Tunnel Site Investigations and Geologic Factors Affecting Mechanical Excavation Methods

WILLIAM H. IRWIN (retired), MALCOLM H. LOGAN, and IRA E. KLEIN,
U.S. Department of the Interior, Bureau of Reclamation, Denver

Major efforts are being made by the Bureau of Reclamation to improve investigation techniques, design of underground structures, and construction procedures associated with the rapidly growing mechanical methods of tunnel excavation. The impact of rapid excavation on engineering geologic investigations and the major requirements of the Bureau of Reclamation now being evolved are discussed. Principal attention is given to efforts to improve engineering geologic investigation techniques to meet the demands of mechanical tunnel excavation by development in areas such as geophysics, computer storage and analysis of geologic data, research on drillability indexing, and aerial remote sensing. The paper briefly discusses the application of geologic data involving the development of quantitative values, the apportioning of these values, and their projection to define successive reaches of rock quality and geologic uniformity at tunnel grade.

•AS MAN PROBES the unknown realm of space, he is also, in a less dramatic manner, reaching deeper into the unknown realm of the underground. The importance of this underground work in numerous fields of endeavor has become progressively more important in the past few years. The Bureau of Reclamation, for example, has plans that include several hundred miles of underground water conveyance systems associated with the construction of hydro projects in the western states. These encompass almost every geologic condition that can be conceived.

Major efforts are being made not only to improve the design but also to adapt to rapidly improving construction procedures. Determination of continuity, soundness, and physical properties of the rock to be penetrated is a major essential. The Bureau is also expending considerable effort to improve the exploration techniques and methods of interpretation and evaluation. This is necessary not only to produce a sound, economical project but also to minimize changes that might be required because of unexpected conditions revealed during excavation and construction.

This paper discusses the state of the art of tunnel investigations as practiced and planned by the Bureau of Reclamation; it does not attempt to present standardized proposals for tunnel line investigations relating to mechanical boring.

ENGINEERING GEOLOGY

Engineering Geology and Machine Tunneling

Machine or "mole" tunneling has generated a strong impetus to the expansion of almost every aspect of geologic investigation. There is greater need for more detailed

Paper sponsored by Committee on Soils and Rock Properties and presented at the 49th Annual Meeting.

information in order to make decisions on the choice between machine and conventional methods. Making this basic decision requires information for evaluating the capabilities of the numerous machines available, for modifying existing machines, or for developing entirely new machines that can cope with projected conditions. It is doubtful whether the tunnel design engineer or the prospective tunneling bidder can have too much information. The point of diminishing returns for investment in geologic investigations is much higher if machine tunneling is in the picture.

Several years ago mole capabilities were limited and could realistically be considered for use only in soft, firm rocks. Now, because of the enormous progress in the ability of tunneling machines to handle hard rock economically, the outlook is entirely different. Practically all proposed tunnels must now be considered for machine as well as for conventional methods. However, adequate care must be given to ensure a balanced, careful investigation, for certainly there are some extremely difficult geologic conditions that will put a machine at a disadvantage or even in an impossible position.

For example, in conventional tunneling the drill-blast-muck cycle may be slowed down or even stopped by hard rock, high groundwater flows, or support requirements. Intermittent progress can still be made by resorting to the use of more dynamite, bigger pumps, or heavier support. There is room to work, and the capital investment in drills and muckers is relatively low.

On the other hand in machine tunneling, if those conditions are encountered, idled capital investment is very high. The lack of room to work may make the obstacles insurmountable and force abandonment of the machine, at least temporarily. If a major change of excavation method is required, extensive extra costs are unavoidable.

The possibilities of combined use of machine and conventional methods on an individual tunnel must always be considered. Blanco Tunnel of the U. S. Bureau of Reclamation's San Juan-Chama Project is an example of a successfully combined operation.

At the present time, the Bureau is studying another project as a possibility for combined tunnel excavation. In this case, a twin bore will be driven parallel to and only 400 ft from one excavated by conventional methods in 1950 with no significant problems. Rock at tunnel grade consists of a series of basaltic lava flows and associated interflow sediments. The basaltic portion of the tunnel will be in rock that varies structurally and texturally from massive nonvesicular to highly vesicular and flow-breccia types. Soft relatively uncemented interflow sediments comprise the remainder of the geologic sequence. Groundwater conditions in the area of the new tunnel have been changed as a result of the operation of the existing tunnel, and saturation of the interflow sediments is now prevalent.

To judge the applicability of a mole, an appreciation of the proportions of the different types of basalt as well as the groundwater and interflow sediments was necessary. Consequently, a core-drilling program substantially larger than the one accomplished for the earlier parallel tunnel was carried out. How the combination of very low-dipping lava flows and wet interflow sediments will be handled as a construction problem remains to be seen, but it is difficult to conceive of an existing tunneling machine that can effectively and economically handle this problem.

Although testing of samples is an integral part of tunnel studies, the amenability of a hard rock mass to either machine or conventional methods is clearly more than a matter of the intrinsic strength characteristics of the rock material as indicated by sclerometer hardness, abrasiveness, compressive strength, elastic modulus, and special boreability index testing. The discontinuities in the rock mass such as joints, bedding planes, and metamorphic cleavage and shears also have a major influence. Therefore, a partial picture (which can be seriously misleading) can be obtained by unbalanced or incomplete selection of samples and application of the resulting laboratory test data. Equal importance must be given to evaluation of systematic descriptions of field geologic discontinuities and the core breakage characteristics.

Even if the value of tests of samples is accepted, there is also a tendency by some to overemphasize the advantages of making laboratory tests on cores directly from the "tunnel elevation" in holes directly on the tunnel line. Except for problems encountered in negotiation of contractor claims, there is often little or no advantage. With a proper understanding of the geologic structures and materials to be traversed by the tunnel, one can generally obtain samples that are entirely satisfactory and representative from suitably located shallow holes that are not "on line." In fact, judicious use of surface outcrop samples collected by a geologist can, under many circumstances, be effective.

Summary Statements

What is new or different about geologic investigations now that the mole, i. e., rapid excavation of tunnels, is ascendant?

1. The scope of investigations required overall has increased greatly. More time, more drilling, more laboratory testing, and more geologic mapping are necessary in reconnaissance, feasibility, and final design stages. Only a few years ago core drilling for feasibility was practically never done; now it is a normal procedure. Previously, in final design, the main emphasis was exploration of the portal cuts; now this is often a secondary consideration.
2. Equal emphasis is now placed on developing information for the bidder and machinery manufacturer as well as for the design engineer.
3. More laboratory testing of core samples is required.
4. In situ testing in bore holes by geophysical and rock mechanics or soils mechanics techniques to evaluate rock properties is being given increasing attention, but this phase of investigations is being approached experimentally; that is, it is still largely a matter of research and development.
5. Adequate geologic data to permit evaluation of support requirements is more critical for machine tunneling than for conventional tunneling.

Investigation Techniques

Major requirements of the geologic investigations for the Bureau of Reclamation presently fall into a sequence that includes the following:

1. Preparation of a program of exploration and laboratory testing that is in balance with the size of the project and the anticipated geologic complexities;
2. Identification and 3-dimensional projection of the various rock units along the tunnel line, which requires detailed knowledge of the stratigraphy in sedimentary rocks and boundary conditions such as flow structure, fracture patterns, and foliation in igneous and metamorphic rocks;
3. Identification, location, projection, and evaluation of secondary structures such as faults, shear and breccia zones, jointing, folding, and unconformities;
4. Evaluation of the potential or calculated risk of encountering adverse groundwater conditions, presence of gas, squeezing ground, abnormally high temperatures, and any other distinctive geologic environments affecting the tunnel bore; and
5. Presentation of these data on clear, concise geologic maps and appropriate cross sections annotated with significant engineering and physical data.

To obtain data on these elements, the Bureau of Reclamation has directed its attention to the development of several engineering geologic aspects pertinent to tunnel excavation by mechanical means. These are briefly discussed in the following paragraphs.

Geophysics

Geophysics is believed to have a good potential as a method for expanding the measurements of many geologic parameters. A research program, now in progress, will evaluate the capability of geophysical techniques to determine, at depth, the attitude of major fault and shear zones and their characteristics with regard to design and construction. Of particular importance in this respect is the effort to provide a basis for judging "moleability" or comparative rock quality by determining the seismic velocity of successive reaches of the tunnel line.

Parallel objectives are (a) developing effective field operation procedures for mountainous terrane and (b) reducing dependence on expensive, deep drill holes and permitting such exploration to be concentrated at strategic points where direct factual exploration data on rock conditions are most beneficial.

Measurement of stress relief or blast damage or both in excavated tunnels by geophysical (seismic) means is an existing capability.

Computer Storage of Geologic Data

The Engineering Geology and Data Processing Divisions have cooperated in developing an initial data storage and retrieval system for geologic information. The main system involves both digital and alphabetical entry of specific geologic data from which subroutine packages may be extracted and analyzed. Separate subroutines have been written for geologic and engineering data such as permeability, joint indexes, fracturing, and degree of weathering, and then provide for storage, retrieval, analysis, and presentation of these data.

The total system promotes organization of these data collection and analyzes, maximizing speed, thoroughness, standardization, and efficiency. In addition it will permit integration of data from numerous projects, both completed and proposed, over long time spans. It stimulates accumulative engineering geologic analyses relating geologic parameters to engineering properties of rock and soil materials in foundations and excavations.

The computer program does not replace the engineering geologist. It provides a modern tool by which he may quickly evaluate a large number of geologic combinations that would be impractical by hand methods of calculation. Thus, for example, searches can be made for combinations of conditions that would produce failure patterns and establish the geologic units in which these circumstances occur.

Joint Studies

A thorough study of the rock joint systems in the terrane through which the tunnel will pass will be of prime importance to the tunnel engineer who must evaluate tunnel excavation techniques and estimate the quantity and suitability of various support methods. In the analysis of the joint data, an attempt is made to answer the following:

1. How many distinguishable joint systems occur in the area?
2. What are the attitudes of these joint systems relative to the proposed tunnel centerline?
3. What is the spacing of the joints within a joint system?
4. What is the typical 2-dimensional extent of joints within a system?
5. What are the widths of the joints in a system?
6. Do joints have a filling, and, if so, what is the filling material?
7. Do joints of one system tend to intersect but not continue across the joints of another system?
8. Has slippage occurred along any joint or system of joints?

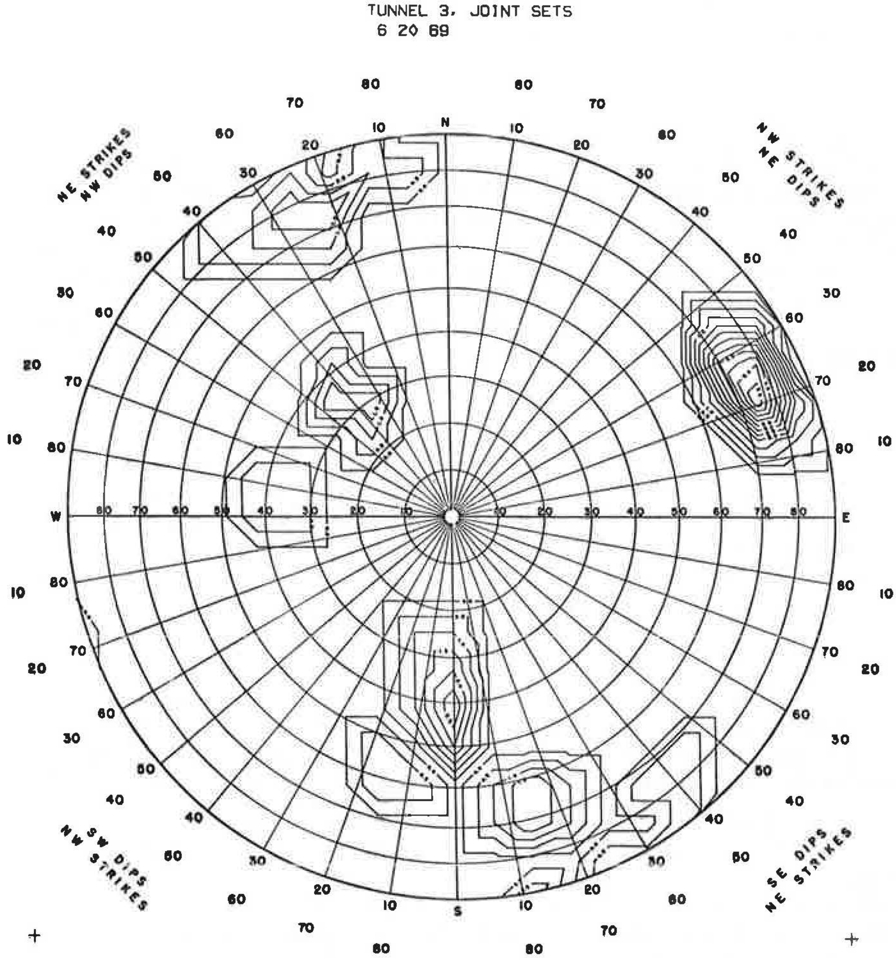
It is quite obvious that even a skeletal evaluation of these data could be extremely difficult. With the services of a computer, successive combinations of different geologic and physical conditions can be analyzed in minutes and, if desirable, presented graphically by automatic machine plotters (Fig. 1).

Drillability Index

During the past year, the Colorado School of Mines has been under contract with the Bureau of Reclamation to accomplish basic studies leading to the development of a drillability index to be used in conjunction with machine tunnel boring projects.

Three basic rock testing procedures have been employed. One consists of a linear cutter, one a button cutter, and the third a single button.

Force-displacement or energy curves for various rock types are being developed. These will be related to standard physical properties and to a commercially available "calibration rock" (Colorado red granite). Interested tunneling contractors can economically obtain samples of the calibration rock. They will have the standardized reclamation test results available for comparison with their own proprietary test techniques and related computations for cutter wear and rate of heading advance. On the limited



Each joint set as recorded in longs of tunnels, drifts, and/or raises is plotted at the equal-area projection of the intersection of its normal with a reference (upper) hemisphere. The value of the point for contouring purposes is 1.0. Points are contoured by summing the value of all points within circles of the 1 percent area on the hemisphere, centered on points that form a grid with a spacing 1/10 of the radius of the reference sphere. Contours represent number of joint sets per 1 percent area. Contour densities indicate the orientation and approximate relative frequence of occurrence of important joint sets. No information on the spacing of the joints within the various sets can be obtained from this drawing. The outer circle of numbers is used for reading strike azimuth and the inner circle of numbers for reading dip azimuth. Numbered circles indicate dip angle.

Figure 1. Contoured joint diagram, equal-area projection, upper hemisphere.

number of samples tested to date, reproducibility of results has been very good. Vertical force response to crushing, cratering, and fracturing have been observed for several reliable samples with close correlation for all data. Numerous test samples have been obtained from reclamation tunnels where the results are being directly compared with the operation and reaction of the tunneling machine.

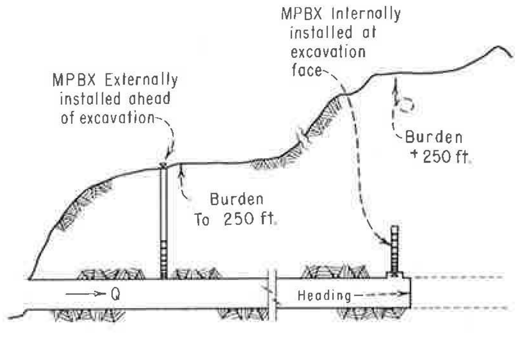


Figure 2. Typical tunnel installation of rock extensometers.

Instrumentation

The Bureau of Reclamation has, to date, installed multiple position borehole extensometers (MBPX) in 6 underground structures to measure the relationship of rock movement to the adjacent excavation. Installation of the instruments has been both external and internal, that is, from both the ground surface and in the tunnel adjacent to the working face respectively. Present capabilities allow installation of the equipment to a depth of 250 ft from the ground surface (Fig. 2).

Evaluation of the tests conducted thus far indicate that tunnels excavated by mechanical means (mole) maintain the inherent competence of the surrounding rock and result in less movement than those excavated by conventional drill and blast methods.

Air-Photograph Interpretation—Remote Sensing

For all but very short water-conveyance tunnels, the interpretation of vertical aerial photographs proceeds concurrently with field geologic mapping along the tunnel route. Such photographic studies supplement and are an indispensable aid to developing an understanding of underground conditions. Lineations may be detected in air photographs that are essentially invisible in ground surface field examinations. The lineations may be a guide to the identification of formation boundaries, wide shear or fault zones, and different joint systems that will have a marked influence on evaluation of geologic conditions at tunnel grade.

Distribution of vegetation, anomalous alignment of ravines, stream patterns, and other drainage or linear features may reveal the need for more detailed mapping or assist in locating drill holes. Air-photo patterns are commonly examined for a considerable distance on both sides of the tunnel line for evidence of discontinuous regional lineations. Such lineations may represent important changes in geologic structure or zones of weak rock that are covered in the immediate vicinity of the tunnel line itself.

Evidence is growing that some techniques of aerial remote sensing can reveal features, such as fault lines and anomalous distribution of near-surface groundwater (reflecting subsurface structure), that cannot be detected in aerial black-and-white and standard color photography. Side-scanning radar, infrared scanning imagery, and color infrared currently show the most promise in potential application to tunnel line investigations.

APPLICATION OF GEOLOGIC DATA

The design of engineering works in rock combines empirical practices, proven theoretical analysis, past experience, and an understanding of the major parameters of the rock involved. Principles from mechanics have been used to predict rock behavior, but most of the time serious shortcomings are inherent and impede the geologic and engineering analysis because of the inability to handle anisotropic rock masses. However, mechanical methods of tunneling are believed to be more amenable to analysis than conventional methods because the blast-damage factor is eliminated, the natural strength and architecture of the rock is retained, and the rock mass at tunnel grade can be more validly related to in situ surface conditions along and adjacent to the tunnel alignment.

In order to effectively utilize the geologic information, an attempt must be made to reduce these data to quantitative or engineering terms. This has commonly been accomplished by a relationship to past tunneling experience in comparable or nearcomparable geologic environments. In other instances, the relative estimated values were established and compared between geologic units anticipated for the individual feature. In some cases the investigations (both field and laboratory) were sufficiently extensive to provide rather complete suites of tested samples from which values could be assigned to the various rock units.

To establish these quantitative values along with the distribution of each, engineering geologists, engineers, geophysicists, and laboratory technicians work together to attack the problem. Typical samples of the various rock types, representing a range of quality for each, are collected and subjected to laboratory tests for physical properties. Petrographic and petrofabric studies are also conducted on the test samples. Once established, these values are projected and apportioned to their respective geologic units at tunnel grade. The engineer then utilizes the quantitative information to develop a design.

Although field experience in machine tunneling is far more limited than in conventional tunneling, lining and supports appear to be the major item of design concern to reclamation projects. In the conventional tunnel, discontinuities or weaknesses in the rock structure are generally accentuated by blasting, and immediate attention is given to support requirements, construction practices, and permanent lining requirements as construction proceeds. Conversely, elimination of blast effects in machine tunnels (commonly neatly cylindrical) obscures the defects in the tunnel wall and slows down the reaction of the rock around the tunnel to the new stress conditions. The newly machine-excavated tunnel walls may, therefore, appear stronger than they actually are and may lead to initial misjudgment of support and lining needs. Thus, although this paper is essentially concerned with investigations in advance of actual tunneling excavation, we believe it is worth calling attention to this significant difference between the machine-bored and blast-excavated tunnels. It would appear that the demands on the engineering geologist for thorough geologic mapping during construction and continued observations on the behavior of the rock are even greater for the machine than for the conventional tunnel; that is, geologic investigations must be continued into and beyond the construction period for machine tunnels to an extent beyond that envisaged for conventional tunnels.

Between the time that the face has passed and stability of the excavation has been achieved, it has been found that the vertical height of the tunnel opening has diminished. The actual distance at which stability is achieved varies from tunnel to tunnel and even in the same tunnel. Instances have been noted where stability of the excavation occurred within 2 tunnel diameters of the face. In other instances, stability has been noted to occur about 200 to 300 ft from the face, or in the order of 10 tunnel diameters. If the concrete lining is in place when this adjustment is taking place, bending moments will be developed in the lining; and cracking may occur unless the concrete is still sufficiently plastic. By delaying placement of lining beyond the rock load adjustment period, abnormal stress buildup in the lining due to instability of the rock can be minimized. The design studies, therefore, require that geologic investigations develop information regarding the geologic structure and its potential for failure in order that the design required to prevent such failure may be developed.

In this respect, a major frontier of subsurface geologic investigations for tunnels is the determination of the actual state of stress (in situ stress) of the rock along the line. This problem can be approached as a rock mechanics problem by devising tests to be made in bore holes and from analysis of the geologic history. Work has hardly begun in this challenging field.

Weakly lithified sedimentary rocks, particularly argillaceous ones such as many shales and claystones, require special attention, especially when traversed at great depths. When these rock types prevail along the tunnel line, the use of mechanical tunnel methods have marked advantages over conventional excavation methods.

The natural groundwater conditions and the influence of construction operations on the moisture content and related strength characteristics must be understood. Sampling for laboratory testing and in situ testing by geophysical or other methods and the evaluation of the results are part of the engineering geologists' work in tunnel investigations.

Inasmuch as the circular tunnel cross section is the strongest geometrical configuration for stress distribution, less or lighter support is required to maintain the integrity of the bore. Also, elimination of the blast damage factor allows a minimum support requirement because of the absence of overbreak.

Shale interbeds, strongly developed joint sets trending parallel to the tunnel, faults, and severely altered or sheared zones are examples of geologic structures that exert a marked influence on support requirements. In machine tunneling an early evaluation of support needs is basic to the selection of the mole type.

CONCLUDING STATEMENT

Engineering geology has had a difficult task in meeting the requirements of conventional excavation methods and the advent of the tunneling machines, for rapid excavation has compounded the requirements for more detailed and reliable geologic knowledge of underground excavations. Machine tunneling or rapid excavation is only in its infancy, and the technology associated with it remains as a formidable challenge not only in the Bureau of Reclamation but in numerous other fields of endeavor.