the desired excavation outline apparently was not properly assessed during the design stage. A common tunnel design philosophy calls for the designer to size and space the elements of permanent support under the assumption that all temporary and initial support and the maintenance of a proper excavation outline are strictly within the purview of the contractor. This philosophy prevents the owner from improperly taking too much responsibility for routine field situations and operations. It may also obscure the need for geotechnical specialists and designers to maintain construction-wise staffs to review the plans from that particular point of view.

Such an approach can work well with small or uncomplicated openings, especially where the tunneling medium is well suited for underground construction. If that was the governing philosophy behind the Edward Hyatt design, it may have been inadequate because ground conditions were not ideal and the opening was neither small nor uncomplicated. Any powerhouse chamber is quite large, and the excavation shape and stress redistribution patterns are made complex by the intersecting tunnels and the benches required for machinery emplacement. Planning for such a structure requires the designer to help ensure its ultimate integrity by giving the greatest amount of thought to how the concept and the desired shape and dimensions can actually be executed in the field. This, in turn, requires that the designer and/or the geotechnical engineer (without usurping the contractor's final responsibility) review plans thoroughly for "constructibility" in light of the geologic situation and make changes where necessary. Indications are that this step was not adequately pursued on the Edward Hyatt project, so there may have been a shortcoming in the final, interpretive stage, of the site investigation.

CASE STUDY NO. 10

Name of Project: Waste Isolation Pilot Plant

Purpose: Exploratory access shaft to determine site suitability for storage of low-level nuclear waste.

Location: New Mexico (approximately 30 miles east of Carlsbad)

Construction Period: July 1981--December 1981

Site Investigation Period: 1974--1980

Size: 2,242 ft deep; 11 ft 10 in. diameter.

Project Cost: Estimated $10,207,109
Bid $10,361,071
As Completed $10,113,904

Mined Shaft Construction Cost: Estimated $6,977,207
Bid $7,419,705
General Contract Mods $ -171,388
Subsurface Related Overruns $0
As Completed $7,248,317

Subsurface Investigation Cost: Not available

Summary of Site Geology: Overburden consisting of 10 to 40 ft of windblown sand (approximately 20 ft at shaft location) underlain by siltstone. Siltstone interbedded with sandstone and mudstone (the Dewey Lake Red Beds) overlies an anhydrite section interbedded with dolomite and mudstone which merges into the massive salt horizon (from a depth of 800 ft to greater than 2,400 ft). The salt horizon contains thin anhydrite interbeds and one zone enriched in potassium chloride.

Design Criteria: Concrete key at 850-ft depth designed for lateral pressure of 75 percent of overburden weight; steel liner and key designed for hydrostatic head of 600 ft.

Contract Provisions:

Type: Cost plus. (Drilling contract on "day work" basis.)

Stipulations:
Schedule and/or time of completion: Unknown
Definition of delay and suspension of work.
Payment: Monthly; 10% retainage until 50% completion.
Construction method: Blind hole drilling.
Disputes resolution: Standard "General Conditions" for federal government contract.

Geotechnical data made part of contract documents: Vertical section (composite of two borings) included in contract drawings. Core samples available for inspection.

Disclaimers: None with respect to owner-furnished information on subsurface conditions.

Changed-conditions clause: Yes

Construction Method: Downhole drilling using drill derrick and hoist with 12-ft diameter rolling cutterhead. Permanent support of steel liner in upper 850 ft; no final lining at greater depths, but with rock bolts and wire mesh for support as required.

Conditions Encountered: As predicted by owner information, but less convergence than expected in salt.

Problems Encountered:

Construction: None of any significance.

Operations and Maintenance: No problems identified.

Resolution of Assertions Re Subsurface Changes: No assertions made.

Analysis/Opinion: The site investigation was carried out almost continuously during 1974-1980 and covered an area of more than 100 sq miles before the final site was selected. The cost of this overall effort was very high--in aggregate more than the cost of the shaft itself. It is not possible to identify and separate those costs that are site specific to the shaft, but only a small percent of the investigation cost can be assigned to site description for design purposes. Two boreholes were drilled near the shaft site. Deliberately, drilling in the immediate area was held to a minimum so as to avoid possible communication pathways into the repository area.

Given that the project was conducted in a glare of publicity, much of it adverse to the concept of a low-level nuclear waste repository, it was essential that unforeseen problems or delays did not occur. Any problem--particularly if unexpected--would have been used as "proof" of site unsuitability. Thus, the preconstruction geotechnical investigations and design were of necessity over-conservative. It was a classic example of "belt and suspenders" design.

The skeletal design criterion was to rapidly construct an access shaft, plus a ventilation/escape shaft. The access shaft would be used to excavate chambers in the salt, at the preselected repository horizon, in which to conduct various long-term tests.

There were two major specific design criteria. One was that the Dewey Lake Red Beds could not be allowed to become water saturated; historically, if wet the beds would swell, spall, and cave. The other criterion was that the minor-flow fresh water aquifer could not be allowed to contact the salt; it would cut channels and could disrupt the shaft fittings in the unlined portion of the shaft (i.e., that portion in salt).

Large diameter drilling was selected as the construction approach for several reasons:

- It was demonstrably much faster, and there was no risk to personnel from working in a shaft bottom (no one entered the shaft until it was completed).
- It was not subject to the delays and problems with water that have accompanied conventional shaft sinking in the area.
- It provided minimum disturbance to the salt, e.g., no blast fractures, so that the necessary measurements of salt creep and long-term stability could be carried out in the shaft as well as in the chamber areas.
- The unlined ventilation/escape shaft could be quickly and economically "slashed" (enlarged) to a size suitable for long-term usage, should the test program demonstrate acceptability of the site for a repository. In the meantime, the small shaft, which was a safety-dictated necessity during the test program, could be constructed very rapidly and at much less cost than a conventional drill-and-blast shaft.

The construction manager developed the contract specifications and, because the technique and methodology had been preestablished by the owner, opted for a "day-work" type subcontract for the drilling operations. (Equipment and personnel operated on a fixed hourly rate, with the rate dependent on the type of work being performed.) The construction manager estimated the number of hours required for each category of work, and the drilling contractors bid hourly rates for their rig, ancillary equipment, and personnel based on their estimated quantities. The minimum size and capacities of the drill rig were specified in detail in the call for bids, and the drilling subcontractor's experience in similar work was also a bid appraisal consideration.

The given geologic data consisted of a geologic column in the form of a strip log, with pertinent geologic and hydrologic comments in the margin. It should be noted that the local geology and hydrology were well known to the construction manager; therefore, with the type of contract, full details including geotechnical data were not essential to the drilling subcontractor.

The construction method was blind shaft rotary drilling with cuttings removal accomplished by a dual string circulation system. With this technique, a mix of high-pressure air and drilling fluid is pumped down the annulus between two coaxial strings of pipe (in this case 7 in. by 13 3/8 in.). The mixture flows into a chamber in the bit body, through jet nozzles in the bottom of the bit, and returns to the surface via the 7 in. inner pipe, carrying with it the cuttings from the hole bottom. A "blanket" of fluid, 150 to 200 ft deep, in the shaft prevents the air-fluid mix from filling the shaft.

The conditions encountered were precisely as anticipated; the formation changes were within inches of where shown on the strip log. Aside from minor operational problems with the dual-string system, the construction proceeded as planned and scheduled.

This project <u>is</u> <u>not</u> a good example of severe construction problems, or of highly critical geologic-geotechnical features. However, it <u>is</u> a good example of how smoothly construction can proceed when the hazard areas are recognized in advance and appropriate plans made for overcoming them.

On this project, the major hazard by far was the tendency of the Dewey Lake Red Beds to absorb water, swell, and slough. Much of the drilling in the area for oil wells has been plagued by this problem, and many holes have been delayed or lost. What is an irritation in an oil well can be a catastrophe in a large drilled shaft. If the shaft walls collapse atop a "big hole" drilling assembly, the cost of the tools lost exceeds $500,000. In addition there is a delay of several months while new tools are procured. At the WIPP site, potassium ion was added to the drilling fluid to inhibit wetting of the shales, and the dual string technique minimized the exposure time.

The project was completed ahead of schedule and under budget--a tribute to good geotechnical data, good engineering, and good estimating.

7.
Interpretation of Case Histories

The original data for the 87 projects discussed herein were obtained through an extensive procedure (see Appendix C) involving extraction of detailed information from documents submitted by owners and personal interviews with staff representing the owner, contractor, and engineers for each project. The procedure was extremely complicated, involving accurate recording of both qualitative and quantitative data. For example, qualitative data included statements regarding problems related to ground conditions encountered during construction, comments on the effectiveness of the site investigation program, and opinions concerning disputes. The quantitative data covered a wide range of items, such as project costs and schedule, tunnel specifications, geologic criteria, types and number of exploration techniques, and construction methods and progress. Subsequently, some basic calculations using these quantitative data were made, for example to derive the face area, volume in cubic yards of excavation, borehole spacing, advance rate per shift, etc. Occasionally there was some overlap; sometimes the actual excavated volume in cubic yards had also been obtained from documents supplied by the owner.

The original data from documents and interviews were recorded on a 15-page data form, with the interviewers often adding several pages of explanatory information. These data were then combined with the basic calculations. Thus, there was a large and complex body of qualitative and quantitative information to be examined.

CHARTED AND PLOTTED DATA

Summary Matrixes

An array of geotechnical problems that occurred during construction of the 84 mined tunnels and 3 deep shafts can be seen at a glance in the summary matrix presented separately as Plate 1. The matrix shows the 87 study projects plotted against the abbreviated "problems encountered" list from the project abstracts. This list allowed for consideration of 31 separate items grouped into 7 categories: unstable ground, groundwater inflow, hazardous environmental factors, mechanical problems (rock and TBMs), soft-ground methods, compressed air, and other.

Through the use of symbols, the matrix indicates which conditions developed into problems and which of the problems were serious enough to cause claims. The matrix makes it clear that most projects encounter not just one, but several construction problems. What may not be apparent is that many conditions interact or affect each other, so that some judgment was required in deciding on the primary culprits in an abbreviated list of problem descriptions.

A second matrix was prepared to chart selected, original numerical data for each of the 87 projects in combination with basic calculated data for each. A total of 57 different items were displayed in the summary matrix, as shown in Table 7.1.

TABLE 7.1 Contents of Data Matrix

Original Data	Calculated Data
Name of project	Months to build
Purpose of tunnel	Factor to escalate costs
Number of bidders	Cost, bid as % of estimate
Start and finish dates	Cost, total as % of estimate
Cost, engineer's estimate	Face area
Cost, bid	Tunnel volume
Cost, total to build	Cost, $/cu yd
Cost, exploration	Cost, $/lin ft
Number of tubes	Exploration, % of tunnel cost
Length of tunnel	Exploration, $/cu yd
Shape of tunnel	Boreholes, average depth
Tunnel volume	Boreholes, lin ft/route ft
Type of ground	Boreholes per 1,000 route ft
Geology (simplified)	Boreholes, spacing
Overburden, max and min	Boreholes, $/lin ft
Water head, max and min	Overall advance per day
Water inflow, max and min	Advance per 8-hr shift
Boreholes, number	Labor, total man hours
Boreholes, lin ft	Labor, man hours/day
Borehole depth, max and min	Excavation, man hours/cu yd
Boreholes, distance from centerline	Excavation, cu yd/hr
Compressive strength tests, number	Claims made, $/cu yd
Compressive strength, max and min	Claims settled, $/cu yd
Construction equipment/method	Claims, $ settled as % made
Primary support	
Advance per day, max and average	
Days worked	
Shifts worked	
Crew size	
Problems, construction	
Liquidated damages in specifications	
Claims made, $	
Claims settled, $	

The information summarized in the data matrix served for initial review of comprehensive results, following which the content of the matrix was expanded by additional basic calculations. This revised data summary formed the basis for plotting graphically and for arithmetic tabulation. Among the tabulations were such items as total claims made and settled, cost in dollars per cubic yard for different methods of excavation, boreholes in linear feet for tunnels in mountainous areas, etc.

A modified version of the data summary matrix is presented separately as Plate 2. It displays 20 of the 57 items of original and calculated information contained in the complete summary.

Plots Generated

During several subcommittee meetings, the complete data summary was reviewed in conjunction with the problem summary in order to select items that appeared to be most promising for study. To accommodate the variety of data selected for examination, the ability to sort and plot graphically at various scales was essential. A specialized computer program was written by personnel of Tudor Engineering Company to select and plot TBM, drill-and-blast, soft-ground and compressed-air tunnels built for rapid transit, railroads or water conveyance, or underground subway stations or hydroelectirc powerhouses. Table 7.2 lists the plots generated to sort the data according to various combinations of parameters. Another computer program without plotting capability, prepared at Virginia Polytechnic Institute to manage the abstract form of the case histories, was also used to search and review the data on a general basis.

TABLE 7.2 Data Plots Generated for Correlation

Plot	X Axis	Y Axis	Method
1	Boreholes, LF/RF	Cost, 1982 $/cu yd	All
2	Exploration, as % cost	Total cost, as % eng. est.	All
3	Exploration, $/cu yd	Cost, 1982 $/cu yd	All
4	Boreholes, number	Cost, 1982 $/cu yd	All
5	Avg. Advance, LF/day	Cost, 1982 $/cu yd	All
6	Claims made, $	Total cost, $	All
7	Boreholes, LF/RF	Total cost, as % eng. est.	All
8	Water inflow, max gpm	Total cost, as % eng. est.	All
9	Bidders, number	Total cost, as % eng. est.	All
10	Boreholes/1,000 RF	Cost, 1982 $/cu yd	All
11	Face area	Cost, 1982 $/cu yd	All
12	Water inflow, max gpm	Cost, 1982 $/cu yd	All
13	Avg. Advance, LF/day	Cost, 1982 $/cu yd	All
14	Boreholes, LF/RF	Exploration, as % cost	All
15	Length, LF	Cost, 1982 $/cu yd	All
16	Advance rate, LF/day	Cost, 1982 $/cu yd	TBM, D&B
17	Advance rate, LF/day	Cost, 1982 $/cu yd	D&B
18	Advance rate, LF/day	Cost, 1982 $/cu yd	TBM
19	Advance rate, LF/day	Cost, 1982 $/cu yd	Soft ground

TABLE 7.2 Data Plots (continued)

Plot	X Axis	Y Axis	Method
20	Boreholes, number	Cost, as % eng. est.	TBM
21	Length, LF	Cost, as % eng. est.	TBM
22	Avg. Advance, LF/day	Cost, as % eng. est.	TBM
23	Exploration, as % cost	Cost, 1982 $/cu yd	TBM
24	Boreholes/1,000 RF	Total cost, as % eng. est.	TBM
25	Boreholes, number	Total cost, as % eng. est.	D&B
26	Length, LF	Cost, as % eng. est.	D&B
27	Avg. Advance, LF/day	Cost, as % eng. est.	D&B
28	Exploration, as % cost	Cost, 1982 $/cu yd	D&B
29	Boreholes/1,000 RF	Cost, as % eng. est.	D&B
30	Boreholes, number	Total cost, as % eng. est.	All
31	Length, LF	Cost, as % eng. est..	All
32	Avg. Advance, LF/day	Cost, as % eng. est.	All
33	Exploration, as % cost	Cost, 1982 $/cu yd	All
34	Length, LF	Cost, as % eng. est.	All
35	Boreholes/1,000 RF	Total cost, as % eng. est.	All
36	Exploration, as % cost	Claims paid, as % total cost	All
37	Boreholes, LF/RF	Claims paid, as % total cost	All
38	Boreholes/1,000 RF	Claims paid, as % total cost	All
39	Boreholes, number	Claims paid, as % total cost	All
40	Exploration, as % cost	Claims made, as % cost	All
41	Boreholes, LF/RF	Claims made, as % cost	All
42	Boreholes/1,000 RF	Claims made, as % cost	All
43	Boreholes, number	Claims made, as % cost	All
44	Length, LF	Cost, 1982 $/cu yd	TBM
45	Boreholes, LF/RF	Cost, 1982 $/cu yd	TBM (water)
46	Total cost	Cost, as % eng. est.	All
47	Boreholes, LF/RF	Avg. Advance/8 hr	All
48	Overburden, max	Avg. Advance/8 hr	All
49	Avg. Advance/8 hr	Length	D&B
50	Avg. Advance/8 hr	Cost, 1982 $/cu yd	D&B
51	Avg. Advance/8 hr	Face area	D&B
52	Excavation, cu yd/hr	Length	D&B
53	Excavation, cu yd/hr	Cost, 1982 $/cu yd	D&B
54	Excavation, cu yd/hr	Face area	D&B
55	Avg. Advance/8 hr	Length	TBM
56	Avg. Advance/8 hr	Cost, 1982 $/cu yd	TBM
57	Avg. Advance/8 hr	Face area	TBM
58	Excavation, cu yd/hr	Length	TBM
59	Excavation, cu yd/hr	Face area	TBM
60	Excavation, cu yd/hr	Cost, 1982 $/cu yd	TBM

TABLE 7.2 Data Plots (continued)

Plot	X Axis	Y Axis	Method
61	Boreholes, LF/RF	Bid, as % eng. est.	All
62	Boreholes LF/RF	Bid, as % total cost	All
63	Boreholes, LF/RF	Claims made, as % eng. est.	All
64	Boreholes, LF/RF	Claims made, as % bid	All
65	Boreholes, LF/RF	Total cost, as % bid	All
66	Exploration, as % eng. est.	Bid, as % total cost	All
67	Exploration, as % eng. est.	Total cost, as % eng. est.	All
68	Exploration, as % eng. est.	Claims made, as % eng. est.	All
69	Exploration, as % eng. est.	Claims made, as % bid	All
70	Exploration, as % total cost	Total cost, as % eng. est.	All
71	Boreholes, LF/RF	Total project cost, as % eng. est.	All
72	Boreholes, LF/RF	Total project cost, as % bid	All

"Cost" refers to mined tunnel (or shaft) construction only, excluding claims and modifications awarded. "Total cost" is synonymous with "as completed cost," which includes any claims and modifications awarded. "Project cost" refers to the total contract, of which the mined tunnel is a part.

Review of the plots led to a determination that many of the combinations of parameters reflected a lack of significant or meaningful correlation. Moreover, in cases where the parameters had been further sorted for plotting according to construction method, sampling limitations produced results that were deemed generally inadequate for correlation purposes. The ability to distinguish among the types of projects proved interesting for discussion of the plots but provided no conclusive results.

Variation in sample size was a continuing concern because of its potential for limiting or negating the utility of the plots. As noted above, the sorting technique was a factor that ultimately yielded inadequate samples for more than 30 percent of the plots. However, the plots generated to examine all projects were also subject to some reduction in sample size arising from availability of data for parameters. The effects were most apparent for parameters based on water inflow and on excavation and advance rates combined with work force units (number of length of shifts and crew size). Results for other parameters, such as exploration costs, were monitored for possible sampling influence. From the standpoint of availability of samples, the parameters considered most reliable for correlation purposes included data relating to tunnel length, face area, overburden, cubic yards of excavation, number of bidders, boreholes, engineer's estimate, bid estimate, total cost, and claims made and awarded.

The subcommittee critically reviewed the results derived from the mass of qualitative and quantitative information gathered from the 87 case histories, and selected the more distinct of the pertinent results for presentation. The discussion that follows is confined to matters that bear on the nature of the relationship between geology and construction and the significance of the geotechnical site investigation.

INTERPRETATION OF RESULTS

Data derived from the 84 mined tunnels included in the 87 study projects shown in Plate 1 is tabulated in Table 7.3. Overall, unstable ground is the most prevalent problem encountered during construction, with blocky/slabby and running ground cited most often as specific conditions (38 percent and 27 percent, respectively) for all the projects. Groundwater inflow is cited as a problem in 33 percent of the projects.

TABLE 7.3 Problems and Claims* Reported for Mined Tunnels

	Problems (% of tunnels)	Claims (% of tunnels)
Blocky/slabby rock, overbreak, cave-ins	38	16
Running ground	27	9
Flowing ground	5	4
Squeezing ground	19	8
Spalling, rock bursts	6	4
Groundwater inflow	33	6
Noxious fluids	6	4
Methane gas	7	2
Existing utilities	1	0
Soft bottom in rock	2	2
Soft zones in rock	4	2
Hard, abrasive rock (TBMs)	5	2
Face instability, rock	5	1
Roof slabbing	4	1
Pressure binding (equipment)	4	4
Mucking	5	2
Surface subsidence	9	2
Face instability, soil	11	5
Obstructions (boulders, piles, high rock in invert, cemented sand)	12	11
Steering problems	4	0
Air slaking	1	0

*As noted earlier, in this report the word "claim" is a shorthand expression that encompasses all requests for extras as a result of an unexpected subsurface situation.

The percentage of incidence as a problem indicated for groundwater does not account for its role as a contributor to the incidence or severity of other conditions (e.g., flowing ground, face instability), which would raise its rating significantly. As explained in Appendix C, there may have been instances where unclear original sources of information led the subcommittee to label occurrences of "flowing" ground (which is wet) as "running" ground (which is dry). This is one of the reasons that the problem tabulations do not give as much weight to groundwater as it deserves. The subcommittee believes that water plays a large and varied role in tunnel construction difficulties; yet it may not always appear in the simplified listing of problems encountered in a project because it is a secondary contributor to the primary problem. For example, face instability would in many cases not have been a problem without the presence of water to reduce friction along joint surfaces or create seepage pressure, although the water might exist in quantities too small to deserve mention under groundwater inflow. In the same way, if only half of the recorded occurrences of running ground were really flowing ground, then that would raise by 12 the number of projects for which groundwater was a contributing cause of significant problems.

Of all the problems, the highest incidence of claims (16 percent) was recorded for the grouping with the highest incidence of occurrence, i.e., blocky/slabby rock, overbreak, cave-ins. Of the other five conditions reported most frequently, three exhibit a similar relationship to claims. However, groundwater ranks several positions higher in problem incidence than in claim incidence; the ranking for obstructions is the reverse. Even so, the overall relationship is unchanged: the six conditions causing the most problems cause the most claims. Generally thereafter, it is difficult to determine a pattern by ranking.

However, the significance of a problem is related not only to frequency of occurrence but also to magnitude of impact. The tabulations in Table 7.3 can be translated to obtain a measure of impact by relating the incidence of claims to the occurence of problems. This method reveals that the relationship between occurrence and impact can be inversely proportional, as shown by the ratings presented in Table 7.4. For comparison purposes, Table 7.4 lists the problem conditions according to their frequency of occurrence, from highest to lowest. The impact rating is on an ascending scale, with a maximum value of 10. (For quick comparison between problem occurrence and significance, the impact rating can be multiplied by 10--i.e., a rating of 9.2 indicates a 92 percent incidence of claims per occurrence.)

Table 7.4 reflects considerable impact--a rating higher than 6.5--for six specific conditions, all of which occur infrequently: soft bottom in rock, pressure binding, obstructions, flowing ground, spalling and rock bursts, and noxious fluids. At this point the impact rating decreases suddenly, revealing six conditions closely grouped in the range from 5.0 to 4.0. In this grouping, the impact rating is moderately high and the frequency is generally low, but a trend begins toward more direct proportion (i.e., for blocky/slabby rock and squeezing ground). For the remaining problems, the impact rating then drops to 3.3 (running ground), clusters again with five conditions (including groundwater inflow) between 2.8 and 1.8., and then falls to 0.

TABLE 7.4 Impact Rating for Problem Conditions

Conditions (% problems or occurrence)	Impact Rating
Blocky/slabby rock, overbreak, cave-ins (38)	4.2
Groundwater inflow (33)	1.8
Running ground (27)	3.3
Squeezing ground (19)	4.2
Obstructions (12) (boulders, piles, high rock, cemented sand)	9.2
Face instability, soil (11)	4.5
Surface subsidence (9)	2.2
Methane gas (7)	2.8
Noxious fluids (6)	6.6
Spalling, rock bursts (6)	6.6
Hard, abrasive rock, TBMs (5)	4.0
Face instability, rock (5)	2.0
Flowing ground (5)	8.0
Mucking (5)	4.0
Pressure binding, equipment (4)	10.0
Roof slabbing (4)	2.5
Soft zones in rock (4)	5.0
Steering problems (4)	0
Soft bottom in rock (2)	10.0
Air slaking (1)	0
Existing utilities (1)	0

In certain instances (e.g., pressure binding), the severity of a problem can be linked with the sensitivity of the construction method to a particular condition. In others (e.g., overbreak, obstructions), it is less clear whether difficulty is more a function of the existing condition or the technique. It is likely that frequency of occurrence may sometimes be a moderating influence because it results in enhanced experience and ability to cope that offsets the problem to some degree. In part, this may explain why the incidence of claims and/or impact rating for some problem conditions (e.g., runnning ground) is lower in relation to prevalence than might otherwise be expected.

Unfortunately, several important aspects of the relationship between geotechnical conditions and construction problems cannot be readily discerned or computed. They are the length of delays and degree of inefficiencies that are introduced as a consequence, and their associated costs. The cost impact is not limited to construction dollars alone, but extends to project reliability and longevity.

Although certain aspects remain ill defined, the plots and tabulations of numerical data yielded several interesting trends and quantitative values that help delineate the extent of the interaction of geology with construction and the effect of the geotechnical site investigation. The findings relate to the level of exploration, cost estimates, project costs, and claims.

Before discussion of the findings, the manner of reporting the data merits a brief explanation. For the tabulated data, results are generally presented as the arithmetic mean--referred to hereinafter as the "average," in the commonly understood sense of the word. For much of the plotted data, results are cited in terms of the "median." Here, the value expressed by the median is considered more accurate than the everyday form of averaging, because the median accounts for the effects of significant skew in the samples. The techniques for deriving the values differ and, therefore, the terms "average" and "median" are not used interchangeably in this report.

Level of Exploration

In present practice, overall, the average number of boreholes drilled per 1,000 route ft of alignment is 2.4--i.e., a spacing that approaches 415 ft. It should be noted that these figures are based on 84 projects, of which 20 percent are in mountainous areas where tunnel depth can often exceed 1,000 ft and hole-to-hole spacing can reach thousands of feet. When data for these tunnels are excluded in order to reflect more common practice, then the average number of boreholes per 1,000 route ft nears 3.9, for a spacing that is about 260 ft.

Although these tabulations provide a measure of exploration, they do not allow sufficiently for the effect of tunnel depth. Therefore, a more meaningful gauge can be obtained by determining the linear ft of borehole drilled per route ft of alignment. When the level of exploration is expressed in this manner, then the median lin ft of borehole per route ft is .34 in overall practice and .42 in common practice. (In this instance, the averages for lin ft per route ft are similar, .30 and .43, respectively.)

Exploration costs were extremely difficult to compile because separate records of the amounts spent were often not available or were incomplete. In addition, the task of apportioning costs for investigation programs overlapping several projects was complex. As a result, the figures for exploration costs are considered less reliable than others reported herein.

Of the 84 study projects, exploration costs for 36 were obtained. Information was sufficient for 30 projects (except as noted) to permit the extrapolations shown in Table 7.5 Although some inconsistencies in matching samples were encountered, the preponderance of the data was obtained from projects for which figures were consistently available for each item tabulated. Therefore, the small variation in matching samples did not affect the results significantly.

TABLE 7.5 Exploration Costs Compared to Construction Costs

		Exploration Costs ($ millions)			
			Expressed as % Construction		
	Construction ($ millions)	Total	Overall	Range	Median
Engineer's Estimate	829.87*	9.80*	1.18	.01-24.4	.44
Basic Construction**	661.29	11.53	1.74	.02-17.5	.75
As Completed	694.00	11.53	1.66	.01-17.5	.70

*Figures are based on data for 28 projects.

**Costs excluding claims awarded.

Figure 7.1 illustrates more clearly the degree and nature of the scatter indicated by the range cited for exploration costs as a percent of construction costs. It is evident that funds expended for site investigation programs do not rise with increasing project costs. Rather, a significant number of the more costly projects (i.e., those in the upper half of the scale) exhibit a decrease in exploration funds to a point well below the median. It is in the mid range that the number of projects above the median generally equals the number below. However, only about 30 percent of these projects approach the median within a reasonably small range of scatter.

Overall, these results indicate that present practice is to devote a relatively small portion of project costs to a site investigation program. In some instances, low expenditures may be warranted because a sufficient body of information may be available from explorations conducted for overlapping projects, or nearby projects, or from other sources such as aerial surveys and regional geologic reports. However, these circumstances cannot be assumed to explain entirely the general low level of expenditures or the scatter in the data. Even though the cost of construction is not always in direct proportion to the geotechnical complexity or extent of a project, the relationship between these factors is obvious. On that basis, it is apparent that level of exploration costs does not correlate satisfactorily with construction costs.

Estimates of Cost: Engineer and Contractor

The engineer's estimate is a measurement of costs that is used by the owner for a variety of purposes throughout the conceptual to completion phases of a project. Essentially it serves as a benchmark for the development and evaluation of the components of the planning, design, bidding, and construction processes. As such, the engineer's estimate is depended on to predict the actual project costs with reasonable accuracy.

Figures 7.2, 7.3, and 7.4 compare the as-completed costs for mined tunnels with the engineer's estimate. The comparison examines the cost relationship in terms of several parameters representing the level of exploration. The individual results combine to form a more comprehensive basis for correlation.

A review of Figures 7.2 through 7.4 reveals that as-completed costs differ significantly (±50 percent) from the engineer's estimate when the level of effort or funds devoted to geotechnical site investigations are low. However, this degree of variability is a reasonable occurrence only during the earlier stages of the initial conceptual work--i.e., when the exploration program is still in progress. This circumstance suggests that general exploration practice is providing inadequate information for reliably estimating as-completed costs. The suitability of the site investigation also must be considered for its sensitivity to the effort level, an important concern because of its potential influence on reliability.

The deviation between as-completed and estimated costs decreases as exploration increases. Figure 7.2 indicates that the engineer's estimate becomes a more reliable tool for predicting actual costs when sufficient exploration has in fact been accomplished--i.e., boreholes at greater

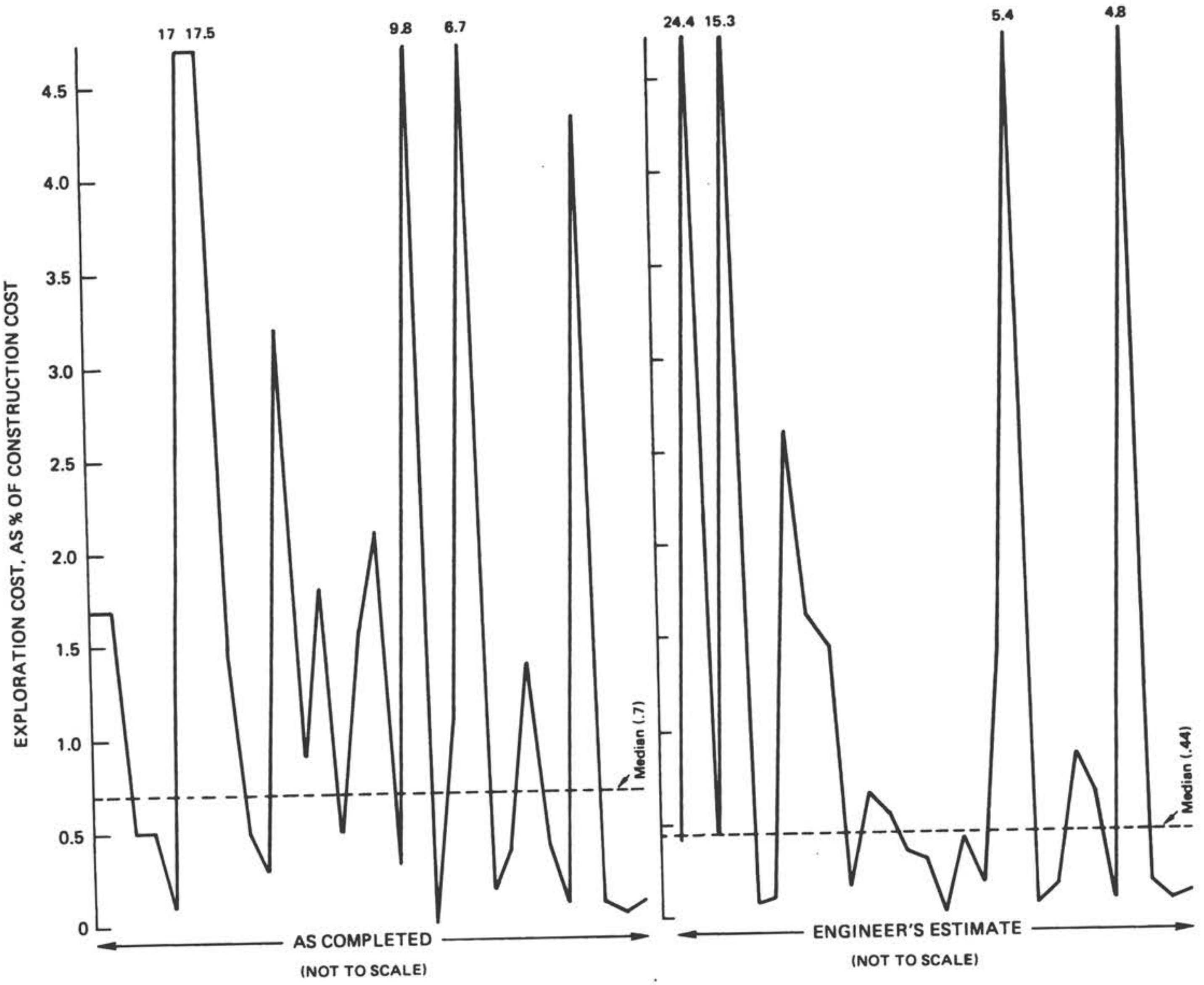

EXPLORATION COST, AS % OF CONSTRUCTION COST
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
17
17.5
9.8
6.7
24.4
15.3
5.4
4.8
Median (.7)
Median (.44)
AS COMPLETED
(NOT TO SCALE)
ENGINEER'S ESTIMATE
(NOT TO SCALE)

FIGURE 7.1

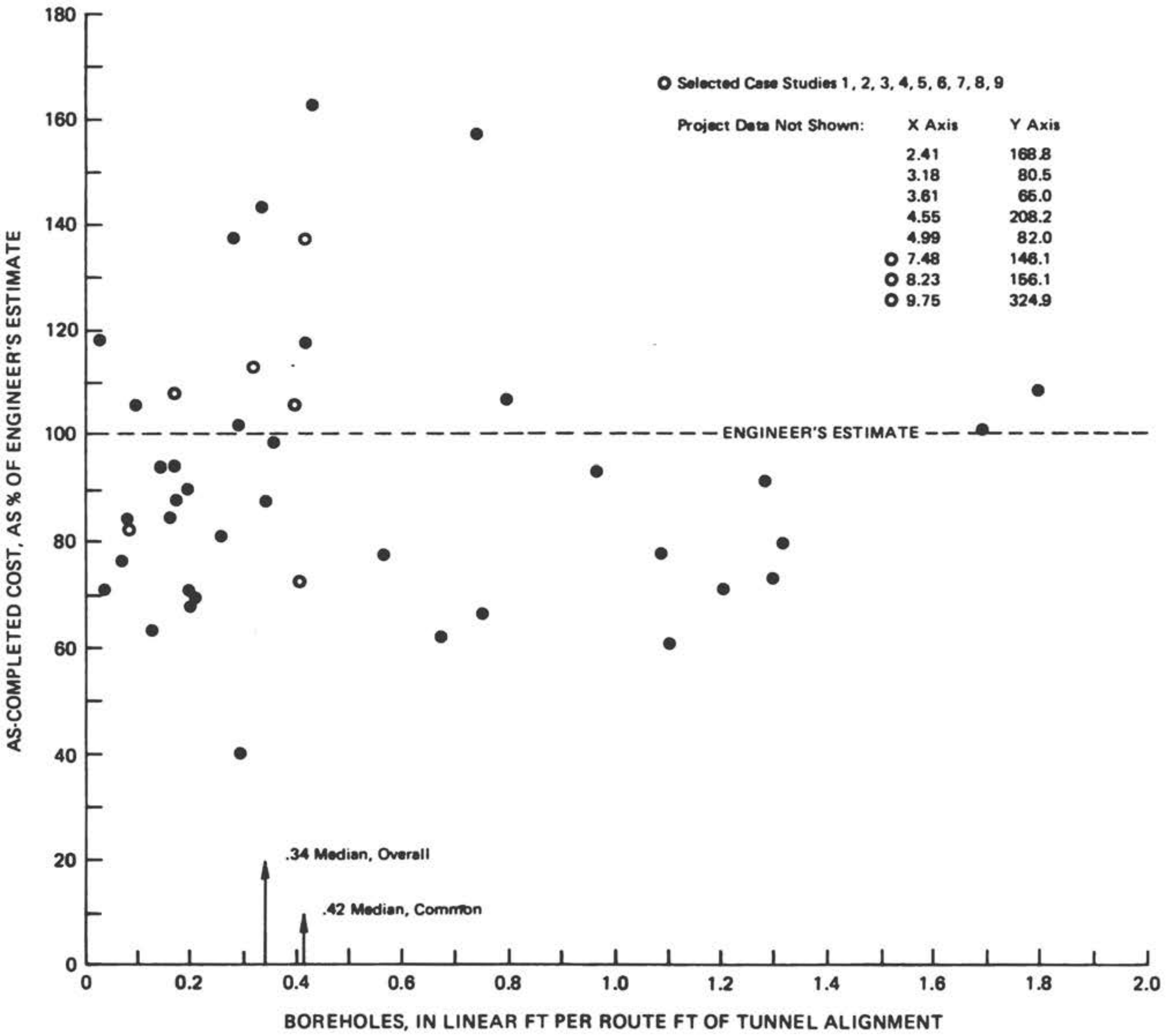

○ Selected Case Studies 1, 2, 3, 4, 5, 6, 7, 8, 9
Project Data Not Shown: X Axis Y Axis
2.41 168.8
3.18 80.5
3.61 65.0
4.55 208.2
4.99 82.0
○ 7.48 146.1
○ 8.23 156.1
○ 9.75 324.9
ENGINEER'S ESTIMATE
.34 Median, Overall
.42 Median, Common
AS-COMPLETED COST, AS % OF ENGINEER'S ESTIMATE
0
20
40
60
80
100
120
140
160
180
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
BOREHOLES, IN LINEAR FT PER ROUTE FT OF TUNNEL ALIGNMENT

FIGURE 7.2

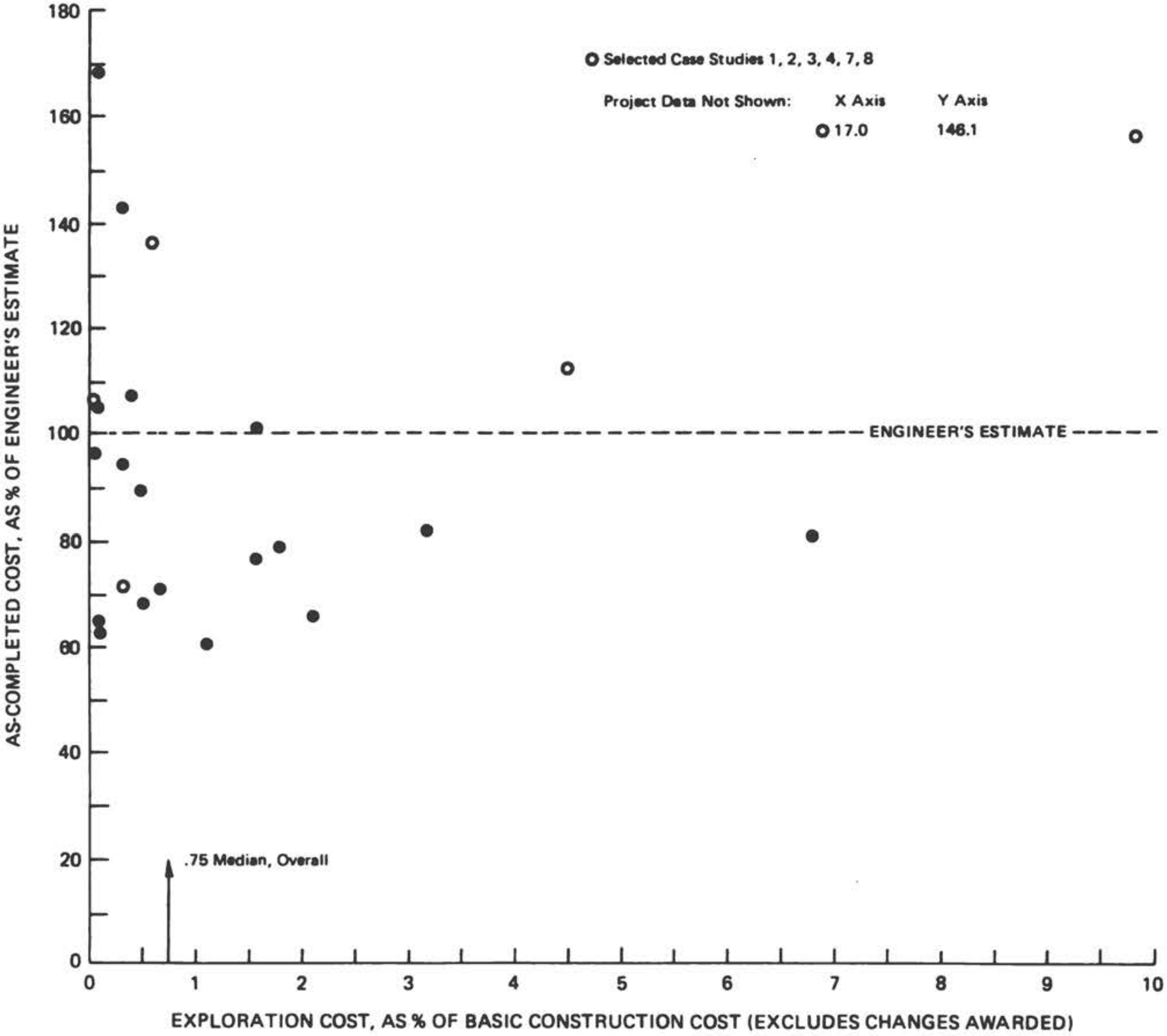

○ Selected Case Studies 1, 2, 3, 4, 7, 8
Project Data Not Shown: X Axis Y Axis
○ 17.0 146.1
ENGINEER'S ESTIMATE
.75 Median, Overall
AS-COMPLETED COST, AS % OF ENGINEER'S ESTIMATE
0
20
40
60
80
100
120
140
160
180
EXPLORATION COST, AS % OF BASIC CONSTRUCTION COST (EXCLUDES CHANGES AWARDED)
0
1
2
3
4
5
6
7
8
9
10

FIGURE 7.3

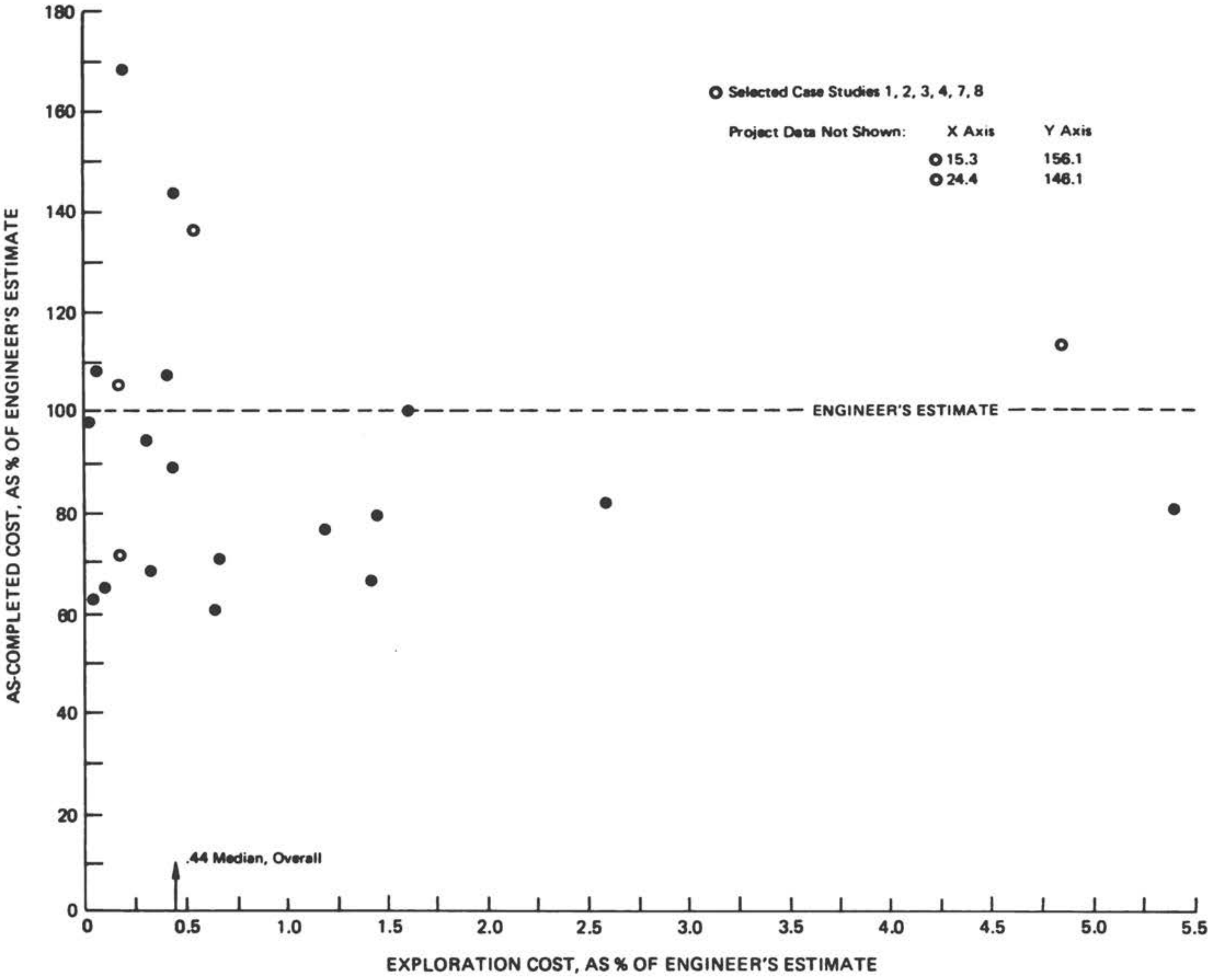

○ Selected Case Studies 1, 2, 3, 4, 7, 8
Project Data Not Shown:
X Axis
Y Axis
○ 15.3
156.1
○ 24.4
146.1
ENGINEER'S ESTIMATE
.44 Median, Overall
AS-COMPLETED COST, AS % OF ENGINEER'S ESTIMATE
EXPLORATION COST, AS % OF ENGINEER'S ESTIMATE
0
20
40
60
80
100
120
140
160
180
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

FIGURE 7.4

than 0.6 linear ft per route ft. At this point, a substantial reduction is reflected in the frequency and degree of scatter above the estimate. A similar trend is exhibited in Figures 7.3 and 7.4, when funds expended exceed one percent. Decreasing scatter below the estimate is less marked in degree, but it is a tendency worth noting.

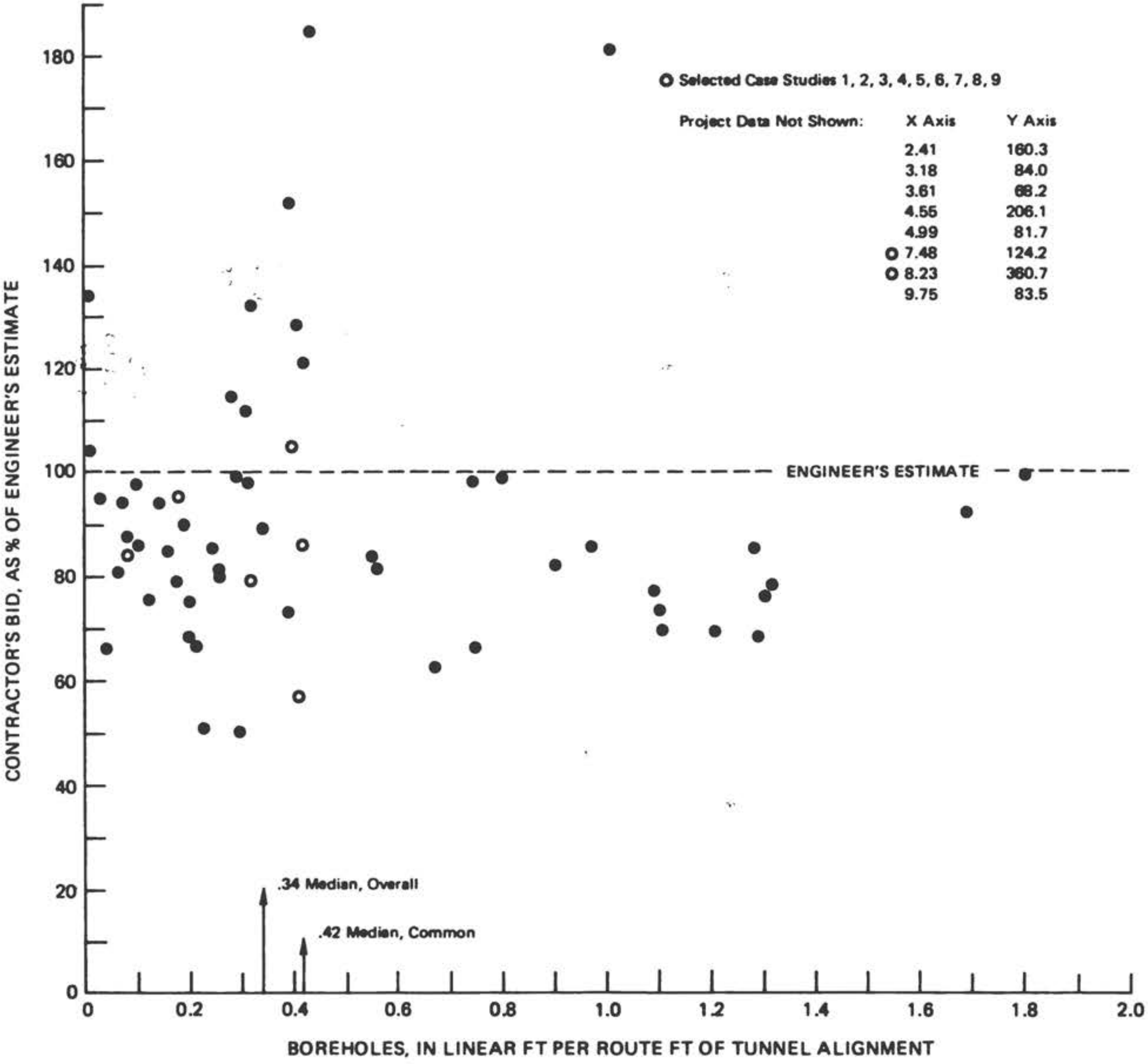
The contractor's bid was examined in terms of two of the three parameters used in evaluating the engineer's estimate. Appropriately, the major difference in approach was to review the relationship of the contractor's bid to both the engineer's estimate and as-completed costs. These results are presented in Figures 7.5, 7.6, and 7.7.

In Figure 7.5 it is apparent that the discrepancy (±50 percent) between the bid and engineer's estimate decreases as the exploration level nears and continues beyond 0.6 linear ft of borehole per route ft of tunnel alignment. Then, the bid begins to approach, and is generally less than, the engineer's estimate. Interestingly, it can be observed that Figure 7.5 reflects results distinctly similar to Figure 7.2 with respect to incidence, degree, and pattern of scatter.

At least a partial explanation for this similarity is provided by a review of Figures 7.6 and 7.7, which compare the bid estimate and as-completed costs. Here, the incidence of scatter is consistent with that exhibited previously for low levels of exploration, but the degree of scatter is less pronounced (±30 percent rather than ±50 percent). Moreover, at more suitable levels of exploration (greater than 0.6 for boreholes or one percent of the engineer's estimate), the convergence of the contractor's bid with as-completed costs is excellent, in terms both of degree and consistent pattern. The benefits resulting from the geotechnical site investigation are obvious.

The difference in effects noted for the engineer's estimate and the contractor's bid merits attention to consider some of the possible causes. First, it might be expected that the contractor would be more experienced in evaluating requirements for tunnel construction suited to various purposes and ground conditions. Moreover, it is the contractor's business to be accurate in determining the cost of individual elements so that an advantageous cash flow can be maintained. The margin between profit and loss is rarely sufficient to accommodate major inaccuracies without severe consequences. In comparison, the engineer's estimate is intended to predict total costs for the entire project (of which the mined tunnel is only a part) with a reasonable degree of accuracy, which permits a more flexible approach. However, this built-in tolerance can be diminished or even eliminated if the estimating process is constrained. Among the elements that particularly influence the results are inflation before and during construction, constructibility, and detailed subsur- face information. If policy, procedures, or circumstances limit the determination or incorporation of any such basic components, then the accuracy of the engineer's estimate can be reduced accordingly and often to a profound degree. As inaccuracies escalate, it is increasingly difficult to avoid distortion of the estimate for the entire project.

Certainly the bases for accuracy differ somewhat between contractor and owner, as well as the strictness of the criteria. In the final analysis, only the owner can determine if the criteria have been satisfied when the engineer's estimate is simply higher than as-completed costs.



Project Data Not Shown:	X Axis	Y Axis
	2.41	160.3
	3.18	84.0
	3.61	68.2
	4.55	206.1
	4.99	81.7
	○ 7.48	124.2
	○ 8.23	360.7
	9.75	83.5

FIGURE 7.5

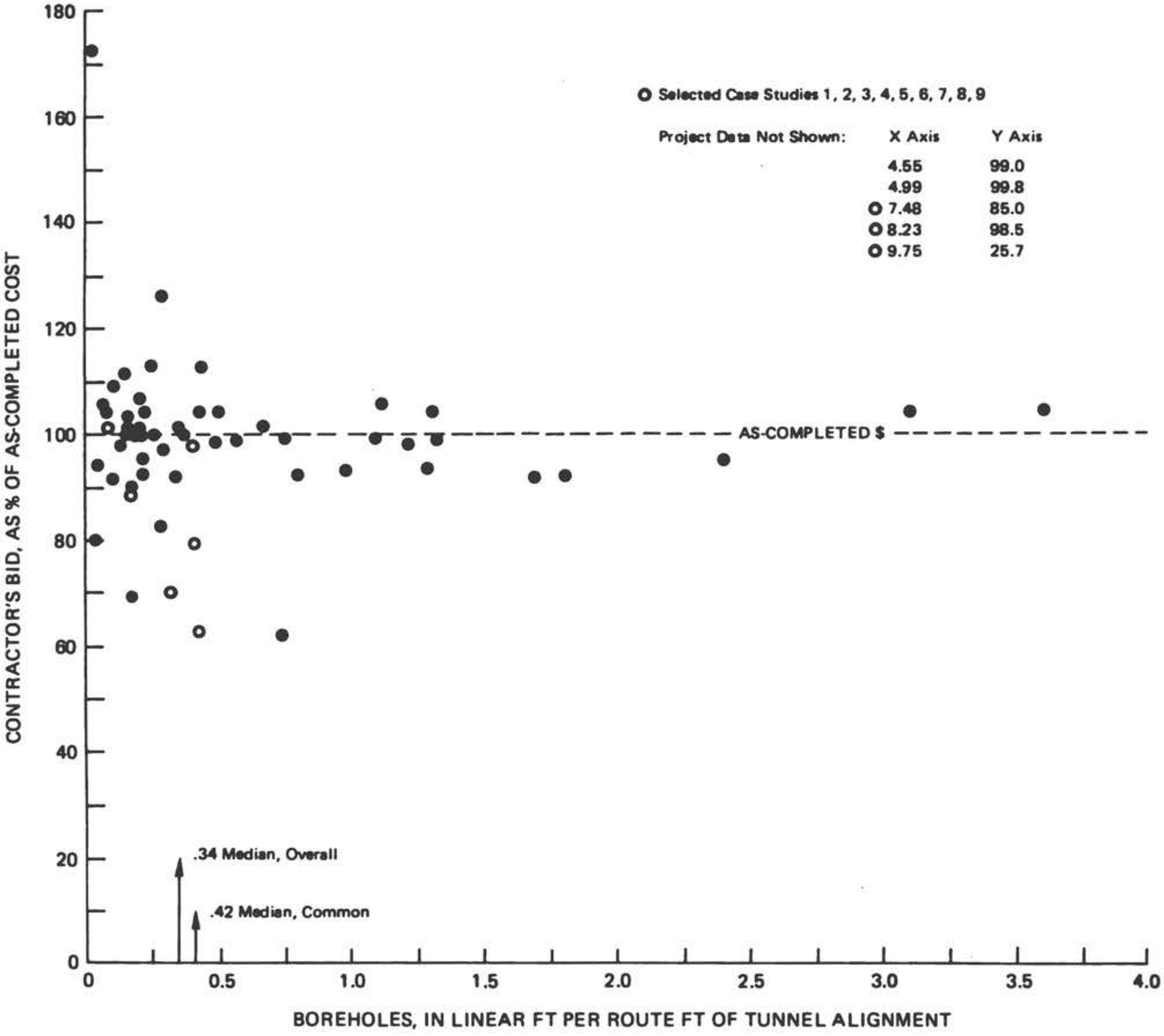

CONTRACTOR'S BID, AS % OF AS-COMPLETED COST
180
160
140
120
100
80
60
40
20
0
BOREHOLES, IN LINEAR FT PER ROUTE FT OF TUNNEL ALIGNMENT
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
○ Selected Case Studies 1, 2, 3, 4, 5, 6, 7, 8, 9
Project Data Not Shown: X Axis Y Axis
4.55 99.0
4.99 99.8
○ 7.48 85.0
○ 8.23 98.5
○ 9.75 25.7
AS-COMPLETED $
.34 Median, Overall
.42 Median, Common

FIGURE 7.6

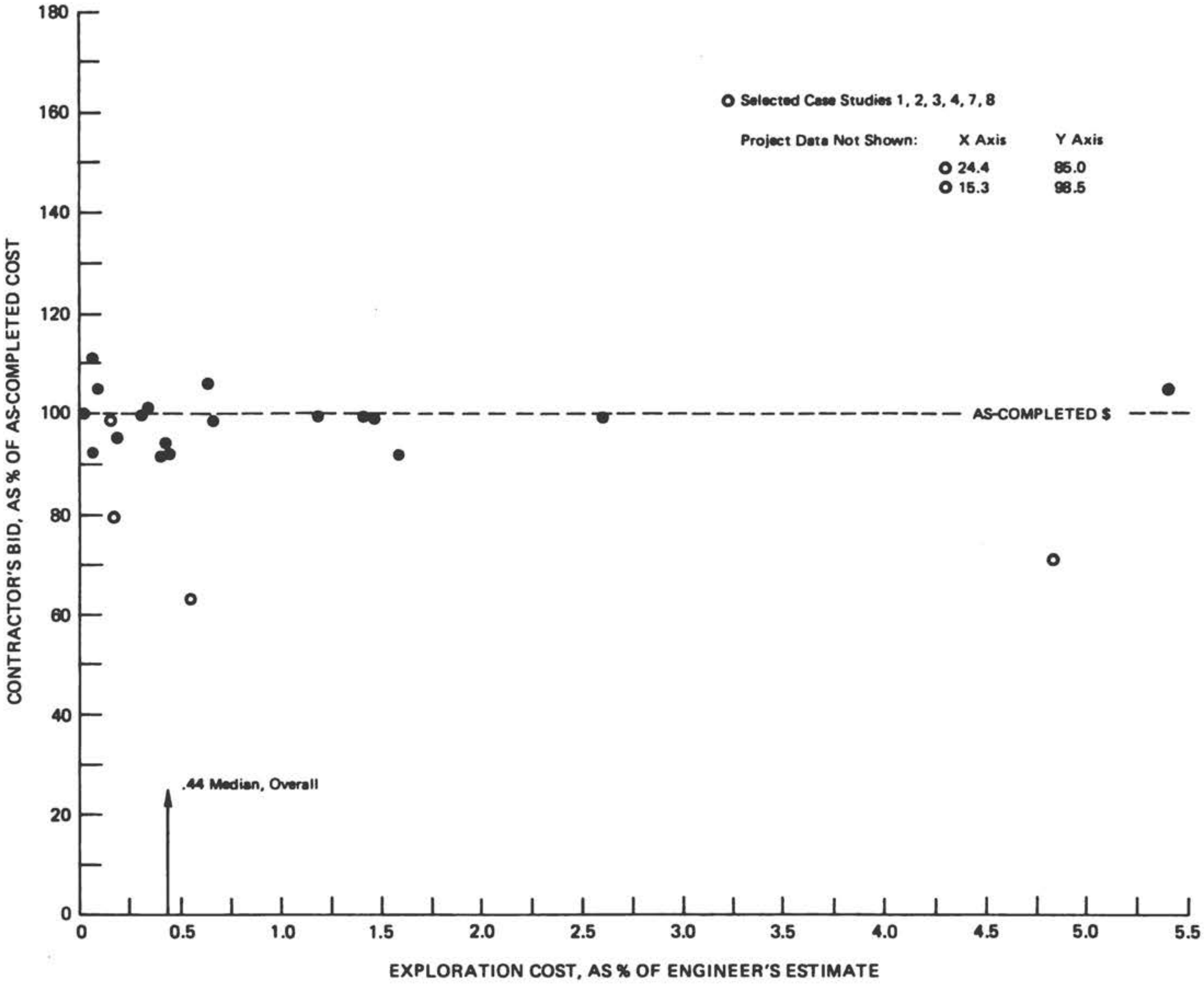

○ Selected Case Studies 1, 2, 3, 4, 7, 8
Project Data Not Shown:
X Axis
Y Axis
○ 24.4
85.0
○ 15.3
98.5
AS-COMPLETED $
.44 Median, Overall
CONTRACTOR'S BID, AS % OF AS-COMPLETED COST
EXPLORATION COST, AS % OF ENGINEER'S ESTIMATE
0
20
40
60
80
100
120
140
160
180
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

FIGURE 7.7

Claims

Requests for extra payments for unexpected subsurface situations--i.e., claims--appear to be a significant part of tunnel cost. Of the 84 mined tunnels studied, 49 reported claims related to geologic and/or subsurface conditions. (Three of these claims were for comparatively small amounts, i.e., less than $25,000.) Projects without claims totaled 29, and there were 6 for which no information was available on whether claims had occurred or not. Overall, then, it appears that about 60 percent* of tunnel projects entail claims, and that claims are substantial for about 55 percent of tunnel projects. Stated differently, of the projects experiencing claims, nearly 95 percent of the claims are for large amounts.

Of the 49 tunnels with claims, there were 32 for which sufficient data were reported (Table 7.6) to permit evaluation. Combining the figures in Table 7.6 yields the following sums (in constant 1982 dollars): total claims of $253.7 million, claims paid of $161.8 million, basic construction costs of $1,364.8 million, and as-completed costs of $1,526.6 million.

Examination of the data for the 32 tunnels reveals that 11 of the claims (8 major and 3 minor) were settled for essentially 100 percent of the amounts requested, one major claim was settled for 115 percent, and 3 major claims were settled for zero payment. The remaining 17 claims were settled for sums varying from 10 to 70 percent of the amount requested, for an average of 39 percent. There is no apparent relationship between the amount of the claim--made or paid--and the original size of the project.

Overall, the indication is that payments were settled at about 64 percent of the original total claimed. These payments amounted to nearly 12 percent of the basic construction costs. (If this average were computed from the claimant's viewpoint--i.e., increase the as-completed total by $91.9 million [the difference between claims made and paid] to reflect construction costs considered justifiable--the settled payment would approach 10 percent.)

In view of these results, the possible influence of the exploration program is an unquestionably relevant concern. Therefore, claims were reviewed in terms of several parameters that served for correlation in the preceding sections. To obtain an appropriate comparison, the data base was expanded by removing the limitations imposed for Table 7.6. Claims made were examined in terms of both the engineer's estimate and contractor's bid, and then compared with the exploration level for boreholes.

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*It is possible that this figure may be low as an extrapolation to industry-wide occurrence. At least two owners who volunteered completed projects are known to have each withheld one newly completed project with claims currently in litigation. If very many of the participating owners faced similar dilemmas, then the sample may be biased toward the "no claims" end of the study spectrum. Also, some projects with litigation completed may have been withheld to avoid possible embarrassment to any interested parties. The subcommittee hopes that the potential for distortion is minimal and limited to unresolved claims.

TABLE 7.6 Comparison of Claims with Construction Costs

Totals* Reported for Claims		Totals* for Construction	
Claims Made	Claims Paid	Basic**	As-Completed
0.008	0.008	4.69	4.7
0.008	0.008	12.59	12.6
0.010	0.010	4.79	4.8
0.060	0.020	10.18	10.2
0.250	0.150	11.65	11.8
0.350	0.350	16.15	16.5
0.600	0.600	14.4	15.0
0.680	0.170	16.43	16.6
0.700	0.700	21.4	22.1
0.747+	0.747+	32.3	33.05
0.787	0.387	25.013	25.4
0.800	0	5.9	5.9
1.000	0.200	15.2	15.4
1.290	0.370	28.83	29.2
1.400	0	19.4	19.4
1.600+	1.600	29.0	30.6
1.800+	1.800	99.9	101.7
2.000	0	275.5	275.5
2.100	2.100	51.2	53.3
2.100	1.200	71.5	72.7
2.600	1.500	32.3	33.8
5.400	2.000	18.5	20.5
6.900	1.300	29.7	31.0
7.500	0.750	19.55	20.3
8.100	2.980	73.22	76.2
11.800	3.400	42.6	46.0
19.200	11.100	104.5	115.6
25.100	7.950	140.55	148.5
25.100+	25.100	44.2	69.3
28.200	20.200	34.8	55.0
37.000	7.500	29.8	37.3
58.500	67.600	29.1	96.7

*Constant 1982 dollars, in millions.
**Costs excluding claims paid.

Results of the comparison, presented in Figure 7.8, indicate a well defined relationship between claims and the exploration effort. At low levels of exploration, approximately 50 percent of the requests were for amounts greater than 10 percent of the engineer's and contractor's estimates. Overall, claims averaged 29 percent of the engineer's estimate and close to 28 percent of the contractor's bid. As soon as exploration exceeds 0.6 linear ft of borehole per route ft of alignment, a marked decrease occurs in the number and size of the claims. This trend downward continues sharply as the borehole level exploration increases. A similar comparison of claims and funds expended for exploration produced matching results. Thus, it is clear that the site investigation program can moderate the occurrence of claims and their severity.

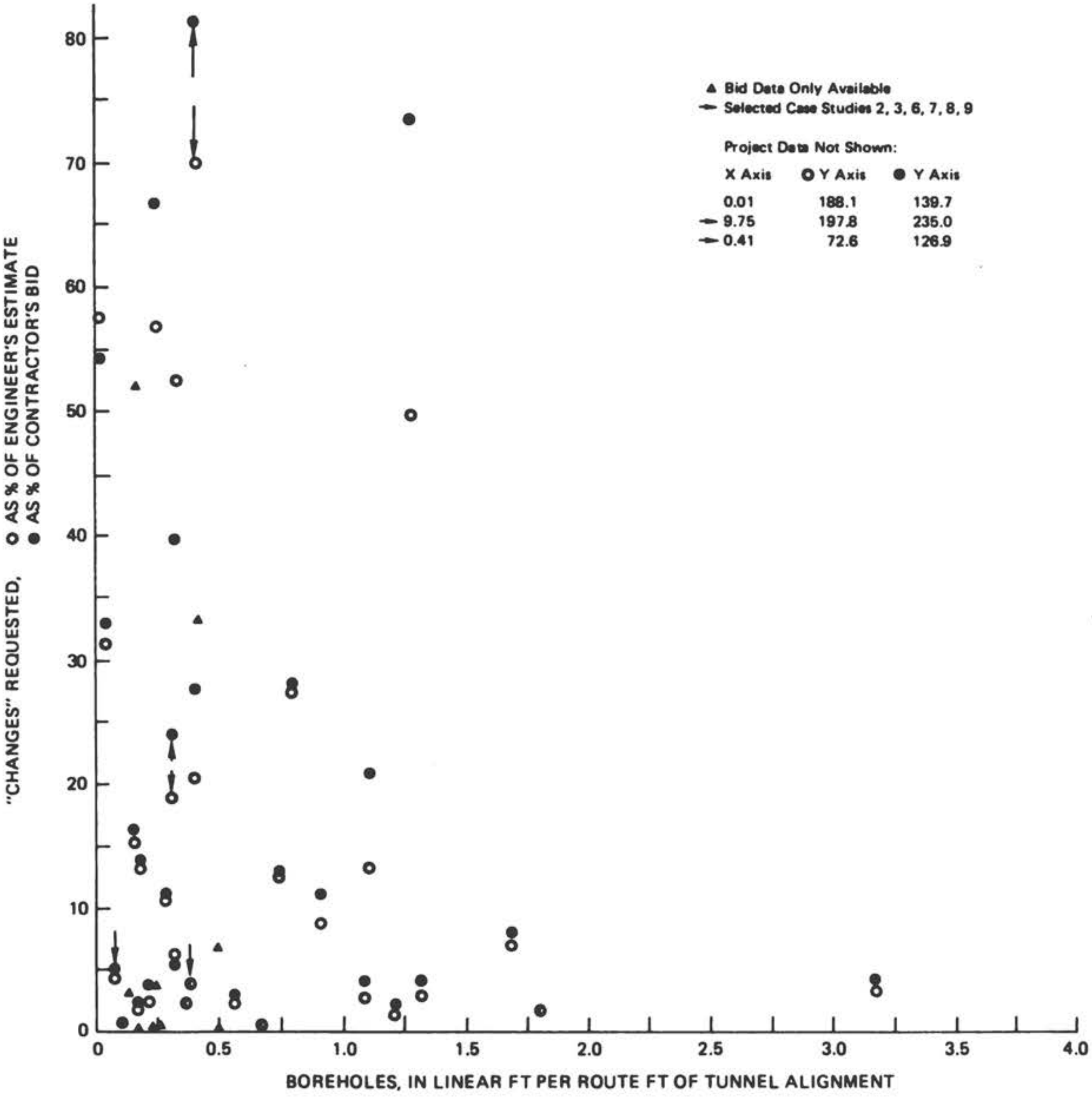
▲ Bid Data Only Available
→ Selected Case Studies 2, 3, 6, 7, 8, 9
Project Data Not Shown:
X Axis ○ Y Axis ● Y Axis
0.01 188.1 139.7
→ 9.75 197.8 235.0
→ 0.41 72.6 126.9
"CHANGES" REQUESTED, ○ AS % OF ENGINEER'S ESTIMATE ● AS % OF CONTRACTOR'S BID
80
70
60
50
40
30
20
10
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
BOREHOLES, IN LINEAR FT PER ROUTE FT OF TUNNEL ALIGNMENT

FIGURE 7.8

Project Costs

The ultimate cost of projects can be estimated accurately and controlled or moderated without sacrificing fair compensation. These goals are attainable when the site investigation program is conducted at a sufficient level to permit thorough evaluation of the subsurface by all parties to the construction process and according to their specific needs. However, the exploration program can only contribute successfully to these goals if the level of effort is increased as a matter of general practice. This belief is based in part on the following findings, which relate to the relationship between exploration and project problems and costs.

- Of all the projects studied, only 11 reported no significant problems and none reported minor problems alone. For more than 85 percent of construction projects, the typical level of site investigation is too low to characterize subsurface conditions adequately in order to plan for or avoid impact on constructibility. This circumstance leads to inaccurate budgets and schedules, inappropriate construction procedures, unnecessarily (often) high increases in as-completed costs, claims and litigation, and difficulties with operations and maintenance.
- The engineer's estimate varies ±50 percent from both bid costs and as-completed costs at the levels of exploration commonly practiced. These deviations are a source of uncertainty for the owner, contractor, and the public, and promote costly adversary relationships. When typical exploration practice is increased, bids and as-completed costs tend to equal or even fall below the engineer's estimate.
- Claims related to unanticipated subsurface conditions occur for about 60 percent of construction projects. In some instances, a claim may be part of the fair cost of a project. Overall, however, claims and disputes result in inefficiencies that are expensive for the owner and contractor. Improving site characterization by increasing exploration reduces the incidence of claims and attendant effects; when unnecessary claims are avoided, construction is more economical.
- A significant portion of project costs stems from claims settlements rather than from investigation of the site for design and construction purposes. The typical one percent (about) of project costs expended for exploration is obviously too low when compared with the average 12 percent of project costs devoted to settled payments for claims. If this figure were extrapolated from 65 to 100 percent of the projects reporting claims, then the average minimum settlement is slightly greater than 7 percent of project costs. However, these averages represent only the amounts publicly paid in settlement of a claim. For the adversaries, there are additional costs for staff and legal services that usually are not disclosed. These "hidden" costs can be tremendously high, and in some instances may reach a total that represents a significant portion of the project cost

The geotechnical site investigation cannot predict every problem that may be encountered, and attempts to do so generally result in programs that are disproportionately expensive for the value received. For every underground project, cost-benefit is a key element. Increasing the level of effort and funds for exploration is demonstrably beneficial and cost-effective.

8.
Conclusions and Recommendations

The basic objective of this study is to discover improvements in practice and procedures that will enable planning and conducting more effective geotechnical site investigation programs. This chapter presents the subcommittee's judgments on matters that bear on achieving the study objective.

The conclusions drawn generally offer a view of current industry practice and areas that could be improved. In a few cases the conclusions are simply observations of fact and required no particular analysis or deliberation. The reader will find some suggestions for changes in current practice--suggestions that are implicit in the way the conclusion is stated.

The recommendations offer the more specific statements on how the tunneling industry can generally upgrade subsurface investigations and expand their uses. Eight of the recommendations are firm proposals for policies that can be implemented within a short time. The others concern areas where research and development would benefit predictions and exploration techniques.

The judgments presented herein are not all strictly verified by the data contained in the case histories. Some of the judgments were influenced by subcommittee experience and knowledge of projects that could not be documented in detail, but include many more than 87 projects over a 20-year time span. Even though the bases for development differed, all of the conclusions and recommendations are equally valid in the view of the subcommittee. In addition, although the subcommittee's study was confined primarily to mined tunnels at relatively shallow depth, the findings can be applied to most underground construction projects because the principles of subsurface investigation and contracting are so similar.

CONCLUSIONS

It is in the owner's best interests to conduct an effective and thorough site investigation and then to make a complete disclosure of it to bidders.

An owner has no legal duty to conduct a site investigation. However, if one is conducted, a variety of legal precedents would make the owner responsible if actual site conditions are found to differ materially from those indicated by preconstruction subsurface explorations. Precontract uncertainty as to risk promotes increased costs for contingencies; post-contract uncertainty as to risk allocation fosters disputes and litigation.

Disclaimers in contract documents are generally ineffective as a matter of law, as well as being inequitable and inexcusable in most circumstances.

Unexpected subsurface conditions are the primary cause of disputes and litigation arising from contracts for underground construction. The geotechnical investigation is a central element in the definition and allocation of risk. Disclaimers of information supplied are an inadequate means of managing risk. It is the policy of most federal agencies and many owners to bear the risk of subsurface uncertainties and provide for differing site condition and changed condition clauses.

Contracting documents and procedures can provide for resolution of uncertain or unknowable geological processes or conditions before and during construction, rather than afterwards.

The provision of clauses covering differing or changed conditions does not necessarily also provide a mechanism for prompt resolution of the issue. Adopting a baseline of risks (or a basis of geotechnical data) before construction would permit timely recognition of a contract change and provision for cost adjustment during construction, if the conditions encountered vary materially. This should assist in reducing or eliminating contingencies for possible delays and disputes, and lead to more realistic cost estimates and more competitive bidding.

On major projects especially, it is important that (a) the owner employ a multi-disciplined team including engineering geologists, engineers, and a construction specialist to develop subsurface data and evaluate their impact on design and construction; (b) designers and geologists possess a thorough working knowledge of construction methods and equipment so that the proper geotechnical data are secured and design is consistent with construction systems; and (c) contractors employ geologists experienced in underground work to evaluate and interpret the data provided at the time of bidding, thus ensuring that all the information obtained is fully considered in preparing bids.

The most extensive and effective geologic site investigations are of limited value if not incorporated fully into the design, estimating, and bidding processes. Too often, the significance of geologic site conditions is not emphasized appropriately in siting, budgeting, and design. Important information either may not have been considered due to poor communication between various disciplines, or may never have been obtained due to a failure to recognize the need. Current and developing underground construction methods demand greater attention to the collection and application of geologic information. The exploration programs, interpretation techniques, and even the potential of the investigator(s) to conduct an effective investigation must be evaluated. It is essential that the owner, designer, and contractor know when additional skills or knowledge may be required. It is the user's responsibility to help ensure that geotechnical investigations reduce, rather than contribute to, risk and the incidence of unanticipated adverse conditions.

Site investigations have to proceed through, but should not always end with, completion of the feasibility/alignment setting/final design programs.

Owners must recognize that the preconstruction site investigation should be an iterative process. A project comprises several phases, and appropriate data must be collected and analyzed to support the requirements of all phases. Anomalies should not be left unresolved by the presumed "final" program, but further explored by another program, and then another, if necessary. All geotechnical data that an owner can sustain economically should be developed. This philosophy should extend to developing additional information when it is important for good bids, even if the information no longer is directly relevant to the design itself. For example, an easily performed but generally ignored investigation procedure is the continued reading of groundwater levels in observation wells as long as there is time to print the information for use by bidders. There is always the possibility of a late-developing change in the groundwater table having major ramifications for construction operations. Moreover, it is not too late to continue exploration after a project is already let for bid; bidders may require data that entails additional exploration. In some instances, post-bid and even post-award investigations may be justified.

Procedures for logging, documenting, and preserving samples from boreholes require improvement.

Boreholes should be observed and logged by experienced engineering geologists. Modern drilling techniques and equipment should be used to allow optimal core recovery. Color photos of all cores should be taken soon after removal from the borehole in order to document the condition of the cores at the time of drilling. Cores frequently deteriorate with time; samples are removed for testing and, through handling, are mixed up or disturbed. Efforts should also be made to preserve cores until at least the completion of construction. Permanent retention of the cores at the project site or an associated facility would be the most desirable approach. For cores that deteriorate rapidly, special preservation techniques such as wrapping in plastic or sealed tubes may be necessary for adequate preservation.

Soil sampling procedures are also in need of improvement and standardization. For example, soil sampling should be essentially continuous through the level of the planned tunnel. Use of high torque equipment such as rotary drilling or hollow-stem augers should be restricted in overburden, particularly below the planned crown of the tunnel.

Geophysical methods can be used to advantage, especially in coordination with boreholes.

Geophysical methods have the potential to greatly expand knowledge of the subsurface when used to interpolate between boreholes. Many geophysical techniques are not widely used or applied to construction projects, but are worthy of continued investigation and development. Seismic refraction surveys profiling the rock surface between boreholes help eliminate the problems associated with high rock in the invert of a soft-ground tunnel and soil intrusion in the crown of a rock tunnel. Other techniques such as resistivity, gravity and magnetic survey can be used to identify anomalies where borings should be made. Ideally, geophysical surveys should be performed prior to drilling the final design borings to allow optimum placement of borings to check different conditions indicated by the geophysical surveys.

Groundwater and its effects on the subsurface materials merit greater attention in exploration programs.

The presence of water accounts, either directly or indirectly, for the majority of construction problems. Most major tunnel projects should have one or more long-term pump tests, executed in accordance with good standard practice and conducted so as to test the various formations and conditions to be encountered during construction. These tests should include observation wells to directly observe pumping effects, as well as drawdown and recovery. Chemical tests of groundwater should be performed on a routine basis. Recent advances in computer modeling of groundwater flow may have applications in improving the ability to predict flow into the excavation, and thus are worthy of investigation.

Laboratory testing of the subsurface materials generally needs to be increased.

Experience has shown, for example, that in rock tunnels at least 50 to 60 unconfined compression tests for each significant lithologic unit are necessary to adequately characterize the range and means of strength values. Silica content is rarely determined in testing programs, yet it is an important parameter in allowing the contractor to predict advance rates and abrasive wear on equipment. In the same vein, sufficient and careful testing of overburden and soft-ground material is important. Truly adequate testing calls for supplementing standard split spoon samples with undisturbed samples from each stratum or zone that affects the tunnel. It must be noted that testing of disturbed rock or soil samples places severe limitations on the value of the resulting data.

Exploratory adits and shafts are generally justified only when absolutely essential to obtain critical design data or when a substantial benefit to construction is indicated.

These exploratory techniques are very expensive and are of questionable cost-benefit in many cases. In some cases, pilot tunnels have actually increased problems during construction of the project; misalignment or exceptionally poor work in the adits or shafts may increase the cost of the final opening. An alternative view is that a significant portion of the pilot tunnel or shaft may be charged to subsequent work if the final opening incorporates the pilot tunnel or shaft. Generally, however, the money expended on an exploratory adit or shaft may be used more effectively for additional boreholes, groundwater investigations, laboratory testing, or engineering evaluations.

Maintenance of technical data obtained during design and construction of underground projects often is not pursued by owners or demanded of their consultants and contractors.

A surprising quantity of exploration, design, and construction data is poorly recorded, filed without easy access, lost, or discarded by owners, construction contractors, and others. In conducting this study, the subcommittee found that records for older projects, as well as for some more recent projects, were often difficult to locate or impossible to obtain. This was because they had either been stored in a manner that discouraged file searching, or simply destroyed. For newer projects, the difficulty in locating information was generally caused by poor recordkeeping. Although this was more often the case for agencies involved in only one construction program, records were not always reasonably available for reference from agencies that build and operate tunnel after tunnel. Experience has shown that relatively few major underground projects fail to develop problems during their operational lifetimes. In many cases, data obtained in the exploration, design, and construction phases of the project are essential to defining the cause of the problem and the best method of correction. If records are not available, the data must be obtained again and the procedure can be time consuming and costly. The difficulty and expense involved in securing suitable data can sometimes lead to inadequate or even "patchwork" solutions.

RECOMMENDATIONS

Expenditures for geotechnical site exploration should be increased to an average of 3.0 percent of estimated project cost, for better overall results.

The low level of expenditure typical of current practice does not correlate well with estimated and actual costs or with construction problems and claims. Overall, increasing exploration can be expected to decrease the incidence and severity of construction difficulties and eliminate a significant portion of the extra costs associated with unanticipated geologic conditions, including project delays, claims, and litigation. Increased exploration should lead to more reliable engineers' estimates and owners' budgets, as well as more accurate bids. It is possible that increased exploration would result in higher engineer's estimates and higher owners' budgets, thereby reducing the direct cash savings resulting from fewer claims. However, savings still would accrue from eliminating attendant delays, lawyers' fees, and hidden costs.

The level of exploratory borings should be increased to an average of 1.5 linear ft of borehole per route ft of tunnel alignment, for better overall results.

Current boring practice is not consistent with the evidence that boreholes are the best single exploration technique for providing reliable information to designers and contractors. Borings provide actual physical samples for direct observation and testing, a feature that makes them less subject to misinterpretation than more indirect methods. However, some factors (including the great depths and/or difficult surface access of some sites) prevent this investigation technique from being given the intensive use it merits. Exploration at 0.6 lin ft of borehole per route ft generally initiates a decrease in the deviations between the final tunnel cost and both the bid price and engineer's estimate. However, an increase to 1.5 produces more desirable results. Beyond this level of effort, the risks of geologic uncertainties, although not eliminated, may be reduced to the point of diminishing returns for borehole footage drilled as a matter of general practice.

The optimum level for borehole footage entails an increase higher in magnitude than the optimum level for exploration expenditures, but the recommendations are not incompatible. A substantial portion of the cost of any drilling program is devoted to initial mobilization, and the more modest programs incur maximum charges per ft of borehole. However, as the number and/or depth of boreholes increases, the unit prices flatten out and even decrease. Moreover, the cost of the overall exploration program includes expenses for report writing and other miscellaneous items which do not rise in direct proportion to borehole footage.

The owner should make all his geotechnical information available to bidders, while at the same time eliminating disclaimers regarding the accuracy of the data or the interpretations.

In the past there has been a tendency among owners to give bidders as little of their interpretive information as possible in order not to be held responsible for any mistakes made in extrapolation from hard data. Owners would make available the logs of boreholes--because they are presumably factual--but withhold the geologic reports because of their interpretive nature. The result was that various contractors were bidding on different bases, depending on their personal experience or access to knowledge apart from the boring logs. Bidding contingencies tended to be high to cover the construction unknowns. This situation is undesirable and can be mitigated significantly if the owner will present all the geotechnical information, and without disclaimers. The owner bears some responsibility for errors in the subsurface predictions, but it creates a fairer bidding atmosphere and can ultimately lower construction costs.

All geologic reports should be incorporated as part of the contract documents.

Some owners follow the philosophy of making all of their subsurface data available to bidders, but not making it a binding contract document. The material is presented for examination, yet not provided or sold with the contract drawings and specifications. Geotechnical documents made available in this manner are often accompanied by a disclaimer stating the owner will not be held responsible for any interpretations or use made thereof. One consequence of this procedure is that some bidders may not rely on the information in spite of its possible accuracy and may not plan their construction operations with all salient facts in mind. A second consequence is that if litigation over changed condition claims is instituted, much time can be spent in arguments over whether the geologic information (or misinformation) can or cannot be blamed on the owner. The procedures should be simplified, even though the owner will then be more surely liable for any errors in interpretations. The result--more consistent and accurate bids--will be worth the added responsibility.

Designers of mined tunnels should compile a "Geotechnical Design Report," which should be bound into the specifications and be available for use by bidders, the eventual contractor, and the resident engineer.

A geologic site investigation is generally completed by the middle stages of design and, therefore, the geologic report cannot comment on many of the late-developing plans worked out by the designer. As a result, bidders are uninformed on many important design/construction matters that may have been given serious consideration prior to the letting of bids. The goal of the Geotechnical Design Report should be to explain the geotechnical rationale for design and the anticipated effect of geology on construction. Such reports should result in much better informed bidders, improved construction procedures, and probably lowered costs associated with a reduction in bidding contingencies and changed condition claims. The WMATA Geotechnical Design Reports (Appendix D) illustrate standard items that should be described in such reports. In addition, including one of the systems for rock classifications (e.g., RSR, RMR, Q-System, or Terzaghi) may be useful, provided that the system is applied properly.

Monitoring of ambient conditions prior to construction should be undertaken to establish a baseline of information for comparison during and after construction.

Records of specific data can be useful in preventing or settling disputes related to construction conditions or effects, as well as in protecting both owner and contractor from frivolous claims. The process can range from visual inspection of structures within a zone of vibration, to a detailed survey of existing damage in adjacent structures, to long-term measurement of groundwater levels. For construction in rock where drill-and-blast procedures are applicable and sensitive structures exist at the site or nearby, preconstruction blast/vibration/noise/sensitivity measurements should be made to compare with later effects and to use in establishing a public relations program. A crack survey, elevation benchmarks, and vibration measurements of non-construction activities should also be undertaken.

Pre-bid conferences and site tours should be conducted to ensure that all bidders have access to the maximum amount of project information.

The end result of a subsurface investigation should be to place as much geotechnical information as possible in the hands of bidders. A good site tour can help accomplish this by allowing bidders to get the "lay of the land" and see the physical features of the project for themselves. However, such tours may lose some of their effectiveness if not conducted by a knowledgeable owner representative. Those bidders not familiar with the territory or the project can miss important features by being left to discover everything for themselves, and bidder ignorance is not in anyone's best interest. In cases where a test adit or shaft has been constructed, the conducted site tour becomes a matter of even more concern.

In the same way, a pre-bid conference is a good way of assuring that all potential bidders have an opportunity to clarify any confusing issues in the contract documents. Some owners choose not to spend time with such conferences because attendees tend to raise few issues for fear of revealing to competitors their amount of knowledge or their bidding strategies. This situation should not deter owners from making the effort. A conference should always include an oral geotechnical briefing by the project designer. This feature is especially important where some policy or circumstance has made it difficult for bidders to obtain the appropriate geotechnical reports or boring information. In addition, the bidders' responses to that briefing can assist the owner in evaluating the effectiveness of the site investigation.

Geologic information from preconstruction explorations and as-built tunnel mapping and construction procedures should be compiled in a report detailing project completion.

It is rare to find wrap-up reports that describe the mapped tunnel geology and construction procedures, even among owners who build tunnel after tunnel. Without such a report, there is no formal way for an owner to confirm geologic predictions and find out where assumptions were right or wrong. There is also no easy way to resurrect records of operations and apply the experience to future projects in order to avoid the repetition of errors. Such information can be invaluable in the event of damage to or malfunction of the tunnel during its operational life. There are cases where post-construction problems (e.g., drain clogging, lining distress) were difficult to diagnose and correct because actual construction (or geologic) conditions were not recorded. As a minimum, the as-built geotechnical conditions should be reviewed by the original exploration team. If practicable, the original team should assist in the post-construction mapping. It is in the owner's interest to create such a record for improving design, contracting, and construction management techniques. Expense would be involved because the "as-built" report could approach the size of the original design report, but it would be to the owner's long-term economic benefit to engage in the effort.

Investigation methods and predictions should be improved for three specific conditions; in-situ stress, stand-up time, and groundwater.

In-situ stress is one of the conditions not always adequately predicted by designers. A better understanding of the geologic history of the site is needed, e.g., eroded cover, normal variation of rock strength, tectonic activity. However, merely paying more attention to the situation during exploration might not be as effective as hoped, because the instruments and predictive techniques need further development. Research is especially needed for predicting stresses at great depth (more than 1,000 ft), particularly when coupled with below average rock strength (less than 6,000 psi compressive strength).

Estimates of stand-up time developed from information available prior to construction are usually indefinite (or not provided). Reliable estimates are important for design and bidding. Stand-up time is a major consideration in selecting appropriate construction methods, equipment, and support system. The Rock Mass Rating (RMR) system may show promise here. In addition, RQDs (when properly determined and recorded), coupled with close inspection of joint and fracture conditions (roughness, filling materials, degree of continuity, spacing, and amount of opening) are useful tools of a semi-quantitative nature.

The occurrence, behavior, and effects of groundwater account either directly or indirectly for the majority of problems encountered in underground construction. This situation is a strong indicator of the need for research and development. First, there is a lack of good quality field pump tests--pump down with observation wells, along with recovery tests. Second, there is inadequate understanding of the effects on ground stability that can result from even a small amount of water flow. In rock tunnels, small quantities of water can substantially reduce friction along joint surfaces; its exit pressure can dramatically affect otherwise stable rock. Water can also cause swelling and induce squeezing in certain types of rock. Development of a data base would assist in sorting and evaluating the complexities of the problems presented by groundwater. One effective and relatively inexpensive way to establish a good data base would be for owners and contractors to begin keeping careful records on quantities of groundwater flowing into the various reaches of tunnels during excavation. Currently, such data are recorded on an irregular basis, and thus much valuable information is irretrievably lost. Ideally, the records should be supplemented with notations regarding the nature and extent of any problems and the effects on construction.

Improved horizontal drilling techniques should be developed that can recover rock core and penetrate long distances without wandering from line and grade.

The need is especially severe for tunnels beneath mountains where, except for portal areas, difficult access and/or great depth generally make the necessary number of vertical boreholes prohibitively expensive. The ability to core drill accurately from a portal and along the tunnel alignment would help investigators to determine not only what is there, but also the true boundaries and thicknesses of geologic features as they would ultimately be encountered in the advancing excavation.

Research and development should be conducted to expand the capabilities of geophysical or other remote sensing methods for obtaining geotechnical data between boreholes and from the surface down to depths too great or too costly for boreholes.

Although boreholes provide the best kind of geotechnical information from within their own confines, interpretation or extrapolation is essential to project that knowledge to some useful distance beyond the borehole. A higher degree of interpretation/extrapolation is required to glean information from depths too great for economical borehole penetration. The process can be greatly abetted by reliable techniques of geophysics and remote sensing. However, in comparison with some industries (e.g., petroleum exploration), engineering investigations make minimal use of these more indirect methods of data collection. A major reason is their relative lack of preciseness, which can lead an owner to the uncomfortable perception that the data are readily subject to more than one interpretation. Considering the ability of remote sensing techniques to cover continuous extents of ground, subsurface investigation would be vastly enhanced if those techniques could be developed to the point that their results were as reliable as borings and trusted equally by both designers and contractors. It should be noted that some federally financed research on deep remote sensing methods is being conducted; the methods are showing promise but still require extensive testing to prove dependability.

Appendix A

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Appendix C

Data Collection and Compilation Procedures

The first step in planning for data collection was to design a form that could be used somewhat like a questionnaire. Pertinent questions were recorded and subdivided into appropriate categories, and blank space was provided for answers. The 15-page form, presented at the end of this Appendix, became the basic case history record of all data collected for each project studied and provided the information extracted for the data matrixes, abstracts, and computer retrieval system.

While the form was being designed, a list was made of all mined tunnel projects known to subcommittee members that appeared to meet the study's needs. The list also included the names of agencies/owners likely to have undertaken projects of possible interest to the subcommittee. The basic criterion was that the project be a mined tunnel, preferably not so new that pending litigation would preclude writing about it and preferably constructed during the last 20 years, because changing technology and difficulty of resurrecting records would otherwise make it less applicable to drawing conclusions about modern tunnels. Several hundred tunnels were considered in the process of selection.

The first step in actual data collection was to contact each owner firm, requesting that a basic data package for each tunnel project be provided to the subcommittee. When no specific tunnel had been selected, the owner was asked to make the decision and volunteer any project(s) that seemed most appropriate. The basic data packages were to consist of the following: contract drawings, specifications, geotechnical reports, bid abstracts or tabulations (including the Engineer's estimate), and any other easily obtained documents considered of interest (often including construction history reports and technical papers).

Meanwhile, Schnabel Engineering Associates of Bethesda, Maryland, was retained as the engineering subcontractor for data extraction. The firm's project manager and his assistant were briefed by the subcommittee's senior consultant on the procedures to be followed and the terminology to be used. (Examples of completed data forms were available for two projects volunteered by the Washington Metropolitan Area Transit Authority.) The need to achieve consistency in recording information from projects from around the country was emphasized as being of prime importance.

When the data packages arrived, they were turned over to the engineering subcontractor. All of the packages from any particular owner were assigned to a single staff member for data extraction; this procedure saved time and achieved consistency in answering questions. In addition, each of the subcontractor's six to eight staff members slated to extract the data had been thoroughly briefed on the proper way of recording answers to questions, so that consistency was achieved in the way information was transcribed from project to project. Further, all data forms were reviewed by the subcontractor's project manager and the subcommittee's senior consultant, which allowed revision of any answers that did not follow the established approach.

Using the basic data packages, the subcontractor was able to fill out each 15-page data form to approximately the 40 percent stage of completion. This percentage varied from project to project because some packages were more complete than others. Also, if a partially completed data form had been received from a volunteer (owner, contractor, consultant, subcommittee member), the amount of information available at this stage increased considerably. It should be noted that the subcontractor used only factual data from the volunteered forms, leaving the clarification of subjective and interpretive answers to a later stage of the study.

The 40 percent complete data forms were then assigned to interviewers who were to complete them to the 90 to 100 percent level by dealing directly with owners and contractors. Interviewers were assigned from the ranks of subcommittee members, the senior consultant, and the subcontractor for data extraction. In a few instances, interview assignments were made to other interested individuals having the proper background.

Consistency among answers acquired by the interviewers was achieved by several means. First, the interviewers were thoroughly briefed on the proper approach to transcribing information. Second, a single interviewer handled all the projects supplied by a particular owner. In addition, that interviewer was expected to acquire information from both the owner and the contractor (and from designers and geotechnical engineers, if necessary). Thus, all projects supplied by a particular source were generally written up by a single individual who had acquired the most familiarity with that source's philosophy of geotechnical investigation, design, and construction. As a final check on consistency, the completed data forms were reviewed and often revised by the senior consultant and by the subcontractor as a prelude to the next stage, the creation of a project abstract.

In completing a data form to approximately 100 percent, an interviewer was expected to combine answers from the owner, the contractor, the 40 percent stage forms, and sometimes the volunteered data forms. In general, most of the information to be collected during the interview stage could be acquired from the owner; personal interviews were usually required to check detailed records and to guide direction of the information flow. Several pages of answers could be provided only by contractors, and this could often be accomplished through an interview by mail. To report fully on the projects, various combinations of the following individuals were interviewed: owners, construction managers, contractors, designers, and geotechnical engineers. For some questions, all principals were asked to reply and it was the interviewer's task to sort through the different responses.

When the 15-page data forms were essentially complete, they were returned to the senior consultant or the subcontractor for reduction into a two-page project abstract designed by the subcommittee. It was during this stage that the forms were checked again for consistency and polished through follow-up telephone discussions with interviewers and original suppliers of information. The two-page abstracts, which present most of the hard, basic data that the reader will wish to review, are printed in Volume 2 of this report.

Just as each abstract is a first stage in the reduction of information from the data forms, the matrix presented in the text is the final stage in which both original and extrapolated data from all the projects can be compared in summary form. The matrix was designed and compiled by subcommittee member Don C. Rose, as part of his task in data analysis. He and another subcommittee member, Howard J. Handewith, used the matrix as the basis for preparing graphs, charts, and curves showing relationships between various aspects of each project. These were major tools used by the subcommittee in analyzing and interpreting the mass of collected data.

A parallel effort in analysis was conducted by G. Wayne Clough and his students at Virginia Polytechnic Institute and State University. Dr. Clough served as the subcontractor for computer programming/processing and created printouts for each project, somewhat in the form of the subcommittee's abstract but in greater detail and with more extrapolated information. The computer was able to quickly re-sort and tabulate the various data according to the key parameters chosen by the analyzer. The final objective of the computer research was to develop a data retrieval system that would allow management of the tunneling information compiled from the case histories. A description of the system and examples of its capabilities are presented in Volume 2.

DATA COLLECTION PROBLEMS AND EXPLANATIONS

As might be expected in a project of this magnitude, problems in data collection developed that cause some of the forms to be somewhat incomplete or not quite consistent with other forms. Many of the problems will become apparent from a review of the data form presented herein and the abstracts (Volume 2). However, other problems are less obvious, and the discussion that follows is intended to illustrate their nature.

- The emphasis on "changed conditions claims" as a yardstick for measuring construction problems and cost overruns had to be changed when it became apparent that many cost overruns are recorded as contract modifications, even when the initial request for payment is in the form of a claim or results in the initiation of litigation. A different method of tabulating the information was formulated, which is indicated by the following note appended to each data form:

> "Cost overrun tabulations make repeated references to claims, claimed conditions, differing

> site conditions, disputes, litigation, and settlements. In actuality, the figures are meant to include <u>all</u> construction cost overruns caused by unexpected geological/subsurface conditions, whether pursued as claims/disputes or executed as mutually agreeable contract modifications. Where such overruns have failed to be included, it is due to the difficulty of sorting out and fully understanding legal/financial matters of some complexity.

The terminology problem was avoided in designing the abstract format. Nevertheless, the reader must remember that the word "claim" (which appears in the data form and recurs frequently in the text of the report) often may encompass many problems and/ or cost overruns that appear in owners' records as "contract modifications."

- Records for older projects, as well as for some more recent projects, were sometimes difficult to locate or impossible to obtain because they had either been warehoused in a manner that discouraged file searching, or destroyed. For newer projects, the difficulty in locating information generally was due to poor recordkeeping. It appears that agencies involved in a "one shot" construction program are much less likely to keep records than are agencies that build tunnel after tunnel. The latter obviously have a need to build on past experience, yet even their records were not always readily available for reference.
- Cost figures were not always available because some owners have an unbreakable policy of not releasing any cost figures. Final costs could not be obtained for projects under construction or for completed projects with continuing litigation over changed conditions claims.
- Mined tunnel costs are rarely tabulated separately by owners, either as estimated or bid, and therefore the cost had to be determined by selecting the proper tunnel bid items from the total project bid items. The project items to be included under mined tunnels were always discussed and agreed upon among the subcommittee, senior consultant, and subcontractor. Therefore, any possible errors in assumptions are probably reflected consistently in every project.
- Apportioning mobilization/demobilization percentages and computing final costs for mined tunnels were judgmental procedures. Choosing the percentage to apply to the mined tunnel and the percentage to relegate to the remainder of the project was often accomplished in consultation with owners and contractors, in order to ensure a reasonable probability of assigning realistic percentages. Computing final mined tunnel costs required judgments because final payments, contract modifications, underruns, overruns, changed conditions, etc., are not categorized or tabulated as neatly as estimates and bids. Even though considerable effort was devoted to determining and properly assigning such payments, the final reported mined tunnel costs may not be as accurate as the estimates and low bids.
- Subsurface investigation costs were not available in most cases because separate records for payments to drilling contractors, testing laboratories, etc., were not maintained. When these costs were available, it was difficult and sometimes impossible to apportion the

correct percentage to the project under discussion because many investigations overlap several projects. The most reliable of the site investigation costs reported pertain to the six WMATA projects, because the owner volunteered a large number of staff and consultant hours to searching files and apportioning the dollars appropriately.

- Cost escalation factors were not applied to the data forms or abstracts. Escalation factors were determined for construction costs, but not until the study was too far advanced to permit revising the data forms and abstracts; reliable escalation factors could not be developed for site investigation costs. Therefore, construction costs are presented as they appeared in the bid tabulations and pay vouchers; the dollars represent the values for the years in which they were obligated or paid. For site investigations also, the costs reported represent the values for the years in which the monies were spent. In addition, Canadian projects are always reported in Canadian dollars, and no adjustments have been applied to make them directly comparable with U.S. projects.

- The number of tabulated boreholes allows no differentiation for clustering of boreholes or boreholes of limited usefulness. Consistency required reporting all boreholes and drilling footages within a reasonable lateral distance of the project being cited. Therefore, certain situations may be less obvious to the reader, such as: off-line borings not directly applicable to final design/construction and hence not tabulated, yet used by designers to understand the complete picture; the percentage of boreholes with too shallow penetration to be of maximum usefulness; and boreholes clustered in certain areas while long stretches of tunnel remained unexplored.

- Deep shafts require a different approach in order to understand their nature and the meaning of the case history data. Deep shafts generally are built for purposes other than those typical of civil engineering and, as a result, procedures common to mined tunnel projects are not always common to deep shafts. For example, deep shafts may proceed through design and construction without performance of a comprehensive site investigation, and many deep shaft projects are acquired by contractors through a process of negotiation rather than bidding. Also, for some deep mine shafts the process of renegotiation, of give-and-take between owner and contractor, may continue as construction proceeds. The reader should be aware of the differing aspects of deep shaft and other underground construction projects, and also of the resulting effects on the ability to collect detailed information on shafts. The case histories for the three shafts studied will generally be less complete than for the typical mined tunnel project.

As indicated in the foregoing discussion, the subcommittee's sources of information included various combinations of contract documents, technical papers, and interviews with owners, designers, contractors, and geotechnical consultants. Design and site investigation answers were relatively easy to determine, but comprehending the construction history of a project was another matter altogether. Each individual providing information had a unique perspective of a project, based on interest, experience, expertise, and access to facts; this often resulted in competing or contradictory responses to questions concerning a particular project. Much of the ambiguity created by such responses was automatically cleared up in cases where a well-reasoned construction history report had been compiled for the record, but such reports seem to be the exception rather than the rule. The subcommittee recognized the problems inherent in data collection and interpretation and took advantage of every opportunity to reduce or eliminate errors, thereby presenting the most accurate case histories possible.

DESCRIPTION OF DATA FORM

The 15-page data form included in this section was the basic means of compiling and recording information on every project selected for study as a case history. Many of the questions and information items are self-explanatory, but others may be subject to interpretations that differ from the subcommittee's intent. Therefore, this section is provided to clarify any possible ambiguities. The items selected for explanation are numbered as they appear in the data form.

I.1.

Length: means total gross linear feet of mining, not just length of alignment (e.g., with twin tubes the tunnel mining length is generally about twice the alignment length). In later headings the delineation is made between footages in different types of ground and construction methods. For shafts, the depth from the ground surface to bottom was substituted.

I.4.

B Line: used actual excavation line if no B line shown on plans.

Face Area: as computed using B line or actual excavation line.

I.5.B.

Range of Depth: used ground surface to the tunnel crown (rather than invert) because of ease in figuring from plans.

I.6.

Purpose of Project: always supplemented with a footnote describing non-mined tunnel items making up overall contract but generally not considered in the study.

I.12.

Date of Design: mostly as taken from dates found on contract drawings.

I.13. & 14.

Dates of Construction Start and Completion: means dates for tunnel mining, or shaft sinking, and installation of initial support (considered more useful than date of final lining completion).

I.17.

Design Criteria, Water Pressure Indicated (Range): generally could not be discovered, so mostly stated in terms of water head above crown.

II.1.

Total Underground Construction Costs: modified to refer to mined (or sunk, or raised, in the case of deep shafts) construction. Involved judgments in choosing from the bid forms those items (or percentage of individual item) that added up to the cost of excavating and permanently supporting the opening. The cost of the total project was included to help judge whether (and if so, how) bids may have been unbalanced. All dollars (U.S. or Canadian) are unescalated and represent values for the year in which they were obligated or spent.

Claims: evolved into a statement of all construction cost overruns caused by unexpected geological/subsurface conditions. Any overruns not included were omitted due to oversight or misunderstanding.

II.3.

Site Exploration Time and Date: for prebid work, generally as estimated from information on boring logs or taken from site investigation reports.

II.4.

Underground Construction Time, Scheduled: means calendar days for excavation and installation of initial support.

III.

Site Exploration: except for a few items, a tabulation of all prebid data development.

III.3.

Boreholes: includes only those along or close to the tunnel alignment (or shaft location).

III.7.

Water Table: range of depths below ground surface.

Head (Range): depths from top of water table to tunnel crown (or bottom of deep shaft).

Actual Inflow, Pressure, etc.: taken from construction records where available (good information was rare).

III.10., 11., 12.

Site Investigation Adequacy, Improvability, Impact on Costs: interviewer's subjective opinion, formed only after all data were considered and all principals with a viewpoint were consulted.

III.13.

Exploration Costs: information not available in most cases. When it was available, an attempt was made to assign the correct percentage of costs from wide ranging investigations to the mined tunnel (or shaft) portion of the project under study.

IV.10.-13.

Bidder/Contractor Actions and Attitudes: mostly available only through an interview with the successful bidder. Answers were many times unclear, especially if contractor's geotechnical consultant was not available for comment.

VI.4.

Advance Rate: stated in ft per day, generally the manner in which it is recorded by owners and contractors.

Minimum Advance Rate: stopped being reported because it always turned out to be zero.

VI.5.

Problems: some overlap with VI.14., which describes circumstances affecting progress of work.

Running Ground: may in many cases be a misidentification. The most acceptable meaning for the term is of a cohesionless material above the water table which runs from a tunnel face until a stable pile is built up at the angle of repose. Below the water table, however, the same material may be transformed into flowing ground, in which the effects of seepage pressures toward the tunnel face create a flowing mass that advances like a thick liquid into the heading. Such descriptive accuracy is not always observed in the field and any invading face material, whether dry or not, is often referred to as "running" ground. The terminology was carried over from the interviews and "as-built" reports and recorded in the data forms in order to avoid second-guessing original sources. Hence, there are probably some instances in which the forms refer to wet tunnel occurrences as running ground when flowing ground would be a better description.

VII.

Litigation and Disputes Related to Geology: "litigation and disputes" evolved into a statement of problems, including ones that the owner immediately agreed were legitimate. "Geology" was expanded to include subsurface conditions in general, in order to accommodate situations such as buried piling (which is not truly geological but should be reported in a good site investigation).

VII.1.-7.

Claims and Claimed Conditions: evolved into descriptions of all construction extras requested, whether pursued as claims or executed as mutually agreeable contract modifications. Any extras not included were omitted due to oversight or misunderstanding.

VIII.

Other: used to comment on any significant facts not otherwise covered. The most common item is a description of operations and maintenance problems in completed tunnels (the data for which was requested by the Transportation Systems Center in Cambridge, Massachusetts).

NATIONAL RESEARCH COUNCIL
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS
2101 Constitution Avenue Washington, D.C. 20418

U.S. NATIONAL COMMITTEE
ON TUNNELING TECHNOLOGY
(202) 334-3136

GEOTECHNICAL SITE INVESTIGATION SUBCOMMITTEE PROJECT

Data Form

I. GENERAL INFORMATION

1. **Name of Project:** Washington Metro Section A-9a, Contract 1A0091*
2. **Location:** Northwest section of Washington D.C.
3. **Shape:** Circular **Length:** 7,620 ft for each of the twin tubes = 15,240 ft
   Grade: -3.5% to +3.23%
4. **Diameter:** A Line = 18 ft 8 in.
   B Line = 19 ft 1 in.
   Face Area: 286 sq ft
5. **Description of Overburden:**
   A. **Classify by Rock or Soil Type:** Bedrock: interfingering gabbro gneiss, quartz-diorite gneiss, chlorite schist, and quartz-mica schist-to-gneiss. Overlain by decomposed rock (saprolite) and man-made fill.
   B. **Range of Depth:** 82 ft to 132 ft surface to crown.
   C. **Other:** ________________
6. **Purpose of Project (water, power, transportation, etc.):** Running tunnels for subway system. (Note: Contract also included 6 shafts, a tiebreaker station, and a pilot tunnel for a future passenger station. Unless otherwise noted, data presented are for running tunnels only.)
7. **Owner:** Washington Metropolitan Area Transit Authority
8. **Designer:** Parsons Associates (Ralph M. Parsons Company)
9. **Construction Manager:** Bechtel Associates
10. **Contractor:** Morrison-Knudsen and Associates
11. **Geotechnical Engineer:** Mueser, Rutledge, Johnston & DeSimone

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Note: For clarity in reading, the answers to the information items have been typed rather than reproduced as originally handwritten. Therefore, this version of the data form is condensed to 10 pages (excluding supplements) rather than the original 15 pages noted in the text, because of the differential in spacing required to accommodate handwriting as well as the longest answer expected to any item.

*The contract also included six shafts, a tiebreaker station, and a pilot tunnel for a future passenger station. Unless otherwise noted, data presented are for running tunnels only.

12. **Date of Design:** 1972 - 1974
13. **Date of Construction Start:** September 19, 1975
14. **Date of Completion:** November 8, 1976 (excavation and temporary support only)
15. **General Ground Conditions Indicated by Specifications:** Foliated to massive, jointed, somewhat sheared, moderately hard rock, suitable for either TBM or drill-and-blast mining.
16. **Design Criteria, Range of Ground Loads Indicated:** Unable to determine.
17. **Design Criteria, Water Pressure Indicated (range):** 70 to 103 ft head of water above crown.
18. **Computerized or Other Special Design Techniques Used (e.g., for temporary and permanent supports, etc.):** Unable to determine.
19. **Monitoring during Construction (ground movement, water flow, gas, temperature, etc.):** Rock movements monitored with extensometers.

II. PROJECT COSTS AND SCHEDULE

1. **Total Underground Construction Cost (excavation, support, and permanent lining):**
   - A. **Estimated:** $25,362,500 excavation/support, running tunnels
$33,293,520 total contract
   - B. **Bid:** $24,993,500 excavation/support, running tunnels
$34,931,600 total contract
   - C. **As completed:**
     Including changes other than claims: $25,189,396 (running tunnels)
     Claims: $1,975,350 (running tunnels)
   - D. **Total (of C):** $27,164,746 (running tunnels)
     $36,950, 201 (total contract)
2. **Site Exploration Costs (if reasonably available):** For breakdown of costs, refer to III, 13.

Prebid:	$101,534	**% of 1.D:**	0.37
Post Award:		**% of 1.D:**	
Total:	$101,534	**% of 1.D:**	0.37

3. **Site Exploration Time and Date (prebid--field and office):** 12 months in 3 programs between April 1968 and April 1973
4. **Underground Construction Time:**
   Scheduled: 286 calendar days for mining and placing temporary support in running tunnels

III. SITE EXPLORATION

1. **Geologic Studies:**
   Literature search, regional (general description): Collection of geologic and topographic maps and government geologic reports
   Site (general description): Rolling piedmont landscape, urban alignment beneath major thoroughfares
   Surface mapping, ground types (rock/soil): Only man-made fill visible at surface.

Rock/soil structure (general description of folding, faulting jointing, bedding, etc.): Complex intruded metamorphics; schistose portion having foliation subparallel to alignment; numerous shear zones; at least 5 joint sets, 3 of them major.

Rock/soil quality (hardness, weathering, consolidation, origin, etc.): Rock varying between 750 and 17,600 psi compressive strength. Upper portions weathered to depths as great as 60 ft, but tunnel profile mostly below this weathered zone.

Cross sections (how many and what kind): One 7,620-ft detailed geologic profile on scale of 1" = 80' horizontal by 1" = 20' vertical.

Boreholes: Yes **If yes, were they detailed?** Yes

RQDs (were they provided?): Yes

Other classification systems (e.g., RSR, joint frequency): ___·___

2. **Geophysical Studies:** No

Type of seismic surveys (reflection, refraction, etc.): ________

Surface resistivity: ________

Type of borehole logging (E-logs, temp., Gamma-ray, etc.) ________

Other: ________

3. **Boreholes--number:**

vertical	45
horizontal	0
inclined	4
Total	49

Diameter: Few 2-1/2"; mostly 3-1/2" with NX coring.

Total footage: 1,774 ft soil sampling; 4,348 ft rock coring.

Maximum length: 162 ft

Minimum length: 24.3 ft

Location with respect to centerline: Generally no more than 40 ft away from centerline of one of the tunnels. However, one 1,600 ft stretch has 7 borings that are 60 to 155 ft away because they were done for an earlier alignment alternative.

Average spacing along centerline: 169 ft

4. **Borehole Tests:** No

Permeability: 41 water pressure tests with packers, and 75 falling head tests in boreholes and observation wells.

Water: ________

Gas: No test.

Other: Borehole photography in 2 vertical borings.

In situ stress/deformability tests: No

5. **Exploration on Pilot Tunnels/Shafts (describe how many, where, lengths, etc.):** None

6. **Construction History Studies of any Nearby Existing Tunnels and Shafts (describe where, what data obtained):** Detailed data collected from Metro Section A-4a, an earlier drill-and-blast tunnel about 2 miles downstation from the subject A-9a tunnels. In addition, the A-9a contractor had just built the adjoining 9,500 ft long section, A-6a; he used the same TBM on both jobs.

7. **Hydrology and Groundwater (describe water bearing layer and properties):** Rock tunnel--no particular water bearing layer noted.

Water table: 70 to 103 ft above tunnel crown.

Porosity: Not noted.

Permeability: Bedrock--low = 1.0 x 10^{-7} fpm; median = 1.8 x 10^{-4} fpm; high = 1.0 x 10^{-3} fpm (packer tests).
Head (range): 70 to 103 ft at crown.
Prebid predicted inflow (maximum volume, length of time, and maximum pressure): No predictions.
Prebid predicted minimum sustained inflow and pressure: No predictions.
Actual inflow (maximum volume, length of time, and maximum pressure): No records.
Actual minimum sustained inflow and pressure: No records.
Chemistry (fresh water, saline, etc.): Fresh, high in dissolved carbonate.

8. **Laboratory Tests:**
   Strength: 75 unconfined compression on rock; unconfined compression, triaxial compression, and direct shears on soil.
   Hardness: None
   Abrasion: None
   Permeability: None
   Density: Yes
   Soil classification: Water contents, atterberg limits, grain size analysis
   Dynamic properties: ____________________
   Other: Few consolidation tests on soil.
9. **Additional Laboratory Testing:** Corrosion potential of soil and water: pH and resistivity plus concentrations of sulfates (SO_4), chlorides (Cl), and carbonates (CO_3).
10. **Was Site Investigation and/or Interpretation Adequate to Prevent "Surprises"? (interviewer's subjective opinion):** Probably not. If the severe conditions were truly obvious from the 2 applicable borings, then the owner would probably have sunk other borings to confirm the conditions and map their extent.
11. **Could Site Investigation and/or Interpretation Have Been Improved or Modified? (interviewer's subjective opinion):** Most likely. However, the owner would have had to foresee the severe conditions from the 2 applicable borings in the area, and then to sink additional ones in precisely the right spots to further define conditions.
12. **Would a Modified Investigation and/or Interpretation Have Had a Significant Cost Impact on the Project? (interviewer's subjective opinion):** A properly modified program would have had an impact. With solid advance warning of the severity of conditions in the one area, the contractor could have taken precautions (such as mining his "rescue" tunnel in advance of the mole's arrival at the spot), thus avoiding considerable delay and saving money.
13. **Breakdown of Exploration Costs (give amount and date):**
    Drill holes: Subprofessional = $47,146; professional = $24,362.
    Mapping: $150
    Geophysical: None
    Other: Lab = $5,456; office = $24,420.
    Total: $101,534 in 1968 through 1973 prices.

IV. BIDDING PERIOD

1. **Number of Bidders:** 3
2. **Requirement for Prequalification:** None
3. **Were Bid Abstracts Available?** Yes
4. **Time Allowed for Bid Submission:** 6 weeks originally. However, an initial bid was rejected because 2 contractors failed to sign minority participation clause, so job was rebid. The effective bidding period was then 14 weeks.
5. **What Subsurface Information was Provided in the Bid Package?**
   Maps: No--none compiled by geotechnical consultant.
   Boring logs: Yes--bound directly into contract drawings.
   Other: Geotechnical reports with profiles and all test results. (The reports were laid out for bidders' examination, and copies could be bought from the National Technical Information Service.)
   If provided, was detailed information set forth? Yes
6. **What Geotechnical Data Were Made Part of the Contract Document?**
   Geotechnical reports: See question 5, above. **If so, identify.**
   Geophysical logs: No geophysical logs created.
   Core samples: Specifically listed as available for inspection on 24 hours notice.
   Age of samples: Between 3 and 8 years.
   Condition of samples: Soil dessicated; rock good.
   Geologic mappings and cross sections: See question 5, above.
   Test data: See question 5, above. **If provided, describe:** Results of all field and lab testing on soil samples, rock cores, boreholes, and observation wells.
7. **Photo (display):** No photos
   Was there a prebid display room exhibiting photos, maps, other documents, etc. (what did it consist of)? Construction coordinator's office, where geotechnical reports could be examined.
   Other: Core shed, where geologic samples could be examined.
8. **What (If Any) Geological Technological Information Possessed by Owner Was <u>Not</u> Provided to Bidders?** Government geologic maps and reports considered 3rd party information and not made available; it was up to interested bidders to locate their own copies.
9. **Was There a Prebid Conference:** No **If so, were questions asked re subsurface conditions?** ____ **Please describe the questions and answers:** ______________________________
10. **Did Any Bidders Obtain Their Own Expert Evaluation of Subsurface Data, Particularly the Successful Bidder?** Yes **If so, identify (briefly describe it):** Consulting geotechnical specialists independently evaluated the rock core and the owner's geotechnical reports. Similar studies also carried out by three major TBM manufacturers.
11. **Did Any Bidders Make an Independent Subsurface Investigation?** Not prior to bid award. **If so, describe briefly:** ______________
12. **What Subsurface Information Did Contractor Rely On in Preparing His Bid? (Object is to discover what contractors rely most on):**
    Boring logs: Yes
    Geophysical data: ______________________________

Core samples: Yes
Geotechnical reports: Yes
Geological mappings and cross sections: Yes
Other: ____
Explain why specific types of information were relied on by the contractor and in order of importance: Relied on all quantified data or documents; reviewed reports but did not necessarily rely on judgments, evaluations, conclusions.
Explain why if any types of information were not relied on: "Facts" were relied on; opinions, not necessarily.
Was there any specific type of data desired by the contractor but not made available? None remembered by the individual who completed the prebid geologic evaluation.
What experience, if any, did the contractor have in comparable underground construction work? 45 years in underground construction. Had just built the adjacent section in similar rock, using the very same TBM.

V. CONTRACT FORMAT

1. **Contract Format:**
   Lump sum: **Unit price:** per ft of single track tunnel
   Cost plus:
   Other:
   If unit price format was used, were estimated quantity variation limits specified? 15% (plus or minus) without adjusting contract price.
2. **Was Differing Site Conditions Clause or Equivalent Included?** Yes, but see question 3, below.
   Was there a changes clause or equivalent: Yes
   If answers in 2 above were no, how was risk of changed conditions dealt with contractually? Since rock was specifically excluded from coverage under the changed conditions clause, the contractor was expected to include sufficient contingency in his bid price to cover any rock condition encountered.
3. **Were There Disclaimers or Caveats on the Owner-Furnished Information on Subsurface Conditions?** (1) Note that data presented for information only with no accuracy warranty. (2) Note that rock not covered by changed conditions clause.
4. **Provisions Re Schedule, Time of Completion:** 915 calendar days for total contract. (The contractor was required to submit for approval a graphic network diagram [schedule] indicating construction dates for various major features, which did include running tunnels estimated at 286 calendar days for mining.)
   Definition of delay: Yes (see Supplement 1).
   Definition of suspension of work: Yes (see Supplement 2).
   Liquidated damages clause: Maximum $5,000 per day of delay.
5. **Payment Provisions:**
   Monthly: Yes

Retainage percent: 10%
Other: Payment related to progress (see Supplement 3).

6. **Pricing for Temporary Support (describe briefly):** Details of temporary support strictly the responsibility of the contractor, with payment to be included in the overall contract unit price per ft for "single track tunnel."
7. **Construction Methods Specified:**
   TBM: Option*
   Drill-and-blast: Option*
   *Job designed as either TBM or drill-and-blast, with contractors to bid the option they preferred. Low bidder chose the TBM option.
   Other:
8. **Restrictions:**
   Hours of work: None for TBM mined tunnel. Some shafts restricted to 7:00 a.m. to 10:00 p.m. or 8:00 a.m. to 6:00 p.m.
   Blasting: Permitted only from 7:00 a.m. to 10:00 p.m., Monday through Saturday, and 2:00 p.m. to 10:00 p.m. on Sunday.
   Hauling: No specified restrictions.
   Other: Noise restrictions (dBA levels) for equipment in various locations and hours of resident activities.
9. **Disputes Resolving Provisions (i.e., arbitration, suit, etc.):**
   To be decided by owner's contracting officer, whose decisions can be appealed to owner's board of directors within 30 days. Board decision final unless question is one of law that results in litigation in court.

VI. CONSTRUCTION

1. **Type of Project:**
   Hard ground: Yes
   Soft ground: ____
   Mixed face: ____
   Other: ____
2. **Length of Work Week:**
   Days: 5 **Shifts:** 3
   Why was <u>this</u> schedule used? ____________________
   Number of Men:
   Day: 20-22 men **Swing:** 20-22 men **Graveyard:** 20-22 men
3. **Major Equipment Used:** Robbins 191-161 tunnel boring machine.
   Mucking and hauling: front end loaders, 25 ton locos, 16 cu yd muck cars, rotary dump cranes.
4. **Advance Rate (per day):**
   Maximum: 125 ft **Minimum:** 0 ft
   Overall average (per day): 65 ft, good rock; 56 ft, poor rock.
5. **Problems:**
   Excessive overbreak: ____________________
   Poor ground stability: In one 650 ft long stretch only.
   Cave-ins: in same 650 ft **Running Ground:** in same 650 ft
   Groundwater: __________ **Gas:** ____________________
   Other: ____________________
   Residual stresses/swelling/squeezing ground: ____________________

6. **Special Conditions:**

Utilizing compressed air: No

Subaqueous (under lakes, rivers, bays): No

Twin bore: Yes; tunnels driven consecutively by same TBM; required complete refurbishing between 1st and 2nd bores. Lost 5 weeks from completion of 1st tunnel to start of the 2nd.

Dewatering problems: No

Grouting (for running ground or settlement): Yes, but it proved ineffective and was quickly dropped.

Other: ______

7. **Primary Support:**

Steel sets (describe): W6x20 on 4 ft centers in bad ground and in portion through the future station location. (Note: Applies to standard tunnel section. Shotcrete, longer rock bolts on different patterns, heavier steel and thicker concrete used in cross adit and shaft breakout areas.)

Rock bolts (describe): 6 ft bolts with wire mesh on 5 ft x 5 ft in top arch used in 63% of tunnel length. (Applies to standard tunnel section, as noted above.)

Shotcrete: ______

Other: ______

8. **Final Linings (none, shotcrete, cast-in-place, segments, other):** Reinforced cast-in-place concrete, 1 ft thick. This final lining omitted in the 653 ft long section where a future station was to be blasted out of the rock between the running tunnels and the pilot drift. (Applies to standard tunnel section, as noted in 7, above.)

9. **Excavation Equipment Manufacturer (TBM, roadheader, etc.):**

Model: Robbins 191-161

Diameter: 19 ft 1 in. (O.D.)

Weight: 285 tons

Cutterhead power: 900 horsepower

Thrust: 1,850,000 lbs.

Torque: 3,500,000 lbs.

Grippers: 2 horizontal opposed

Cutters: 45 (15-1/2 in. discs)

Down time: 18.1%

10. **Shield (description):** Not applicable

11. **Ventilation (type and volume):** Joy 48 in. fan line.

12. **Mucking (describe system):** Endless belt to muck train parked inside back of TBM. Muck hauled through Contract A-9a and Contract A-6a (previous tunnel built by same contractor), stockpiled at the portal and hauled away by truck.

13. **Were Changes in Design Made After Award Due to Unforeseen Geologic Conditions?** No

Was contract flexible enough to allow this? No, not without a formal contract modification.

Other conditions: ______

14. **Was Progress of Work Affected by Any of the Following:**

Redesign: No

Contractor inexperience: No

Squeezing ground: No

Cave-in: In the one bad ground area there was a chimney to the bottom of the street pavement.

Groundwater inflow: Yes, once. But the pocket of water in bad ground drained within a few days.

Fault zones: No

Other: Intensely weathered shear zones associated with a contact zone between country rock and an intrusive.

15. **Was a Contingency for Geologic Uncertainty Included in Bid?** No
    Could it have been reduced if more exploration had been made? ___
    How much reduced? ___
16. **Safety Record with Regard to Geologic Conditions:** Miners' claims of damage by silica from the rock dust.

VII. LITIGATION AND DISPUTES RELATED TO GEOLOGY

1. **Were There Significant Claims by the Contractor?** Yes, one major claim for $7 million.
2. **Were There Significant Claims by Owner Against Contractor?** No
   Against engineers? No
   If so, identify by brief description and amount in dollars: ___
3. **If Contractor Claim Was Based on Differing Site Conditions, Please Describe the Claimed Condition and How it Allegedly Differed:**
   The contractor encountered ground so bad that the mole became stuck and efforts to turn the cutterhead resulted in flows of mud and water into the tunnel, with some caving above the tunnel. The mole fought its way through 300 ft of this ground but a top heading, hand-mined "rescue" tunnel had to be driven from ahead to meet the machine; a similar top heading was driven for 650 ft in the adjacent tube. These operations resulted in much extra work and tunnel support and delays. The contractor claimed the problem was due to unforeseeably deep weathering so bad that there were actually "pendants" of saprolitic soil extending down into the rock tunnel.
   What was the owner's position with respect to any such claims?
   The owner's initial position was that the contractor had simply encountered intense weathering along a concentration of shear zones so common in the area and quite predictable from contract document information. The bad material was sheared and weathered rock and not soil-like until the mole ground it up. The claim was thus denied because rock was specifically excluded from changed condition provisions in the contract. However, during the early stages of litigation, the owner conceded that the condition encountered was unusually severe and agreed to the soil-like nature of some of the material. This made it coverable by the changed condition provisions and freed owner and contractor to negotiate an extra.
4. **Were the Claims Settled?** Yes
   Short of arbitration board or litigation? Litigation began, but settlement was achieved before it actually came to trial.
   What percentage was recovered in settlement of the claims? 28% (asked for $7 million and received $1,975,350).
   Was interest included in settlements? No
5. **If Claims Were Arbitrated, Before What Panel?** Not arbitrated
   What result? ___
   What percentage of claims was recovered? ___
   What was the cost of arbitration? ___
   How long did it take to get a decision? ___

6. **If Claims Were Litigated, Before What Forum?** Corps of Engineers Board of Contract Appeals.
   What result? Litigation proceeded through the pleading and discovery stages, but the parties reached agreement on their own before trial was actually begun.
   What percentage of claims was recovered? 28% (see question 4)
   What was the cost of litigation? No information
   How long did it take to get a decision? No decision; time frame unknown for mutually agreeable settlement.
7. **To What Extent Were Contractor Claims Asserted and Resolved Contemporaneously with Performance?** Asserted during performance but not resolved until several years later.

VIII. OTHER

Operations and Maintenance Problems: Trains are not yet running in these particular tunnels, so the full extent of operations and maintenance problems are not yet evident. There was (and still is) intrusion of diesel fuel into the tunnel from a garage site spill. Although not serious enough to be a safety hazard during or after construction, the oil does continue to seep into the drainage system and to be concentrated at the nearest pumping station. From here it is released into a small natural stream in sufficient concentration to be an environmental problem.

Calcium carbonates are creating the longest-term operations and maintenance problems. The $CaCO_3$ is picked up from calcite joint fillings in the rock. Carried in fairly heavy concentrations in the groundwater, it precipitates when pressure is released as the water emerges into open air inside the tunnels. One-third of the hydrostatic pressure relief (HPR) pipes were clogged by the time of tunnel acceptance, and perhaps three-quarters of them are clogged by this time. The precipitates also clog drainage slots, lines, and gratings, and probably any gravel filter blankets under the concrete inverts. They tend to form messy, slippery deposits that can be a hazard on the safety walks.

It has proved practically impossible to ream the carbonates from the small HPR pipes, but the drainage slots, lines, and gratings can be kept relatively clean by periodic treatment with a rotary cleaning tool and high pressure water. It is important to attack the deposits while they are still in a gel state and not completely solidified. Testing the degree and speed of calcification of the gravel filter blankets and then trying to stop or reverse it is still an unsolved problem.

Interviewer
C.W. Daugherty

Supplement 1
Washington Metro Section A-9a

1.5 TERMINATION FOR DEFAULT - DAMAGES FOR DELAY - TIME EXTENSIONS

(a) If the Contractor refuses or fails to prosecute the work, or any separable part thereof, with such diligence as will insure its completion within the time specified in this contract, or any extension thereof, or fails to complete said work within such time, the Authority may, by written notice to the Contractor, terminate his right to proceed with the work or such part of the work as to which there has been delay. In such event the Authority may take over the work and prosecute the same to completion, by contract or otherwise, and may take possession of and utilize in completing the work such materials, appliances, and plant as may be on the site of the work and necessary therefor. Whether or not the Contractor's right to proceed with the work is terminated, he and his sureties shall be liable for any damage to the Authority resulting from his refusal or failure to complete the work in the specified time.

(d) The Contractor's right to proceed shall not be so terminated nor the Contractor charged with resulting damage if:

(1) The delay in the completion of the work arises from unforeseeable causes beyond the control and without the fault or negligence of the Contractor, including but not restricted to, acts of God, acts of the public enemy, acts of the Authority in its contractual capacity, acts of another contractor in the performance of a contract with the Authority, fires, floods, epidemics, quarantine restrictions, strikes, freight embargoes, unusually severe weather, or delays of subcontractors or suppliers at any tier arising from causes other than normal weather beyond the control and without the fault or negligence of both the Contractor and such subcontractors or suppliers;

and

(2) The Contractor, within 10 days from the beginning of any such delay (unless the Contracting Officer grants a further period of time before the date of final payment under the contract), notifies the Contracting Officer in writing of the causes of delay. The Contracting Officer shall ascertain the facts and the extent of the delay and extend the time for completing the work when, in his judgment, the findings of fact justify such an extension, and his findings of fact shall be final and conclusive on the parties, subject only to appeal as provided in the "Disputes" article of these General Provisions.

Supplament 2
Washington Metro Section A-9a

1.38 SUSPENSION OF WORK

(a) The Contracting Officer may order the Contractor in writing to suspend, delay, or interrupt all or any part of the work for such period of time as he may determine to be appropriate for the convenience of the Authority.

(b) If the performance of all or any part of the work is, for an unreasonable period of time, suspended, delayed, or interrupted by an act of the Contracting Officer in the administration of this contract, or by his failure to act within the time specified in this contract (or if no time is specified, within a reasonable time), an adjustment shall be made for any increase in the cost of performance of this contract (excluding profit) necessarily caused by such unreasonable suspension, delay, or interruption and the contract modified in writing accordingly. However, no adjustment shall be made under this article for any suspension, delay, or interruption to the extent (1) that performance would have been so suspended, delayed, or interrupted by any other cause, including the fault or negligence of the Contractor or (2) for which an equitable adjustment is provided for or excluded under any other provision of this contract.

(c) No claim under this clause shall be allowed (1) for any costs incurred more than 20 days before the Contractor shall have notified the Contracting Officer in writing of the act or failure to act involved (but this requirement shall not apply as to a claim resulting from a suspension order), and (2) unless the claim, in an amount stated, is asserted in writing as soon as practicable after the termination of such suspension, delay, or interruption, but not later than the date of final payment under the contract.

Supplement 3
Washington Metro Section A-9a

2.9 DETERMINATION OF PROGRESS

(a) Independent of progress payments made pursuant to Article 1.7, Payments to Contractor, progress schedules prepared under the requirements of Article 2.8, Progress Schedules - Network Analysis, shall provide as schedules progress for only 50 percent of the estimated invoiced cost of materials or equipment delivered to the site but not incorporated in the work as of the time of the scheduled delivery thereof.

(b) In determining progress accomplished, the Engineer will allow as an element of work accomplished (progress toward completion) only 50 percent of the invoiced cost of materials or equipment delivered to the site but not incorporated in the construction up to the time the materials or equipment are actually incorporated in the work.

Appendix D

Geotechnical Design Reports, Rock Tunnels and Earth Tunnels

The Designer shall prepare geotechnical design reports for each rock and/or earth tunneling construction contract. The reports are to provide the Authority, the Authority's General Consultants, and the Board of Engineering Consultants with the geotechnical basis of the design and of the construction specifications for their assessment of the recommended design. Further, the reports will be issued to bidders, will become part of the Construction Contract Documents, and will be reference information for the Engineer acting for the Authority during construction.

It is intended that the reports will be based on and present the most current subsurface information pertaining to the Design Section and each particular construction contract. On that account, where applicable, the reports are to be prepared in successive stages as follows:

Stage 1, for presentation to the General Engineering Consultant at the preliminary review stage of design.

> The Designer's Geotechnical Design Report is to describe the basis of their design and the provisions to be made in the design and specifications for the geological conditions. Considerations with respect to requirements for additional subsurface investigations and proposals regarding other major design and construction aspects are to be included.

Stage 2, for presentation to the General Engineering Consultant at the final review stage of design.

> This will be an update of Stage 1 and will incorporate further information developed or obtained up to that time. The update will reflect, among other things, comments made at the preliminary presentation, the newest information from GSC (General Soils Consultant) subsurface investigations, and applicable data from experience on other Authority construction projects. (For rock tunnel stations, the data may include detailed geologic mapping of shafts, pilot tunnels, and running tunnels carried out in the area by the General Construction Consultant during the course of the preceding tunnel contract.)

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*In the formal terminology of WMATA (Washington Metropolitan Area Transit Authority), the "Geotechnical Basis of Design and Construction Specifications."

The report shall conform to the Geotechnical Design Report format furnished to the Designer by the Authority. The completed report is to reflect the comments made at the final review presentation and is to be printed as an appendix to the construction specifications.

FORMAT FOR ROCK TUNNELS
GEOTECHNICAL DESIGN REPORT

A. TITLE

Geotechnical Basis of Design and Construction Specifications.

B. INTRODUCTION

This report describes geological conditions anticipated along the route of Section ______ tunnels of the ______ Route of the Washington Metropolitan Area Transit System, and the influence these anticipated geological conditions have had upon the design. In addition, the report is intended to assist prospective bidders in evaluating the requirements for supporting the tunnel; to enable the Contractor to plan his work; and to assist the Engineer in reviewing Contractor's submittals and operations.

Add a general, one-paragraph description of the project.

C. SOURCES OF INFORMATION

Subsurface investigation reports by GSC (General Soils Consultant).

Construction experience reports by GCC (General Construction Consultant).

Geologic reports by other agencies or individuals.

Technical publications.

D. GEOLOGIC SETTING

Regional geology: discussion, geologic map, and generalized cross section of Washington, D.C., area.

Site exploration: description of subsurface investigations that have been carried out.

Site geology: geologic profile along the tunnel route with discussions of physiography, stratigraphy, and structure.

E. GEOLOGIC FEATURES OF ENGINEERING SIGNIFICANCE

Lithology (rock types)
Weathering profile
Joints, foliation, bedding
Shear zones and faults
Rock hardness and drillability
Groundwater.

F. SELECTION OF TUNNEL SUPPORT

Definitions: initial support, permanent lining.

Types of initial support considered, such as:
- Steel ribs
- Shotcrete
- Rock bolts.

Types of permanent lining considered, such as:
- Cast-in-place reinforced concrete lining
- Rock bolts
- Shotcrete
- Steel ribs and shotcrete composite.

G. DESIGN OF TUNNEL SUPPORT

- Initial support:
  - Contractor designed
  - Minimum requirements
  - Early installation.
- Permanent lining:
  - Loading conditions
  - Basis of stress analysis
  - Design thickness.

H. ANTICIPATED CONSTRUCTION PROBLEMS, GROUND BEHAVIOR

- Geological reasons.
- Potential effects on:
  - Tunnels and pillars
  - Shafts
  - Portals
  - Double crossovers
  - Stations and entrance excavations
- Solutions:
  - TBM design
  - Excavation sequences
    - Blasting requirements
    - Early initial support
    - Grouting
    - Groundwater control.
- Instrumentation.

I. CONSTRUCTION SPECIFICATIONS

- Discussion of the reasons for important or unusual requirements.

FORMAT FOR EARTH TUNNELS
GEOTECHNICAL DESIGN REPORT

A. TITLE

Geotechnical Basis of Design and Construction Specifications.

B. INTRODUCTION

This report describes geological conditions anticipated along the route of Section ______ tunnels of the ______ Route of the Washington Metropolitan Area Transit System, and the influence these anticipated geological conditions have had upon the design. In addition, the report is intended to assist prospective bidders in evaluating the requirements for supporting the tunnel; to enable the Contractor to plan his work; and to assist the Engineer in reviewing Contractor's submittals and operations.

Add a general, one-paragraph description of the project.

C. SOURCES OF INFORMATION

Subsurface investigation reports by GSC (General Soils Consultant).

Construction experience reports by GCC (General Construction Consultant).

Geological reports by other agencies or individuals.

Technical publications.

D. GEOLOGIC SETTING

Regional geology: discussion, geologic map, and generalized cross section of Washington, D.C., area.

Site exploration: description of subsurface investigations that have been carried out.

Site geology: geologic profile along the tunnel route with discussions of physiography, stratigraphy, and structure.

E. GEOLOGIC FEATURES OF ENGINEERING SIGNIFICANCE

Bedrock, weathering profile (if it impinges on tunnel).

Engineering properties of:
  Strata of the Cretaceous Age Potomac Formation
  Strata of the Pleistocene river terrace deposits
  Recent alluvium
  Fill

Groundwater

Present streams and old stream channels.

F. SELECTION OF TUNNEL SUPPORT

Definitions: initial support, permanent lining.

Types of initial support considered, such as:
    Steel ribs and lagging
    Metallic plate liner

Types of permanent lining considered, such as:
  Cast-in-place reinforced concrete lining
  Fabricated gray iron segmented lining
  Fabricated ductile iron segmented lining

    - Fabricated steel segmented lining
    - Precast concrete lining.

G. DESIGN OF TUNNEL SUPPORT
  - Initial support:
    - Expansion of steel ribs
    - Grouting tail skin void
    - Grouting voids behind lining
    - Construction and short-term loadings
  - Permanent lining:
    - Loading conditions
    - Basis of stress analysis
    - Design thickness

H. ANTICIPATED CONSTRUCTION PROBLEMS, GROUND BEHAVIOR
  - Geological reasons.
  - Potential effects on:
    - Streets
    - Utilities
    - Buildings
  - Solutions:
    - Shield design
    - Tunneling sequences
    - General construction procedures
    - Underpinning
    - Grouting
    - Groundwater control
  - Instrumentation.

I. CONSTRUCTION SPECIFICATIONS
  - Discussion of the reasons for important or unusual requirements.

Selected Bibliography

The publications listed herein fall into three basic categories:

- The majority are more-or-less related to site investigations, including both field and laboratory work. Also included in this category are publications on ground classification systems and behavior predictions, which are two major products of a good site investigation.
- Some of the publications are textbook-like volumes which contain good background material on almost all aspects of tunnels and shafts. Practically all of them contain sections on site investigations and ground classification systems. Deserving special mention are the proceedings of the Rapid Excavation and Tunneling Conference (RETC), which are so wide-ranging as to constitute an advanced text. Sponsored by ASCE and AIME every two to three years, six of these conferences have been held since 1972. They attract technical papers from almost every specialty associated with mining, tunneling, and shaft construction. Each proceedings, although presupposing some knowledge of each subject covered, is an easily obtained storehouse of information on up-to-date design, construction, and site investigations.
- Many of the publications are technical papers that provided background material on one or more of the projects that were researched for this study. The papers appeared in newsletters, technical journals, symposia proceedings, and other sources generally available to the public at large.

Not listed are the scores of site investigation reports and construction history reports compiled by project owners or their geotechnical consultants for specific sites and jobs. Even when made part of a contract document package, such reports are not readily available to the public and little purpose would be served by publishing their titles.

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Glossary

Many tunneling and geological terms can have multiple, and even somewhat contradictory, meanings. The following definitions have been written or chosen to be consistent with usage in this report. Underlined words are separately defined under their own entries. However, a few words are generally not noted in this manner because they occur so frequently in other definitions that underlining would prove a distraction. Therefore, before proceeding to other entries in the glossary, the reader may wish to refer to the definitions for "earth," "ground," "rock," "shaft," "soil," and "tunnel."

"A" LINE
A dimensional line in a tunnel, inside of which rock projections are not permitted.

ADIT
(a) A short length of tunnel driven from the surface to the main tunnel for access or mucking out. (b) A short transverse tunnel connecting two parallel main tunnels; often called a "cross adit."

ADVANCE
The distance excavated during a given time (shift or day) in tunneling, drifting, or in raising or sinking a shaft.

ARCH
The configuration of the upper portion of a tunnel section above the springline; the crown, roof, or back of a tunnel.

"B" LINE
A dimensional line in a tunnel, outside of which excavation is not paid for; may also be referred to as the pay line.

BACK
The overhead portion of a tunnel, i.e., ceiling; less commonly used than the synonymous term roof.

BEDDING
The arrangement of rocks in layers, strata, or beds of varying thickness and character; usually applied to sedimentary rock, in which case it is synonymous with "stratification."

BED ROCK

(a) Any solid rock exposed at the surface of the earth or overlain by unconsolidated material. (b) Rock of relatively great thickness and extent in its native location.

BENCH

The lower portion of a tunnel which is constructed by first excavating and supporting an upper portion and then excavating the lower portion. A system used in large-diameter or questionably stable tunnels.

BLOCKING

Blocks of wood or concrete installed between the lagging or steel sets and the rock surfaces of a tunnel to transfer stress to the supports.

BLOCKY ROCK

Rock having joints or cleavage spaced and oriented in a manner such that it readily breaks into loose blocks under excavation conditions.

BLOW OUT

The sudden escape of air from a tunnel driven under compressed air.

BOOMHEADER

A relatively soft-rock mining machine that can mine selectively and cut any shape or size of tunnel by use of a cutting head on a hydraulically controlled boom or arm that is generally centrally positioned on the unit and extending cantilever-fashion in front of the machine in such a way that it can be vertically raised or lowered or swung in an arc from side to side.

BORE

In reference to construction operations, the making of a relatively large hole in earth or rock with an excavating device, while removing the muck mechanically or with the aid of gravity. Distinguished from drill.

BOREABILITY

A value expressing the boring properties of rock in terms of the penetration rate with certain numbers/types of cutters and amount of pressure applied. Equivalent to "tunnelability," the ease or difficulty with which a rock type can be penetrated by a tunnel boring machine.

BOREHOLE, BORING

An exploratory hole made in the earth with a drill, auger, or drive sampler for the purpose of determining soil, rock or groundwater conditions.

BOULDER

A detached and rounded or much-worn mass of rock greater than 10 inches in diameter, typically carried some distance from the parent rock by natural forces and worn by a stream, ocean waves, or glacier, or by weathering in situ.

BREAST BOARDS, BREASTING

Boards placed and braced temporarily across the face of a tunnel drive to support incompetent materials.

BRIDGE ACTION TIME

The time that elapses between the exposure of an area at the roof of a tunnel and the beginning of noticeable, unprovoked inward movement of the ground above this area; sometimes described as "stand-up time."

CAVERN OR CHAMBER

A relatively short, underground room-type opening of large cross-sectional area, generally built to house a special structure such as a hydroelectric power plant, hardened defense facility or storage for waste.

CHANGED CONDITION

Physical site condition revealed by excavation to be substantially different from the condition that could reasonably be anticipated from information in the contract documents. Common basis for litigation by contractor, sometimes resulting in an extra paid by owner.

CHEMICAL GROUT

A combination of chemicals that gel into a semi-solid after they are injected through drilled holes to strengthen incompetent ground (generally soil), or to prevent groundwater from flowing into the excavation.

CIRCULAR TUNNEL

A tunnel of circular cross section, generally made with a full circular shield or tunnel boring machine.

COMPETENT GROUND

Ground that can stand for relatively long periods with no support or only minimal support when a tunnel is excavated through it.

COMPRESSED AIR

Air supplied to the tunnel at greater than atmospheric pressure, either to operate pneumatic tools or to facilitate tunneling in very soft or wet ground. See also high air and low air.

CONSOLIDATED MATERIALS

Earth materials, generally of sedimentary origin, which have been firmly densified or converted into rock by compaction, deposition of cement in pore spaces, and/or by physical and chemical changes in the constituents.

CONSOLIDATION

(a) In classical geology, any or all of the processes whereby loose, soft, or liquid earth materials become firm and coherent. (b) In soil mechanics, the adjustment of a saturated soil in response to increased load involving the squeezing of water from the pores and decrease in void ratio.

CONTRACT MODIFICATION

Change in a construction contract that either increases or decreases the scope of work, amount of materials, or length of performance time originally envisaged.

CONVENTIONAL MINING

Traditional, labor-intensive excavation such as hand mining in soft ground and drill-and-blast mining in rock. Distinguished from the more highly mechanized methods of mining.

CORE RECOVERY

In rock core drilling, the amount of the drilled rock withdrawn as core (i.e., recovered); generally expressed as a percentage of the cored interval or coring "run." Example: a 5-ft coring run that yields 4 ft of rock core constitutes a recovery of 80 percent.

COVER

The material, including soil and/or rock, as measured along a perpendicular from the tunnel crown to the ground surface. See also overburden.

CROWN

The highest point of an arched tunnel cross section; the roof or back of a tunnel.

CROWN BARS

Timbers or steel members cantilevered from previously installed sets nearest the heading to temporarily support a rock tunnel roof while the next set is being installed.

CUT-AND-COVER TUNNEL

A tunnel constructed by excavating a trench from the surface and then decking it over, usually with timber, so that traffic can be maintained while the structure is built within the trench.

CUTTERHEAD

The rotating front end of a tunnel boring machine, serving as a mount for the ground-abrading cutters.

DEEP SHAFT

A shaft of relatively (but not formally defined) great depth, usually associated with mines and underground waste storage and less often with civil engineering projects which are relatively shallow. In this report, a 1,225-ft deep penstock shaft used as a study project might not be considered a "deep" shaft by some specialists.

DIFFERING SITE CONDITION

Same as changed condition.

DISC CUTTER

The most common type of roller cutter, taking the form of a single circular disc or cutter blade of hardened steel alloy which revolves freely about its axis as it rolls around the rock face. May carry double or triple disc blades on a single cutter mounting.

DRIFT

A mined passageway or portion of a tunnel. In the latter sense, depending upon its location in the final tunnel cross section, it may be classified as a "crown drift," "side drift," "invert drift," etc.

DRILL

In reference to construction operations, the making of a relatively small circular hole in earth or rock with a cutting tool, while removing the cuttings by means of a circulating fluid. Distinguished from bore.

DRILLABILITY

A specific value expressing the drilling properties of a rock in terms of the penetration rate with a certain type of bit and feed pressure.

DRILL-AND-BLAST

A method of excavating rock by drilling small-diameter holes on a planned layout, packing these with explosives, and then firing to a fixed program to shatter the rock in a desired form. Distinguished from machine mining, mechanical excavation.

DRILL JUMBO

In drill-and-blast tunnel construction, a rubber-tired or track mounted movable frame with platforms to support men and drills.

DRIVE

To excavate horizontally or at an inclination, as in a drift, tunnel, adit, or entry. Distinguished from sink or raise.

EARTH

(a) Loose material of the earth's surface; the disintegrated particles of solid matter, as distinguished from rock. (b) Material which can be removed and handled economically with pick and shovel or by hand, or which can be loosened and removed with a power shovel. See soil for related definition.

EARTH-BALANCE SHIELD

A closed-face shield designed for tunneling in fine-grained soils by trapping excavated materials against the face and removing them at a rate slow enough to maintain pressures that counterbalance earth pressures, stabilize the face, and prevent ingress of water.

EARTH TUNNEL

A tunnel driven in relatively easily excavated earth or soil rather than in rock. Also commonly referred to as a soft-ground tunnel.

EXPLORATORY SHAFT

A shaft constructed for the purpose of studying ground conditions in the vicinity of a future underground opening.

EXTRA

Additional payment made to a contractor as a result of work or use of materials beyond the scope of the original contract.

EXTRADOS

The exterior surface of an arch; in a tunnel it is the arch surface lying against the excavated rock or soil surface.

FACE

The advance end or wall of a tunnel at which work is progressing.

FAULT

A fracture or fracture zone in the ground along which there has been displacement of the two sides relative to one another, parallel to the fracture. The displacement may be a few inches or many miles.

FEELER HOLE

A small-diameter exploratory hole drilled ahead of the tunnel face in order to determine ground conditions.

FINAL LINING

Long-term shaft or tunnel support installed for permanent stability or other user requirement, often incorporating the initial support elements; also referred to as "permanent lining," "permanent support," "final support."

FIRM GROUND

Consolidated sediments or soft sedimentary rock in which the tunnel heading can be advanced without any (or with only minimal) roof support, and the permanent lining can be constructed before the ground begins to move or ravel.

FLOWING GROUND

Soil below the water table so affected by seepage pressures toward the tunnel working face that what might otherwise be running or ravelling ground is transformed into a flowing mass that advances like a thick liquid into the heading.

FOLIATION

General term for a planar arrangement of textural or structural features in any type of rock, especially the planar structure that results from flattening of the constituent grains of a metamorphic rock. See also schistosity.

FOREPOLE, FOREPOLING

Sharpened planks or steel sections driven from the arch to extend at an upward angle ahead of a soft-ground tunnel face to provide temporary support and overhead protection while another increment is being mined. Generally driven over the last set near the face, with the butt end wedged beneath the next to last set.

FREE AIR

Air at atmospheric pressure.

FRICTION ROCK STABILIZER

A 3- to 8-ft long steel bar with a slot along its entire length, inserted in drilled holes of slightly smaller diameter around the periphery of a tunnel. The slot causes the stabilizer to be in compression and exert an outward anchoring force to tie rock-blocks or strata together and prevent their loosening or falling out.

FULL FACE

Tunnel excavation to full cross-sectional size with each blast or shove. Distinguished from heading, bench, and multiple drift.

GOUGE

Finely abraded or pulverized rock particles and claylike altered rock found between the walls or within the fractures of a fault or shear zone; the result of grinding movements that crush the affected rock.

GRADE

(a) The overall vertical alignment of an underground opening. (b) Locally, the same as "gradient," i.e., the rate of incline or decline in terms of degrees from the horizontal, percent of rise to the horizontal distance, or in feet of vertical projection per mile of horizontal projection.

GRIPPER SHIELD

A shielded rock or hard-earth tunnel boring machine equipped to move forward by reacting (i.e., exerting shove forces) against the tunnel walls through a hydraulic gripper reaction system.

GRIPPER TBM

A rock tunnel boring machine which generally utilizes roller disc cutters as excavation tools and which moves forward by reacting (i.e., exerting shove forces) against the tunnel walls through a hydraulic gripper reaction system.

GROUND

The medium, whether soil or rock, through which a tunnel is driven.

GROUND ANCHOR

Part of a ground support system consisting of a tendon inserted in a drilled hole, secured at the remote end, usually by means of a grouted plug, and tightened or tensioned against the ground retaining member in the system. See also rock bolt.

GROUT

A pumpable slurry of neat cement or a mixture of neat cement and fine sand, commonly forced into holes drilled from a tunnel to strengthen incompetent soil/rock or to prevent groundwater from flowing into the excavation. See also chemical grout.

GUNITE

A form of mortar consisting of fine sand, cement, and water which is sprayed on freshly excavated rock by air pressure to prevent deterioration of the rock, and in some instances to provide structural support.

HAND MINING

(a) Tunnel excavation by means of hand-held tools rather than by heavy, mechanized cutting or digging equipment. (b) Term sometimes applied to drill-and-blast operations in order to emphasize a distinction from TBM-mining.

HARD ROCK

In construction, rock having a strongly bonded nature such as to require excavation by blasting or the use of specially hardened cutters; generally includes igneous and metamorphic rock and the more strongly bonded sedimentary rocks.

HEADING

(a) The wall of unexcavated ground at the advance end of a tunnel; similar in use to face. (b) A small advance tunnel driven for the purpose of enlarging to create the main tunnel; similar to drift, but generally driven above the springline as a top heading.

HEADING-AND-BENCH CONSTRUCTION

A tunneling method in which a top heading is excavated, followed (within one to a few blasts or shoves) by excavation of the lower bench. Distinguished from top heading construction.

HEAVY GROUND

Very incompetent rock, usually found in faults or in shear zones; highly weathered or decomposed material having a tendency to move into the open tunnel area.

HIGH AIR

Compressed air used in tunnels to operate pneumatic tools. Generally supplied at 100 psi.

HIGH ROCK

A rock surface extending above the invert of a tunnel that would otherwise be driven entirely in soft-ground conditions.

HOLE THROUGH

To "daylight" a tunnel at a portal or to meet another tunnel face which results in a continuous tunnel.

HORSESHOE TUNNEL

A tunnel of roughly horseshoe-shaped cross section, oriented like an inverted "U." Many variations on the basic configuration are possible.

INCOMPETENT GROUND

Essentially the opposite of competent ground or firm ground. See heavy ground for related definition.

INITIAL SUPPORT

Relatively short-term tunnel or shaft support installed for stability and safety during construction operations, with elements generally left in place and incorporated into the final lining. Initial support is often referred to as primary support.

INTRADOS

The interior curve of an arch, as of a tunnel lining.

INVERT

The lowest point of a tunnel, i.e., the floor. On a circular configuration, it is approximately the bottom 90 degrees of the arc of the tunnel. On a square-bottom configuration, it is the bottom of the tunnel.

JOINT

In rock, a naturally occurring fracture or parting along which there has been no visible movement parallel to the fracture plane or surface.

JUMBO

See drill jumbo.

JUMP SET

One steel rib or unit of timber framing installed between two overstressed sets or between two pre-existing sets.

LAGGING

Wood planking or other structural materials spanning the area between ribs.

LINER PLATE

Iron or steel plates which can be fastened together to support the arch, sides, and in some cases the invert of a tunnel.

LINING

A casing of brick, concrete, shotcrete, iron, steel, or wood placed in a tunnel or shaft to provide support and/or to finish the interior.

LOW AIR

Compressed air used to facilitate tunneling in soft or very wet ground by counterbalancing external hydrostatic pressures. Supplied at 5 to 40 psi.

MACHINE MINING

Continuous tunneling by means of boomheaders, tunneling machines, TBMs, etc. Distinguished from drill-and-blast.

MASSIVE

(a) In geology, the homogeneous structure of a rock without any planar, directional arrangement of textural or structural features. (b) A durable body of rock that is essentially free of fractures and other discontinuities, and possesses a strength that does not vary appreciably from point to point.

MECHANICAL EXCAVATION

The removal of soil or rock by means of heavy cutting or digging equipment (not hand-held). Distinguished from hand mining and drill-and-blast excavation.

MINED TUNNEL

A tunnel excavated without removing the overlying rock or soil and, except for shaft connections, open to the surface only at one or both ends during construction.

MIXED-FACE TUNNEL

A tunnel requiring excavation of both earth and rock materials in the same heading at the same time. Some owners may extend the definition of rock to include boulders larger than 3 ft in diameter because of similar difficulties of removal.

MOLE

See tunnel boring machine (TBM).

MUCK

Excavated soil or rock that must be removed from the tunnel or shaft in order to continue advancing. The removal operation is termed "mucking" or "mucking out."

MULTIPLE-DRIFT EXCAVATION

A tunneling method in which two or more parallel drifts are pre-excavated in order to install partial ground support before the full tunnel cross section is opened up between them.

OPEN-CUT TUNNEL

A tunnel constructed by excavating a trench from the surface, building the structure within the trench, and then backfilling to restore the surface.

OVERBREAK

The quantity of rock that is actually excavated beyond the perimeter established as the desired tunnel outline (i.e., the pay line), owing to the irregular pattern of rock breakage.

OVERBURDEN

In this study, essentially the same as cover, the total depth of soil and/or rock overlying the tunnel crown. Distinguished from another common definition as the mantle of soil or loose material overlying bed rock.

PAY LINE

A dimensional line in a tunnel, outside of which excavation is not paid for.

PENETRATION RATE

The optimum speed with which a drill or excavator can advance through the ground in a short time before it is slowed or stopped by mechanical breakdown, ground instability, or the like.

PILOT TUNNEL

A small tunnel excavated over the entire length or over part of a larger tunnel, to explore ground conditions and/or to assist in final excavation. May also be referred to as a "pilot drift."

POLING BOARD OR PLATE

See forepoling.

POPPING ROCK

An overstressed rock condition involving the spontaneous and violent detachment of rock slabs. See also rock burst.

PORTAL

The entrance from the ground surface to a tunnel.

POSTS

The vertical members of a steel rib or timber support system.

PRE-SPLITTING

A technique of inducing cracks roughly following the periphery of the rock shape to be excavated by the use of closely spaced holes and reduced explosive charges prior to main blasting; a subdivision of smooth blasting.

PRIMARY SUPPORT

See initial support.

PULL

The length of rock broken when a round is fired at the face.

QUARTER ARCH POINTS

Those areas between the tunnel crown and springline covering approximately the spread from the 1:00 to 2:00 o'clock and the 10:00 to 11:00 o'clock positions.

RAISE

(a) To excavate a shaft upwards, in distinction from sinking. (b) A vertical or inclined shaft driven upward from an underground opening, most frequently to connect with another underground opening or the surface.

RAISE BORE

To raise a shaft by means of a rotating mechanical device generally powered and/or guided upward by a drill stem fed through a small down-drilled pilot hole.

RAISE BORE AND REAM

To raise bore a shaft of moderate size, then enlarge to a greater diameter by pushing or pulling a mechanical "reaming" device through the initial opening.

RAISE BORE AND SLASH

To raise bore a shaft of moderate size, then enlarge to a greater diameter by means of blasting, or "slashing."

RAVELLING GROUND

Poorly consolidated or cemented materials that can stand up for several minutes to several hours at a fresh cut, but then start to slough, slake, or scale off.

RIB

A part of the tunnel support, usually of structural steel, curved to suit the shape of the tunnel section. See also set.

ROADHEADER

See boomheader (currently a synonymous term).

ROCK

(a) Ordinarily any consolidated or coherent and relatively hard, naturally formed mass of mineral matter; stone. (b) In engineering, a natural aggregate of mineral particles connected by strong and permanent cohesive forces (i.e., interlocking crystals, closely packed grains, natural cement). (c) Any material which requires blasting or the use of powerful, hardened equipment for effective removal.

ROCK BOLT

A round steel bar, sometimes very long but usually less than 25 ft long, equipped with an expandable anchor at the far end, inserted in drilled holes around the periphery of a tunnel to tie rock-blocks or strata together and prevent their loosening or falling out. It may be locked into the hole mechanically or with some type of grout. It may be tensioned or untensioned.

ROCK BURST

A spontaneous and violent detachment of a slab or slabs from overstressed rock. See also popping rock.

ROCK DOWEL

A 5- to 40-ft long steel reinforcing bar inserted in drilled holes around the periphery of a tunnel and anchored or sealed with mortar or polyester resin to tie rock-blocks or strata together and prevent their loosening or falling out.

ROCK QUALITY DESIGNATION (RQD)

A modified core recovery percentage in which only sound pieces of rock core 4 in. or more in length are counted as recovery. RQD is considered a more accurate gauge of a rock's engineering "quality" or competence than is the gross recovery percentage. It is stated as the cumulative percent of the core run occurring in pieces greater than 4 in. long.

ROCK TUNNEL

A tunnel driven in consolidated natural material (i.e., "rock") which requires use of rock excavation methods such as blasting, channeling, wedging, or barring, or a tunneling machine making use of specially hardened cutters.

ROLLER CUTTER

A cutter consisting of a circular metal disc with hardened rim or teeth, mounted on bearings set in the rotating face of a TBM and rolled in an arc across the rock face under force; the resulting concentration of force or of stress spalls the rock. See also disc cutter.

ROOF

The overhead portion of a tunnel, i.e. ceiling; a more common term than the synonymous back.

ROOF BOLT

Physically the same as a rock bolt.

ROUND

A cycle of rock excavation consisting of drilling blast holes, loading, firing, and then mucking.

ROUTE FOOT

A measurement of alignment that distinguishes between single tube and multiple tube configurations for the purpose of equating the utility of borehole surveys. For example, one borehole may be used to survey (theoretically) twice as many linear ft of tunnel for a double tube system as for a single tube system. Thus, one route ft in a double tube system comprises two linear ft of tunnel alignment; in a single tube system, route ft and linear ft are the same.

RUN-IN

Relatively sudden, uncontrolled flow of material into a tunnel from the face or the tunnel circumference.

RUNNING GROUND

Perfectly cohesionless materials (such as dry sand or clean, loose gravel) above the water table which run from any unsupported lateral face until a stable pile is built up at the angle of repose.

SCALING

The removal of loose pieces of rock adhering to the solid tunnel surface after blasting.

SCHISTOSITY

The foliation in schist or other coarse-grained, crystalline rock due to the parallel, planar arrangement of mineral grains of the platy, prismatic or ellipsoidal type, such as mica.

SEGMENTS

Sections of iron, steel, or precast concrete which can be bolted or keyed together to make up a ring of support or lining. Iron or steel segments are generally referred to as liner plates; concrete segments may be referred to as "panels."

SET

One steel rib or unit of timber framing to support the sides and roof of a tunnel.

SHAFT

An excavation of limited area compared with its depth, constructed for access, ventilation, or conveyance of water to an underground opening. The term is often specifically applied to an approximately vertical shaft as distinguished from an incline or inclined shaft.

SHEAR ZONE

A local geologic structure resulting from the relief of earth stresses by the formation of a multitude of minute, closely spaced fractures with slight slipping or faulting along each.

SHIELD

A movable steel tube, framework, or canopy shaped to fit the excavation line of a tunnel and used to provide immediate support for the tunnel and protect the men excavating and providing the longer-term supports. May be fitted with a cutting device for excavating the tunnel and/or a form and mechanical devices for placing the tunnel lining. See also soft-ground shield and gripper shield.

SHOTCRETE

A form of quick-setting concrete with aggregate generally no larger than 3/4 in., sprayed on freshly excavated rock by air pressure to provide early, flexible support and sometimes applied more thickly to provide permanent support.

SHOVE

The act of advancing a mole or shield with hydraulic jacks.

SINK

To excavate a shaft downwards from the surface, in distinction from raising.

SLABBY ROCK

Rock cut through by finely parallel joints and/or cleavage planes so that it breaks into tabular plates upon exposure in an excavation.

SLAKING

The crumbling and disintegration of rock or hard soil upon exposure to air or water.

SLICKENSIDES

The polished and sometimes striated surfaces on the walls of faults and shear zones, resulting from rubbing during earth movements. Sometimes referred to by construction people as "slicks."

SLURRY SHIELD

A closed-face shield designed for tunneling in very soft, wet, or running ground by use of circulating, pressurized clay slurry against the face to counterbalance earth pressures, prevent ingress of water, and also to carry away the cuttings.

SMOOTH BLASTING

A technique of using carefully controlled shot hole drilling and specially prepared charges in peripheral blast holes to reduce overbreak. See also pre-splitting.

SOFT-GROUND SHIELD

Any tunnel shield which moves forward by reacting (i.e., exerting shove forces) against the tunnel lining and generally utilizing drag type excavation tools that can be mounted on a backhoe, rotating wheel or oscillating arm.

SOFT-GROUND TUNNEL

Same as earth tunnel. The ground may be hard or soft in consistency, the word "soft" differentiating it only from "hard" rock.

SOFT ROCK

In construction, rock having a weakly bonded nature such as to permit excavation by air-operated hammers or other equipment only slightly more powerful than earth excavation equipment. Generally includes the more weakly bonded of the sedimentary rocks, such as clay shales.

SOIL

(a) In geology, any loose surface material overlying solid rock. (b) Broadly and loosely, the regolith, or blanket of unconsolidated rock material that lies on the bed rock. See earth for related definition.

SPALLING

The breaking off of thin surface sheets or plates in rock under excessive tension.

SPILES, SPILING

Essentially the same as forepoling, but may also include steel bars drilled ahead of a rock tunnel face.

SPRINGLINE

The point where the curved portion of a tunnel roof meets the top of the wall. In a circular tunnel the springlines are at the opposite ends of the horizontal centerline.

SQUEEZING GROUND

Weak material, generally clayey, that behaves plastically under the weight of overlying ground and tends to close a tunnel opening by slowly advancing into it without perceptible volume increase.

STAND-UP TIME

See bridge action time.

STOPE

(a) A highly inclined or vertical excavation driven from the main tunnel or drift in an upward direction. (b) Excessive overbreak occurring for only a short distance and extending to a considerable height above the crown of a tunnel; may also be referred to as a "chimney."

SWELLING GROUND

Material that expands in volume by absorbing or adsorbing water so that it tends to move into a tunnel opening or to exert great pressure upon the supports.

TAIL VOID

The annular space at the back (tail) end of a shield between the outside diameter of the shield and the outside of the primary lining.

TEMPORARY SUPPORT

Essentially the same as initial support, except that the elements can be (and sometimes must be) removed because of non-contribution to or incompatibility with the final lining.

TOP HEADING

The upper portion of a tunnel, often extending from springline to crown, pre-excavated in order to install arch support before opening the tunnel to full size.

TOP HEADING CONSTRUCTION

A tunneling method in which a complete top heading is excavated end-to-end before excavation of the lower bench is begun. Distinguished from heading-and-bench construction.

TUNNEL

An elongate, essentially linear excavated underground opening, generally with a length greatly exceeding its width or height.

TUNNEL BORING MACHINE (TBM)

A machine that excavates a circular tunnel by cutting and/or abrading the heading to full size in one operation. Also referred to as a mole. The term has so commonly been associated with rock tunneling that when a TBM is used in earth it is often prefaced by the qualifier "soft-ground."

TUNNELING MACHINE

A continuously excavating machine utilizing one or more rotating cutterheads which are revolved under force against the tunnel face.

WATER TABLE

The upper limit of the portion of the ground at which water levels stand, as measured in piezometers or observation wells.