Practical Geotechnical and Engineering Properties for Tunnel-Boring Machine Performance Analysis and Prediction

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Given the ever-increasing range of geological conditions that can be and have been excavated by tunnel-boring machines (TBMs), both new and used, it behooves the industry to enhance the potential for mechanical excavation during the early stages of project conception and planning. Early planning will allow appropriate geological data and rock tests, necessary to clearly establish anticipated conditions, to be developed. Clear definition of anticipated conditions protects contractors from risk and owners from spurious claims. In this paper methods of estimating anticipated TBM performance are outlined and examples of analysis used on encountered TBM performance are presented. Methods outlined herein should only be used by persons who have appropriate TBM expertise. Analyses of past TBM performance are essential to prediction. In effect, prediction and analysis are related, one feeds the other.

More than 125 years have passed since the first tunnel-boring machine (TBM) was built and 30 years have passed since the first successful TBMs were built by Robbins and Jarva in the 1950s. In the last 15 years an increasing number of tunnel projects and the availability of used machines have made it possible to excavate marginal tunnel projects by TBM. The growing TBM lifespan is reflected by an increasing number of new ventures that specialize in rebuilding used TBMs.

After a method of predicting TBM penetration rates and cutter wear was provided by Tarkoy *(1–5)*, the focus shifted to the prediction of TBM utilization. Prediction of utilization was outlined in a paper by Tarkoy *(3)*. Since then, more refined methods based on extensive TBM performance data and analyses have been developed. Refined methods permit the preparation of accurate, reliable, and responsible estimates of TBM penetration rates, cutter costs, and as many as 20 categories of TBM downtime.

In the last 15 years, TBM case history data have been collected and microcomputers have been introduced. This combination of events has permitted detailed analyses of performance data, heretofore impractical. The microcomputer facilitated development of a large TBM data base with a wide variety of TBM performance, backup system, project management, and geotechnical variables.

Custom software, originally developed on mainframes for analyzing encountered TBM performance *(1, 2)* and later moved to microcomputers, was used to prepare detailed estimates of anticipated TBM performance *(3)*. With the development of generic software, such as electronic spreadsheets, it was possible to develop simpler, faster, and more flexible methods of estimating TBM performance on a microcomputer.

Estimating anticipated TBM performance with the microcomputer-based system relies on a large data base that represents a wide variety of conditions and produces estimates that would have been impractical to calculate otherwise.

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Unique and economical advantages of TBM excavation have been put to widespread use, even in marginal conditions, and the commensurate benefits are being reaped. The greatest benefits of TBM excavation can be enjoyed when mechanical excavation is considered during project conception and planning.

CONSIDERATIONS FOR TBM PROJECTS

TBM excavation must be considered at an early stage to

1. Establish accurate economic and technical TBM feasibility,
2. Plan exploration to provide information necessary to prepare an optimum design and a competitive bid for TBM excavation,
3. Design a project to enhance the capabilities of a TBM and minimize the effect of its limitations, and
4. Successfully execute TBM excavation and project completion.

During the various stages of project development, increasingly more complex and detailed information is necessary and becomes available. Consequently, TBM excavation feasibility, anticipated performance, project design, and costs can be recalculated and refined.

Project Feasibility Stage

Mechanical excavation is generally more economical than conventional tunneling, particularly on longer tunnels. Therefore it is essential to determine TBM excavation feasibility at project conception and enhance the planning, exploration, design, bidding, and construction for mechanical excavation. On the basis of simple feasibility-level exploration, it is possible to evaluate TBM feasibility and prepare comparative estimates of conventional and TBM excavation.

Decisions made by planners and designers in the early stages of conception have the greatest impact on project cost. Therefore it is essential that planners and designers avail themselves of current state-of-the-art knowledge and experience regarding exploration, design, contracting, bidding, and excavation using TBMs. It is important that

1. Exploration be appropriate to anticipated conditions and anticipated type of construction equipment and methods,
2. Geotechnical testing be appropriate to anticipated conditions and anticipated type of construction equipment and methods,
3. Rock testing include total hardness (H_T) for all rock units to be encountered, and

4. Construction expertise for anticipated conditions be utilized during project conception.

Feasibility Exploration

Feasibility exploration consists of a fact-finding survey that is generally limited to a literature search, simple establishment of route alignment, preliminary design and selection of preliminary construction methods, and preparation of a feasibility estimate. The exploration program is established on the basis of the information obtained from the fact-finding survey. Typical sources are summarized in Table 1.

General geology, lithologies, structure, water table, and major features can be determined during the feasibility phase to provide information adequate for evaluation of TBM (penetration, utilization, advance rate, cutter costs) feasibility. However, the preliminary exploratory program does not provide sufficient information for design or construction and further investigations are required.

Local and Pertinent Experience

Armed with fundamental and general knowledge of geology and geologic conditions of the proposed site and a catalog of local and similar tunneling and excavation experience, it is possible to establish

1. Experience in similar geological conditions,
2. Local tunnel excavation costs, and
3. Local experience with similar excavation methods.

It is important, however, to ascertain that conditions and methods are truly comparable. The types of excavations that may be surveyed include

1. Transportation (railroad, highway, subway) tunnels;
2. Water and sewer tunnels;
3. Hydroelectric and associated tunnels;
4. Mine access and development tunnels; and
5. Other applicable excavations.

Feasibility Estimate of TBM Performance

Rock hardness directly affects TBM penetration and cutter costs. Indirectly it also affects downtime, which in turn inversely affects utilization and advance rates. For very rough and general estimates, penetration rates and cutter costs can be determined from known average rock properties shown in Figure 1 and applied to empirical relationships between total hardness and TBM penetration rates (Figure 2) and between total hardness and cutter costs (Figure 3). Quantitative calculation of penetration rates and cutter costs may be supplemented by case histories, summaries of TBM experience, and reports of TBM performance to provide a rough estimate of utilization and to permit calculation of shift and daily advance rates.

Utilization is proportional to total hardness (Figure 4) and directly dependent on a variety of interrelated factors that are more difficult to define. These factors include various elements of project management and the TBM backup system available to deal with geotechnical conditions, both expected and unexpected. Utilization is also inversely proportional to TBM diameter.

Utilization greater than 30 percent should not be used for feasibility estimates unless a detailed study is carried out or specific utilization requirements are stated in the contract specifications, or both.

Project Exploration Stage

Exploration, design, and construction are inextricably intertwined and cannot be considered separately. Inasmuch as the design depends on geological conditions, the type of geological exploration necessary will depend on the design and construction methods envisioned.

Objectives and Scope of an Exploration Program

The objectives of an exploration program are simply to satisfy the needs of the parties involved. The owner's need is to have a facility that is suitable for the purpose intended, compatible with the existing environment (urban or rural), and constructable at the lowest possible cost.

The engineer's need is to have the information necessary to permit the selection of optimum location, design, and construction methods in order to provide the facility at the lowest cost.

The contractor's needs must be served to permit him to choose the most appropriate and cost-effective equipment and methods. In addition, a contractor must estimate progress and costs related to excavation, stabilization, support, lining, and any potential problems.

The primary goal of exploration has classically been to provide a minimal amount of information for design. The needs of the contractor require more detail than those of the owner or designer because construction is much more sensitive to geological conditions than is design.

Consideration of excavation by TBM, particularly under marginal, difficult, or challenging conditions, brings with it the added responsibility of providing geotechnical information essential to TBM performance prediction. In other words, TBM excavation requires that results of pertinent and appropriate rock testing be made available to bidders so that more competitive and responsible bids can be made.

The competitive bidding environment is conducive to optimism, particularly when information to the contrary is lacking. Therefore optimism may lead to unsupportable differing site condition claims, which can be prevented by leaving little to interpretation.

Professional geotechnical interpretation by the owner or his engineer, made available at bidding time, should define clear and reasonable anticipated conditions, methods of evaluating encountered conditions, and methods of establishing legitimate claims of differing site conditions, should they occur.

Factual data relevant to TBM excavation are not considered adequate for prebid interpretation. Providing professional interpretation of anticipated conditions and comments regarding TBM performance is considered essential to assure that all contractors are bidding the same conditions and have reasonable expectations. Presentation of factual data during bidding permits and promotes a wide variety of interpretations and optimism by individuals least familiar with the project and its geology and least qualified to interpret those data.

TABLE 1 SUMMARY OF FEASIBILITY EXPLORATION METHODS

Category	Specific Items
Archives	Plans of old civil structures, shorelines, former watercourses, swamps, and fill areas
Regional	Physiography; geomorphology; drainage patterns; geologic material characteristics; and soil, agricultural, glacial, bedrock, and structural maps
Literature	Textbooks (geomorphology, physiography); city search (original topography, shorelines, archive maps, etc.); county (soils and geologic maps, water well data); universities (geology, civil engineering, agricultural, mining and minerals); state (geological and water surveys, agricultural experiment station, mining and minerals, wells and boreholes for oil, gas, and minerals); tourist pamphlets; federal (U.S. Geological Survey, Bureau of Mines, Bureau of Reclamation, USDA Forest Service)
Maps	Country; airline (physiographic); highway (highway alignments, other features); American Association of Petroleum Geologists (geologic and highway); state geology and soils; county (agricultural experiment station, land use, topographic, geologic, landform analyses)
Remote sensing	Aerial photography, multispectral scanning, radar sensing imagery, infrared imagery (useful to determine lithology, structure, groundwater conditions)
Local experience	Excavation of any type, quarries and mines, road construction cuts, water wells, borings
Site visit	Geology, physiography, field mapping, surficial features, sources of water, highways, railrailroads, chemical plants, gas pipelines, structures

Ambiguities in such data promote either large contingencies or optimistic assessment of anticipated conditions. Optimism invariably results in differing site condition claims, which make the project costlier than when interpretations are provided.

Definition of anticipated ground behavior and comments about construction performance leave little room for interpretation and thus establish a common basis for all estimates, bids, and adjudication of bona fide differing site conditions.

It is clear that a great deal of the responsibility rests with the owner and his engineer. This is appropriate because they are involved from the inception, for the longest period of time, and throughout the project. They produce the geotechnical reports and contract documents and are most familiar with all relevant conditions. The contractor is generally involved only during the bidding period, which may be as short as 1 to 2 months.

Detailed geotechnical information will decrease the uncertainties to which mechanical excavation is uniquely sensitive. The magnitude and nature of an exploratory program should be determined on the basis of the

1. Importance (use and cost) of the project to be constructed,
2. Nature of site geology,
3. Sensitivity to construction methods and equipment, and
4. Evolution of exploration with project design to suit geotechnical conditions.

There is no standard scope for an exploration program; instead, its sophistication varies with the complexity of the project and its geology and with method of construction, funds available, and parties involved.

The responsibility for organizing and developing exploration for the design and construction of a project should lie with an individual who has qualifications that include knowledge of general geology, intimate knowledge of engineering geology, familiarity with geotechnical engineering associated with design of a structure, intimate familiarity with construction equipment and methods, and an understanding of costs associated with construction methods.

Exploration and Testing for TBM Excavation

It is important for the director of exploration to be familiar with the latest exploration, testing, and empirical relationships, particularly those relevant to TBM excavation equipment and methods. Table 2 gives a summary of common field exploration data that are pertinent and must be acquired for determining construction methods, equipment, and behavior. Laboratory tests relevant to construction and anticipated rock behavior must also be provided (Table 3).

Preliminary Selection of Construction Methods

During the initial stages of exploration, potential construction methods should be selected to tailor and provide appropriate exploration, preliminary design, and rock tests for all construction

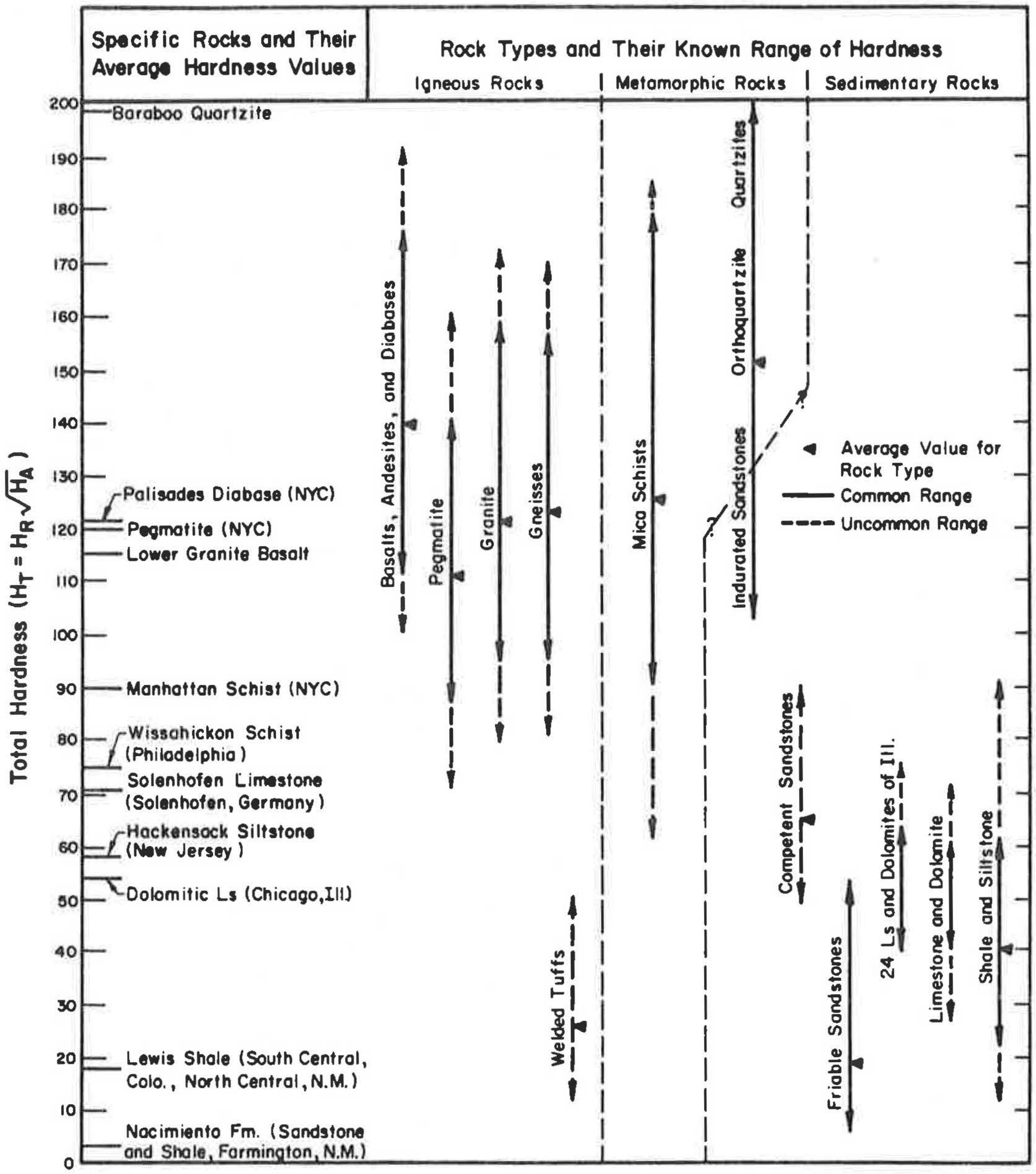

FIGURE 1 Total hardness for common rock types bored by TBM.

alternatives being considered. To assist with evaluating the appropriateness of TBM excavation on a particular project, the advantages and disadvantages can be summarized as follows:

- Advantages
  - High and predictable excavation rates
  - Continuous (noncyclical) excavation
  - Smooth bore, hydraulic advantage
  - Less disturbance of the rock
    - Negligible overbreak
    - Less support (about 10 to 20 percent of drill-and-blast support)
    - Less water inflow
    - Increased inherent safety
  - Tunnel may stand permanently unsupported
  - Concurrent concrete lining is possible
- Disadvantages
  - 6- to 12-month lead time to manufacture new TBM
  - High initial capital expenditure
  - Difficult or limited access to the face (probe drilling, grouting, presupport)
  - Impractical to change excavation method if problem develops

A preliminary selection of mechanical excavation, at an early stage of the project, will enhance the consideration of the inevitable savings for initial support, less overbreak, and final support. In competent rock, a lining may be unnecessary because it is possible to take advantage of the hydraulic properties of a smooth machine-bored tunnel. Support methods that are incompatible with TBM tunneling should be avoided. Exploration and testing must provide information required for predicting anticipated TBM penetration, downtime, and cutter wear.

Project Design Stage

The choice of design is interrelated with the method of construction. Unless the structure can be built (economically), the

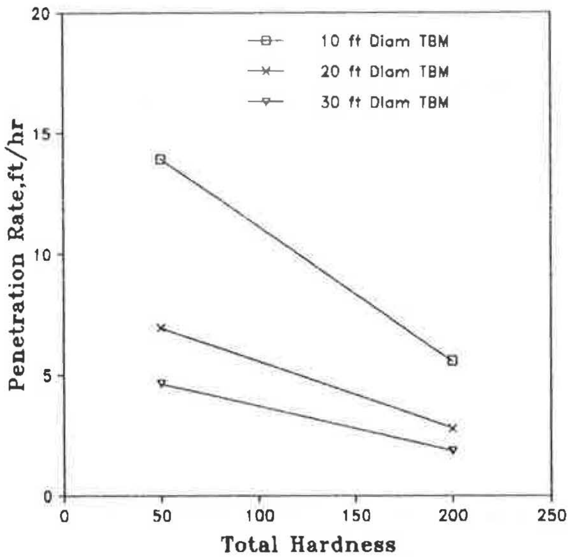

FIGURE 2 Empirical relationship between total hardness and TBM penetration.

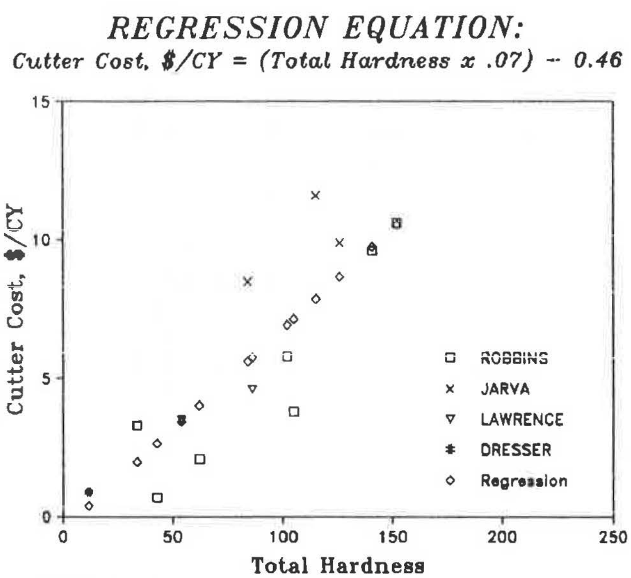

FIGURE 3 Empirical relationship between total hardness and TBM cutter costs.

design will never come to fruition. When the preliminary design is envisioned, anticipated construction methods should be selected and associated cost estimates prepared.

The design of a project is based on the requirements of the desired facility and the ability to construct the facility at a reasonable and lowest possible cost. In other words, design must reflect geological conditions as well as economic constructability. Consequently, it is clear that geology is the independent variable and design and construction are the dependent variables. As a result, the importance of geology and geotechnical properties of the site becomes much more apparent.

Selection of Excavation and Support Methods

Some of the major reasons why TBM excavation is commonly selected are

1. Economic considerations (faster and cheaper excavation),
2. Imposed time limitations (faster project completion),
3. Design advantages (unlined hydraulic properties),
4. Cost advantages (less initial and final support), and
5. Imposed environmental limitations (noise, vibrations).

Many choices can be made no later than the project design stage. These choices fix the cost and approach throughout exploration, design, and construction. Changes are costly and associated with delays and claims.

TBM excavation will generally require less support than conventional excavation for the same ground conditions. The effect of supports on costs in a TBM tunnel will be the result of decreased excavation rates and the cost of materials and installation. The method of support must be structurally adequate and compatible with the high penetration and advance rates common with TBM excavation. Compatibility of the support and excavation system can have a profound effect on excavation rates.

Common tunnel support systems, in decreasing order of desirability for TBM excavation, are as follows:

1. Unsupported,
2. Rock bolts,
3. Steel ribs and lagging,
4. Precast segments and liner plate,
5. Surficial protective epoxy and coatings,
6. Gunite and shotcrete, and
7. Spiling or forepoling.

An attempt should be made to select support that requires consistent crew sizes, occasions no delay or stoppage of the excavation system, and has no adverse effects on the equipment (shotcrete).

Unsupported tunnel requires no downtime for support. Spot bolting can generally be maintained without downtime by assigning one or more drillers. Pattern bolting will require a large enough crew of drillers and chucktenders with drills to handle twice the average anticipated penetration rate.

Precast segments and ribs and lagging will require a crew and support-erection equipment adequate to prevent downtime while advancing at double the average anticipated penetration rate. In the case of steel sets, the crew may have to be adjusted continuously, depending on rock hardness, penetration rate, and advance, to prevent downtime.

The placement of protective coatings to prevent deterioration of the rock may be performed without downtime only if an adequate crew and well-maintained equipment are provided.

Application of gunite or shotcrete, installation of spiling and forepoling, and installation of a combination of supports will generally require a total shutdown of TBM excavation.

Classification schemes are available for predicting support requirements in tunnels; however, few if any take into account the effect of mechanical excavation. For general purposes (no allowance was made for diameter), Table 4 may be used to establish anticipated TBM support. Common practice provides for pattern bolting in TBM tunnels larger than 15 ft in diameter.

Design Considerations for TBM Excavation

Design considerations to minimize construction cost, enhance successful excavation, and optimize advantages of TBM excavation are given in Table 5. Unusual anticipated conditions that may affect tunnel excavation should be identified early in project

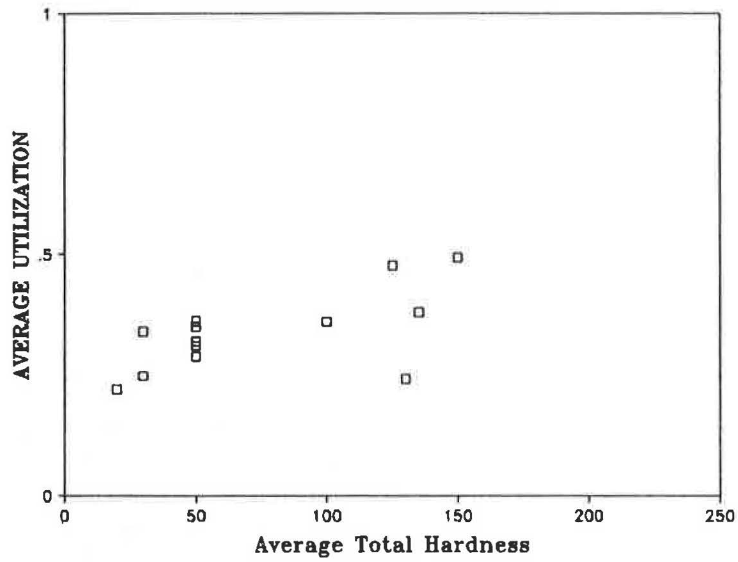

FIGURE 4 Experience with total hardness and TBM utilization.

TABLE 2 EXPLORATION DATA FOR TUNNEL CONSTRUCTION

Exploration Method	Useful Data Provided
Core logs	
Rock type	Inherent and unique rock characteristics
Core recovery	Quality of the rock mass
Fracture index	Rock rippability (*6*, p. A7)
Rock quality designation	Rock quality *(1)*, rippability (*8*, p. A47)
Drilling rate	Relative rock hardness for boreability, cuttability, and rippability *(2)*
Discontinuities	Rock structure, behavior, and stability
Core sampling	Necessary for determining rock properties by testing
Nx	Preferred core size for testing
Triple tube	Preferred samping equipment especially under marginal rock conditions
Field seismic velocity	Rippability and rock quality *(9, 10)*
Acoustic probing	Cost-effective method for locating top of rock
Water testing	Required for determining permeability, water quality for effect on structural concrete, and toxic gases

TABLE 3 ROCK PROPERTIES PERTINENT TO TUNNEL CONSTRUCTION

Test	Application
Thin section analysis	Lithology and fabric for hardness
Unit weight	Design of lining
Hardness	
Total hardness (H_T)	Boreability by TBM *(2, 3)*
Point load	Roadheader cuttability *(11)*
Uniaxial strength	Rippability *(12)*
	Rough estimates of TBM penetration *(2)*
Modulus	Deformability and design of lining
Shale durability	Stability of excavated surfaces
Laboratory sonic velocity	Rippability *(9)*

development. For example, the incidence of faults, shears, weathered and altered rock, high in situ stresses, water inflow, and infiltration of gasses along the tunnel alignment can have disastrous consequences on tunnel excavation unless they are taken into account in the design of tunnel, support, construction system, and TBM.

Project Bidding Stage

At the time of bidding the primary goal of the owner's and engineer's exploration is to produce clear, concise data to promote a narrow spread of low-cost construction bids devoid of large amounts allocated for contingencies. The contract documents and data should also serve to protect the contractor in the event that conditions worse than anticipated are encountered. Thus the risk (and contingencies) of encountering high-impact features without hope for compensation or the inclusion of costly allowances for contingencies is eliminated.

The objective is simply to have bidders bid the same geological conditions, to exclude contingencies for geological uncertainties,

TABLE 4 COMMON SUPPORT TYPES USED IN TBM-EXCAVATED TUNNELS

	Rock Quality Designation				
Rock type	0–25 (very poor)	25–50 (poor)	50–75 (fair)	75–90 (good)	90–100 (very good)
Igneous	E	D-E	C-D	B	A
Metamorphic					
Foliated	E	D-E	C-D	B-C	A-B
Nonfoliated	E	D-E	C-D	B	A
Sedimentary					
Sandstone	E	D-E	C-D	B	A
Shale	E	E	D-E	C	A-B
Limestone	E	D-E	C-D	B	A

Note: A = bald, unsupported; B = spot bolting; C = pattern bolts; D = pattern bolts and straps; and E = ribs and lagging, precast segments, etc.

TABLE 5 TUNNEL DESIGN TO ENHANCE TBM EXCAVATION

Consideration	Remarks
Tunnel length	Provide maximum length of tunnel per contract and per single run; minimum 5 to 15,000 ft
Adverse conditions	Avoid Faults Joints at adverse angles to tunnel alignment Faults at adverse angles to tunnel alignment Water inflow, salt water inflow
Geometric limitations	Avoid Sharp curves Downgrade excavation Steep inclines and declines Small-diameter access shafts Unusually large-diameter machines Noncircular tunnel section if possible, otherwise permit drill-and-blast over-excavation to desired shape
Undesirable methods	Shotcrete, gunite, forepoling, steel ribs Grouting ahead of the face Probe drilling ahead of the face
Access	Provide easy access to the work area and tunnel portal or shaft for installation of the TBM; for long tunnels, provide periodic access through shafts for mucking and utilities
Construction schedules	Construction schedules should provide for TBM manufacturing and delivery and permit access to development work to receive TBM; provide adequate power on site before bid
Mobilization cost	Part of the TBM cost should be allowed in the mobilization costs

and to protect the contractor from encountered conditions worse than anticipated.

Although by bidding time owners and engineers may be satisfied with their knowledge of anticipated site and project conditions, contractors are only beginning to familiarize themselves in the limited time of 1 to 2 months allowed for the bid. The contractor takes the risk that his conception, interpretation, and approach are reasonable. It is at this stage that communication between the owner or engineer and the contractor becomes crucial.

Essential Information

As stated earlier, it is essential to provide results of exploration and rock testing (total hardness), descriptions of geotechnical conditions (jointing, faulting, water inflow, etc.), project design, contract language, conditions, and considerations appropriate to TBM excavation.

Selection of Construction Methods

At the bidding stage, conventional and machine excavation alternatives may have been preselected. However, if alternatives still exist, the geotechnical consultant and estimators require information to evaluate the most economic alternative. The selection is usually made by the contractor on the basis of economy, scheduling, availability of equipment, and ability to deal with anticipated conditions.

Evaluation of Prebid Conditions

The estimator, engineering geologist, or geotechnical engineer must be intimately familiar with construction methods and equipment. Fundamental responsibilities for geotechnical assessment require

1. Review of all pertinent literature and available information;
2. Review of all contract documents, boring logs, material samples, test results, geological reports, and specifications;
3. A site visit to examine and photograph geological and physical conditions, alignment, perimeter, adjoining structures, and so forth;
4. Gathering of data, experience, and analytical methods pertinent to the project;
5. Additional investigation and testing, if necessary; and
6. Quantitative opinions regarding anticipated construction conditions, performance, and potential problems.

Data and methods used for evaluation of TBM feasibility are too general and rough for prebid estimating. Project-specific data and methods must be used to estimate construction performance. Project data should be provided in the contract documents. Case history experience and empirical relationships should be developed in-house by the contractor or the geotechnical consultant.

The contractor's need to know can be summarized by, "Where, what, and how much?" To answer this question, it is necessary to consider

1. Excavation methods and support requirements,
2. Rate of progress,
3. Water and gas infiltration,
4. Any other conditions affecting tunnel construction, and
5. Materials and equipment that will be required.

The quantitative answers to these questions will be the foundation of a responsible, accurate, reasonable bid.

MEASURE OF TBM PERFORMANCE

Universal terms established to measure TBM performance are as follows:

1. Penetration rate (ft/hr) = Length of tunnel bored (ft per shift)/ Elapsed boring time (hr per shift)
2. Utilization (%) = Elapsed machine time (hr per shift)/ Excavation shift time (hr per shift) = Total shift time − Downtime
3. Cutter costs, $\$/yd^3$ or \$/ft of tunnel

The term "downtime" is used to define the nonutilization of the TBM. The advance rate, a combination of the penetration rate and utilization, is the unit most commonly used in estimating.

4. Downtime (%) = Total shift time − Machine time
5. Advance rate (ft/day) = Penetration rate × 24 hr × Utiliza-

tion (for three 8-hr shifts). Ft/shift = Penetration rate × 8 hr × Utilization (for an 8-hr shift)

"Availability" was the term used in the past to imply reliability when TBM breakdowns were common. It is no longer used because there is no universal agreement on its definition and it is therefore misleading.

GEOTECHNICAL PROPERTIES THAT AFFECT TBM PERFORMANCE

Feasibility of TBM excavation is based on the ability of a TBM and associated backup system to perform under the average and the most adverse geological and tunneling conditions. Consequently, it is necessary to define both average and most adverse anticipated geotechnical conditions for the alignment. Project costs and conditions, TBM design, and backup system variables must be specified to accommodate these conditions.

Average Conditions

The average geological conditions are the basis for design of the TBM and preparation of the construction estimate. The TBM, excavation backup system, and project management are designed for the average anticipated conditions in terms of support requirements, utilities (e.g., water pumping and discharge facilities, ventilation for gassy tunnels, mucking system capacity), and crew sizes to deal with average anticipated conditions. Average conditions are used to calculate average performance (penetration, utilization, cutter consumption, and advance rate). Average performance is the basis on which the estimate is prepared.

Average conditions are defined by the intact rock properties in terms of the total hardness (H_T). Rock mass properties affected by the extent, orientation, and characteristics of rock structures (joints, faults, and shears); rock mass characteristics [weathering, alteration, rock quality designation (RQD), stress conditions] and permeability; and mass behavior (squeezing, swelling, slaking, water inflow, and gas infiltration) all intimately influence tunnel stability and support requirements.

Adverse Conditions

Adverse geological conditions are those that are worse than the average anticipated conditions. These conditions must be evaluated carefully because their spatial extent and their degree of severity will significantly affect TBM performance and may alter feasibility or even constructability. Adverse conditions may consist of intact as well as rock mass properties.

Harder-than-anticipated rock or more extensive hard rock than anticipated is effectively an adverse condition. Both will decrease penetration and increase cutter costs. Unusually high cutter loads will be required for efficient cutting of occurrences of hard rock.

Hard rock no longer has the disastrous effect that it did in the earlier history of TBM development. High rock hardness has had different effects on performance of TBMs depending on their mechanical design. Advances in the state-of-the-art TBM design (cutter bearings, cutter metallurgy, cutter profiles, maximum sustainable cutter loads) have extended the limit of rock materials that may be bored economically and successfully.

Intact Rock Properties

Rock hardness is the most relevant property for evaluating TBM excavation performance. The rock property that is most commonly used to predict TBM penetration rates and cutter costs is total hardness (H_T), which is based on Schmidt (L-type) hammer hardness (H_R) and the modified Taber abrasion hardness (H_A), supplemented by the Shore (D-type) scleroscope hardness (H_S). These tests are described elsewhere *(13, 14)* (Table 6).

A number of unsuccessful attempts have been made to use other mechanical rock properties to predict TBM performance. Many of the test methods are nonstandard, inapplicable to boreability, proprietary, and of limited use because the property and performance relationships are unproven in the literature.

Total Hardness

Total hardness is determined from two individual tests, namely, the rebound hardness (H_R) and abrasion hardness (H_A) tests. Total hardness (H_T) is equal to

$$H_T = H_R(H_A^{1/2})$$

The range of total hardness for common rock types is shown in Figure 1.

Total hardness has been empirically related to TBM penetration rates *(1, 2, 13–15)*, utilization *(3)*, and cutter costs *(3, 4)*. These relationships have been successfully used to predict accurate anticipated TBM performance for contractors' estimates.

Total hardness was developed specifically to make reliable predictions of TBM performance *(2)*. A study funded by the National Science Foundation was based on extensive field work (collection of cores from bored tunnels), field experience based on TBM shift reports, and laboratory testing of core collected from bored tunnels. The objectives of the study were to

1. Develop empirical relationships between rock properties and TBM performance,
2. Study the effects of mechanical design of machine and cutting structures on performance,
3. Document the effects of mechanical design of machine and cutting structures on performance, and
4. Document case history data for use in evaluation of TBM feasibility for future projects.

The results were reported in part by Tarkoy *(1, 13, 14)* and in their entirety by Tarkoy *(2)* and Tarkoy and Hendron *(15)*. Subsequent development through experience on more than 100 projects was incorporated in the estimating method reported by Tarkoy *(3)*.

Detailed test specifications have been described *(13)* and have also been submitted to the American Society for Testing and Materials for standardization.

The Schmidt rebound hardness (H_R) is determined by taking readings using a calibrated Schmidt (L-type) hammer on Nx core seated in a standard core cradle. H_R tests were designed to be performed on Nx (2⅛-in.-diameter) core. Although Nq (1⅞-in.-diameter) core may be used with inserts in the test anvil, it has been noted from experience *(2)* that the use of Nq core may yield

TABLE 6 SUMMARY OF ROCK HARDNESS TESTS FOR TBM PERFORMANCE, AFTER TARKOY (13)

	Hardness Test	Description	Remarks
H_R	Schmidt (L-type) hammer hardness (calibrate and determine correction factor)	10 readings taken with core mounted in standard anvil; five highest readings are averaged; use correction factor	Best for mass property measurements because contact point is (1.3 cm) larger than scleroscope point
H_S	Shore scleroscope (D-type) hardness (calibrate and determine correction factor)	20 readings taken with core mounted in standard anvil; 10 highest readings are averaged; use correction factor	Contact point is fine (1 mm); therefore measurements more accurately represent individual grains and crystals, but statistical sampling must be taken and averaged for mass properties; can be used to estimate H_R if necessary when sample breaks during H_R test
H_A	Modified Taber abrasion hardness	Two Nx-sized discs (0.6 cm thick) abraded for 400 revolutions on each side; determine weight loss; use average values of two discs; H_A = 1/ weight loss (g)	This test is sensitive to factors that influence small-scale strength, shearing, crushing, and abrasion
H_T	Total hardness	$H_T = H_R/(H_A{}^{1/2})$	The rock hardness properties that correlate best with TBM performance in terms of penetration rates, repair and maintenance, and cutter consumption

lower readings than does Nx core. For that reason, it is useful to determine the Shore scleroscope hardness (H_S) to estimate H_R.

H_S is useful as an indicator of rock hardness and has been related to TBM penetration rates *(2)* with limited success. H_S is also useful in estimating the Schmidt (L-type) hammer rebound hardness (H_R) when samples are too small for testing or when they break during testing with the Schmidt (L-type) hammer *(2)*.

To have a complete set of dependable total hardness (H_T) test results, in spite of rock breakage during testing and the effect of undersized (Nq instead of Nx) core, the values of H_R were projected from the H_S values as described by Tarkoy (2, pp. 74, 78, Figure 5.6). This method was used by Tarkoy *(2)* and is used as standard laboratory practice. The values of H_R thus determined were also used to calculate total hardness (H_T).

The modified Taber abrasion hardness (H_A) is determined by taking two ⅛-in.-thick slices of Nx core and abrading each side for 400 revolutions on a modified Taber abraser. The inverse of the average weight loss is taken as the abrasion hardness (H_A). The prescribed modifications of the equipment and the testing procedure must be followed to produce consistent and accurate results. Detailed specifications for the modification of the Taber abraser are available from the author.

To obtain consistent and accurate results, equipment, equipment modifications, and detailed testing procedure must be followed precisely according to prescribed methods. Detailed specifications for the fabrication of the core cradle are available from the author.

Other Tests

The unconfined compressive strength (q_u) is not reliable for predicting TBM performance, particularly in foliated or other relatively anisotropic rock. Empirical relationships nevertheless have been developed between strength and penetration rates *(2)* for relatively homogeneous rock such as limestones, sandstones, and horizontally bedded shale. Uniaxial strength (q_u) is unnecessary yet useful in high-strength rock as an indication of the normal cutter load (F_n) necessary for efficient rock breakage.

The point load index is a simple test often used in lieu of the unconfined compression test because it is easier to perform. The test was originally described by Broch and Franklin *(16)*. Descoeudres and Rechsteiner *(17)* used a modified version of the test to relate to penetration. The correlation was poor and considerable judgment had to be exercised to reduce the scatter.

Results from the point load test are less reliable and consistent than are those from the uniaxial strength test. Furthermore, the point load test was originally meant to be applied to rocks of low strength, less than 10,000 psi (68.9 MPa), and preferably 5,000 psi

(34.4 MPa). It has since been applied (with special redesign) to testing of lumps that have an index (I_s) as high as 58,000 psi.

Rock Mass Properties

Rock mass properties affect TBM performance directly by requiring downtime to deal with adverse conditions. Indirectly, familiarity with anticipated rock mass properties is essential in the design of the TBM and backup systems to minimize downtime associated with adverse geological conditions such as squeezing ground, support placement, and protection against and countermeasures for dealing with water inflow. TBM system design for adverse rock mass conditions is intended to eliminate downtime and adverse effects on performance.

Joint Spacing

Jointing has been considered, overoptimistically, beneficial to TBM boreability. The beneficial effect of discontinuities depends on their spacing, attitude, and characteristics as well as the cutter head (false face, scraper, muck bucket, cutter mounts) design. The characteristics and orientation of discontinuities continually change along the tunnel length, and they interact with and are masked by other variables. Thus the difficulty of quantitatively defining the effect of jointing on boreability is compounded by the scarcity of substantiating data.

Field experience confirms that, for all practical purposes, adverse effects of discontinuities overshadow beneficial effects. The adverse effect of jointing on boreability occurs when joints are totally absent or very closely spaced.

Faults, Shears, and Weathered and Altered Rock

When faults, shears, shear zones, and weathered and altered rock are encountered, the physical conditions include soft, blocky, squeezing, and swelling rock (causing the TBM to get stuck) and associated water inflow. These conditions generally require installation of heavy supports. When such conditions are anticipated, the facilities for shielded support, support placement behind the TBM, and protection against water must be included in the TBM design to avoid downtime and the inevitable decrease in TBM performance.

High-Stress Conditions

Stress conditions may be encountered by a TBM as a result of

1. High in situ stresses,
2. Squeezing rock,
3. Swelling rock,
4. Slaking rock, and
5. Loosening of rock blocks.

The loosening of rock blocks can generally be prevented by initial support if a shield and subsequent primary rock support are used. Similarly, slaking can be prevented by protection of the susceptible material with shotcrete; gunite; or, more economically, epoxy sealant.

High in situ stresses, squeezing, swelling, and slaking that cause inward movement generally cannot be prevented and should be included in TBM design. Tunneling in such rock results in

1. Stresses exceeding material strengths and causing rock failure,
2. Squeezing of material around the TBM, and
3. Stress relief failure on tunnel wall around the gripper.

Water Inflow

Intact rock is relatively impermeable and rock permeability is controlled by secondary features (discontinuities) that make the definition of rock permeability difficult. Consequently, prediction of water inflow from a rock mass is inevitably no more than an educated guess. Nevertheless, the following information is necessary to estimate anticipated water inflow:

1. Hydraulic head above the tunnel,
2. Intact and rock mass permeability,
3. Storage capacity of the rock mass,
4. Recharge potential, and
5. Location of major conduits or inflows in the tunnel.

A reasonable way of establishing the range of rock mass permeability is to use the intact rock permeability as a lower limit and the highest permeability test results (usually in a permeable discontinuity) as the upper limit.

The method proposed by Goodman et al. *(18)* can be used to take into account the average rock permeability and the high permeability of discontinuities. Using this method, an average "background" inflow can be calculated using the intact rock permeability and the tunnel surface area. Similarly, local high inflows can be calculated using the permeability of joints and faults, appropriate spacing, and surface areas on the tunnel wall. The two flows should be averaged proportionately. The process requires sound judgment and must be tempered with professional experience.

Because water inflow cannot be avoided, there are a number of countermeasures that can be incorporated in the TBM design to protect it from water and to minimize the effect that water may have on construction performance.

Infiltration of Gasses

The accumulation of hazardous (toxic, flammable, asphyxiating, and radioactive) gasses is the second leading cause of injuries and fatalities in underground construction. Although it is difficult to estimate rate of gas infiltration in typical civil construction, subjective judgments can only be developed with factual information about potential gas conditions.

Although little can be done to prevent gas infiltration, there are a number of countermeasures that can be incorporated in the design of the TBM and backup system to minimize the effect on TBM performance.

Tunneling by machine in gassy (and water-bearing) conditions is safer than by conventional methods because

1. There is less disturbance and fracturing of the surrounding rock,
2. Continuous and consistent ventilation is possible at the face,
3. A TBM can be manufactured to be explosion proof,
4. Continuous TBM excavation is less likely to produce gas concentrations, and
5. Continuous monitoring at the tunnel face is easy with a TBM.

Other Adverse Conditions

High rock temperatures are uncommon for most civil tunnels; however, TBMs have been used extensively in deep underground mining applications in which high temperatures are normal. Problems associated with existing high temperatures have been and can be solved through TBM and backup system design.

ESTIMATE OF ANTICIPATED TBM PERFORMANCE

Basis of Estimate

Estimates of TBM performance are based on empirical relationships that have been developed between total hardness (H_T) and

1. Penetration rates *(1, 2)*,
2. Utilization *(3)*,
3. Maintenance and repair *(3)*, and
4. Cutter consumption *(3, 4)*.

The method was enhanced by

1. Including subsequent experience with more than 100 projects,
2. Continuing research, and
3. Refining the method of estimating TBM performance.

The empirical relationships and the method of predicting TBM performance *(3)* have been used extensively to provide the basis for contractors' tunnel excavation estimates. Results have been field tested in a number of cases in which prebid and postbid data were available; results have been within 5 percent of anticipated performance.

Project and Construction Assumptions

Project, TBM, and backup system assumptions are the foundation of a performance analysis. TBM performance estimates rely strictly on these assumptions and must be consistent with anticipated conditions. Important assumptions, given in Table 7, strictly control TBM performance.

Calculation of Anticipated TBM Performance

Penetration rates and cutter wear may be determined from total hardness (H_T), machine design, and cutter design. Downtime prediction is based on backup system design and construction experience. An example of a detailed cost appraisal reported by Persson and Schmidt *(19)* has been computerized *(3)* for prebid evaluation of TBM performance.

The emergence of microcomputers has radically changed traditionally subjective and qualitative methods of estimating TBM performance. Availability of generic software, particularly spreadsheets, has facilitated the refinement of TBM performance-estimating methods.

TBM Penetration Rate

The rate of penetration is calculated from empirical relationships based on total hardness (H_T) as shown in Figure 2. The design configuration of the TBM (cutter head rotational rate, cutter gauge velocity, cutter forces, cutter spacing, cutter type and diameter, etc.) is selected from empirical relationships. The empirical relationships between rock properties and TBM performance associated with respective TBM design variables will assist in designing the TBM that has the highest penetration rate to deal with anticipated geotechnical conditions.

TBM Downtime

Total downtime may be calculated for as many as 26 different categories. However, downtime generally falls into the categories given in Table 8.

Calculated downtime and geological downtime are generally determined in units of minutes per shift hour. Downtime based on case history experience and prevented downtime are usually available as a percentage of total excavation shift time. All downtime is converted to minutes per shift hour and back into percentage of total excavation shift time to calculate utilization.

Determination of many of the downtimes requires circular calculations with numerous iterations to obtain a stable number. This is a result of interrelated variables and relationships. For example,

TABLE 7 PROJECT ASSUMPTIONS THAT AFFECT TBM PERFORMANCE

TBM	Cutters	Project	Backup System
Head diameter	Cutter type	Tunnel diameter	Cutter change
Stroke length	Gauge velocity	Lunch time	Stroke cycle
Total thrust	Cutter spacing	Shift change	Support
Total torque	Normal cutter load	Repair and maintenance	Mucking
Cutter head drive	Tangential cutter load	Precautions for gas	Utilities
Cutter head rpm	Cutter costs	Union regulations	Engineering
Gripper size	Cutter diameter		Electric delays
Gripper bearing	Cutter geometry		Conveyor delays
Weight/grip	Cutter material		Crew size
Structural strength			

TABLE 8 DETERMINATION OF TBM DOWNTIME

Determined by	Category of Downtime
Calculation	TBM regrip/stroke
	Change trains
Geology	Frequency of cutter changes
Experience	Time to change cutter
	Unpredictable (breakdowns) downtimes
Prevention	Backup system design
	Support system capacity double average rate
	Mucking system capacity double average rate
	Contractor's job setup (planned repair and maintenance, review of performance records, etc.)
	TBM construction experience

at a faster penetration rate, more tunnel is excavated per hour and the more often the TBM has to be regripped/restroked; thus the amount of time available for excavation decreases in that hour. Consequently, the less excavation time in an hour, the less often downtime is required to reset the machine.

The new generation of electronic spreadsheets available for microcomputers has made it possible to do these circular iterations easily. Penetration rate can thus be calculated for each geological unit along the tunnel alignment *(3)*.

TBM Utilization

Utilization is calculated by subtracting the total percentage of downtime from unity. Unity is a single shift, day, or excavation shift hour. However, utilization should be calculated on a daily basis if a daily maintenance shift or period is set aside from the excavation shift. Maintenance shifts or periods outside the normal 24-hr day, such as on weekends, are not included in the estimation of utilization.

Experience has shown that utilization can range from a low of 10 percent (TBM excavation in a mine environment with a low priority) to an average of 30 percent. Utilization as high as 75 percent has been achieved on a number of projects with careful backup system design, aggressive project management, positive preparation, and flexibility for the unanticipated.

For bidding purposes, utilization should not be estimated directly from Figure 4. A direct estimation of utilization is unacceptable for bid estimates because many variables, such as the effect of TBM diameter and backup system, cannot be taken into account.

TBM Advance

The advance rate is calculated by using the penetration rate and projecting it for the shift time during which the machine is operating. It is the common unit used for bidding and for determining feet per shift, day, week, or month.

TMB Cutter Wear and Costs

Cutter costs may be determined from the total hardness and the empirical relationships shown in Figure 3. More precise results require the contractor's proprietary experience and empirical relationships between total hardness and cutter rolling path life and complex relationships that include cutter gauge velocity, cutter forces, and cost of cutter parts. Cutter costs can then be calculated for each geological unit along the tunnel alignment *(3)*.

TBM Design Considerations

The design of the TBM is as important as the TBM performance estimate. TBM design must take into account all of the anticipated intact rock properties, rock mass properties, average conditions, and adverse conditions in order to perform as anticipated. TBM design must also be consistent with assumptions made during estimating the variables given in Table 7.

TBM Mechanical Variables

The mechanical variables that have the greatest influence on penetration rate and cutter costs are fixed at the time of manufacture and cannot be varied during the excavation of the tunnel. They are

1. Normal cutter load (F_n),
2. Tangential cutter load (F_t),
3. Cutting coefficient (F_t/F_n),
4. Cutter head rotational rate (rpm), and
5. Cutter spacing.

The penetration of a cutter is proportional to the cutter normal load (F_n). The thrust must be adequate to provide the required normal cutter load (F_n) for each of the cutters and the additional thrust load necessary for pulling the backup equipment.

After the cutter has penetrated the rock as a result of the normal force that has been applied to it, a tangential cutter load (F_t) must be applied for the cutter to continue to pass through the rock with the given depth of penetration. The torque necessary to provide the tangential force can be calculated by taking the sum of the tangential forces and their respective moment arms.

The cutter head rotational rate determines how often the cutters pass over the face in a given unit of time. The rotational rate is limited by the maximum allowable gauge cutter velocity, which results from mechanical considerations associated with available horsepower, and torque.

For all practical purposes, the cutter spacing is generally fixed within relatively narrow limits (2.5 to 4 in.) when the TBM is designed and built. Cutter spacing is determined on the basis of the strength and hardness of the rock. This variable should be determined in association with the TBM manufacturer.

The evaluation and selection of a TBM should be done on the basis of forces available at the cutter-rock interface, mechanical variables, machine structural strength, available optional equipment, cost, design and manufacturing experience, innovative expertise, and field performance of the manufacturer's equipment.

Backup System Variables

The backup system should be designed specifically for anticipated conditions and should include

1. Muck disposal (conveyor, gantry, track, train, and portal-shaft systems);

2. Installation of utilities (water, air, water discharge, ventilation, and track);
3. TBM shield for high stresses and swelling and squeezing ground;
4. Rock support facilities;
5. Protection against water (waterproofing, probing, and grouting);
6. Countermeasures for gassy ground;
7. Countermeasures for high temperatures;
8. Routine maintenance programs; and
9. Crew size.

To sustain average anticipated penetration rates, the capacity of the mucking system must be adequate to keep up with peak penetration rates. Similarly, high advance rates can only be sustained with a crew size adequate to install utilities (water, air, discharge, rail, electric) and support (drills, bolts, ribs, etc.) at peak advance rates.

In blocky, squeezing, swelling, and slaking ground that can cause loosening or inward movement, a slotted roof or full shield may be required for support until temporary support can be installed. Slotted roof shields are adequate for blocky rock; however, a full shield capable of a decrease in diameter is generally necessary in squeezing and swelling ground. Past experience in swelling and squeezing shales, in shears, and in faults has shown that the ability to decrease the diameter by 2.5 percent is inadquate. In one case in which a machine became lodged by squeezing ground, the TBM was redesigned to act as a walking blade shield capable of very-large-diameter changes in excess of 10 percent.

In blocky rock, fallout at the face may cause jamming of rock between the cutters and the face and in the muck openings. Damage to the cutters and buckets is usually controlled with a false face and grillwork on the buckets.

TBM design to protect components against damage by water inflow and adverse effects on excavation performance are given in Table 9. Countermeasures to deal with gassy underground excavation can be summarized as follows:

- Limit ignition sources by using explosion-proof equipment,
- Continuous probing for gas-producing features,
- Degasification by tunnel ventilation or predrainage,
- Provide air turbulence to prevent dangerous concentrations,
- Safety training of all engineers and personnel, and
- Provide monitoring of hazardous gasses at tunnel face with automatic shutoffs.

Countermeasures for excavation under high-temperature conditions include ventilation or the use of water heat exchangers for hydraulic oil and drive motors. In small-diameter tunnels with high TBM power requirements, drive motor cooling may also be used for dust suppression and cooling at the face.

Although routine maintenance is not an absolute requirement, it will minimize the occurrence of unexpected downtime at inopportune times. Routine maintenance is best carried out during the boring cycle and other extended and unavoidable downtimes. For example, during cutter changes that are limited to a few crew members, greasing, lubricating, and filling of hydraulic tanks can also be accomplished.

ANALYSIS OF ENCOUNTERED TBM PERFORMANCE

Analysis of encountered TBM performance is essential to maintaining case history data; TBM experience for evaluating feasibility; and reliable empirical relationships among geological conditions, rock properties, and TBM performance for estimating TBM performance and evaluating differing site condition claims.

TABLE 9 TBM DESIGN FOR ANTICIPATED WATER INFLOW

Objective	Design Component
Protection against water	Forced or pressurized main bearing seal lubrication
	Waterproof motors and electrical system
	Overhead protection from water
Limit effect of water	Ribbed low-angle conveyor at least for the TBM
	Deeply troughed and flashed conveyor
	Buckets designed to rescoop wet sloppy spilled muck
	Narrow bucket openings to prevent muck spillage
Countermeasures	TBM design for drilling probe and grout holes
	TBM design to permit easy access for grouting
	Enough water pump, discharge, and disposal capacity
Construction management	On site, closely monitoring construction
	Planned alternatives
	Maintenance of detailed construction records

Analyses provide a better understanding of TBM excavation and potential for TBM application and performance enhancement. Results of construction performance analyses have been and are used to predict, prevent, and focus on developing problems as well as to solve existing problems.

Analysis of performance concurrent with construction permits monitoring and improvement of TBM performance. Graphic performance data displays permit correlation with geological conditions, and planning of repair and maintenance allows project management to be the cause of efficiency rather than at the mercy of TBM downtime.

Four types of TBM performance analyses are commonly used:

1. Excavation progress and major delays;
2. Performance (penetration, utilization, advance, cutters);
3. Downtime; and
4. Excavation efficiency.

TBM Major Delay Analysis

The TBM major delay analysis is simply a velocity chart; that is, the cumulative length of tunnel (x-axis) excavated is plotted against cumulative shift time (y-axis). Any substantial vertical jog in the line indicates a major delay (generally more than 24 hr).

This type of plot is used to provide a summary of construction progress and identify major delays. It can also be prepared on the same scale as available surface or tunnel geological mapping for correlation with geological conditions. An example of such a plot is shown in Figure 5.

TBM Performance Analysis

Variables used to quantify TBM performance are penetration rate, utilization, advance rate, and cutter costs. Results of analyses consist of as many as 100 variables per day; thus graphic presentation is necessary for comprehension. A plot along tunnel length permits comparison of tunnel geology and performance. TBM performance variables may also be plotted against cumulative shift time to illustrate performance variables as a function of elapsed time as shown in Figure 6.

Penetration will often be related to changes in rock hardness and lithologies, particularly changing lithologies in a sequence of sedimentary rock.

Utilization is indirectly related to encountered geological conditions and directly related to the TBM backup system design for dealing with those conditions. Utilization reflects backup system design and construction management available to deal with encountered adverse conditions.

The cutter replacement plot lags behind cutter wear and cannot be related to concurrent geological conditions. The cutter plot has illustrated cutter damage sustained as a result of improper TBM operation in a small-radius curve. The cutter replacement data have also been instrumental in the identification of unusual cutter wear problems. Cutter rolling path life has also been graphed; however, cutter changes may have an inordinately high effect on

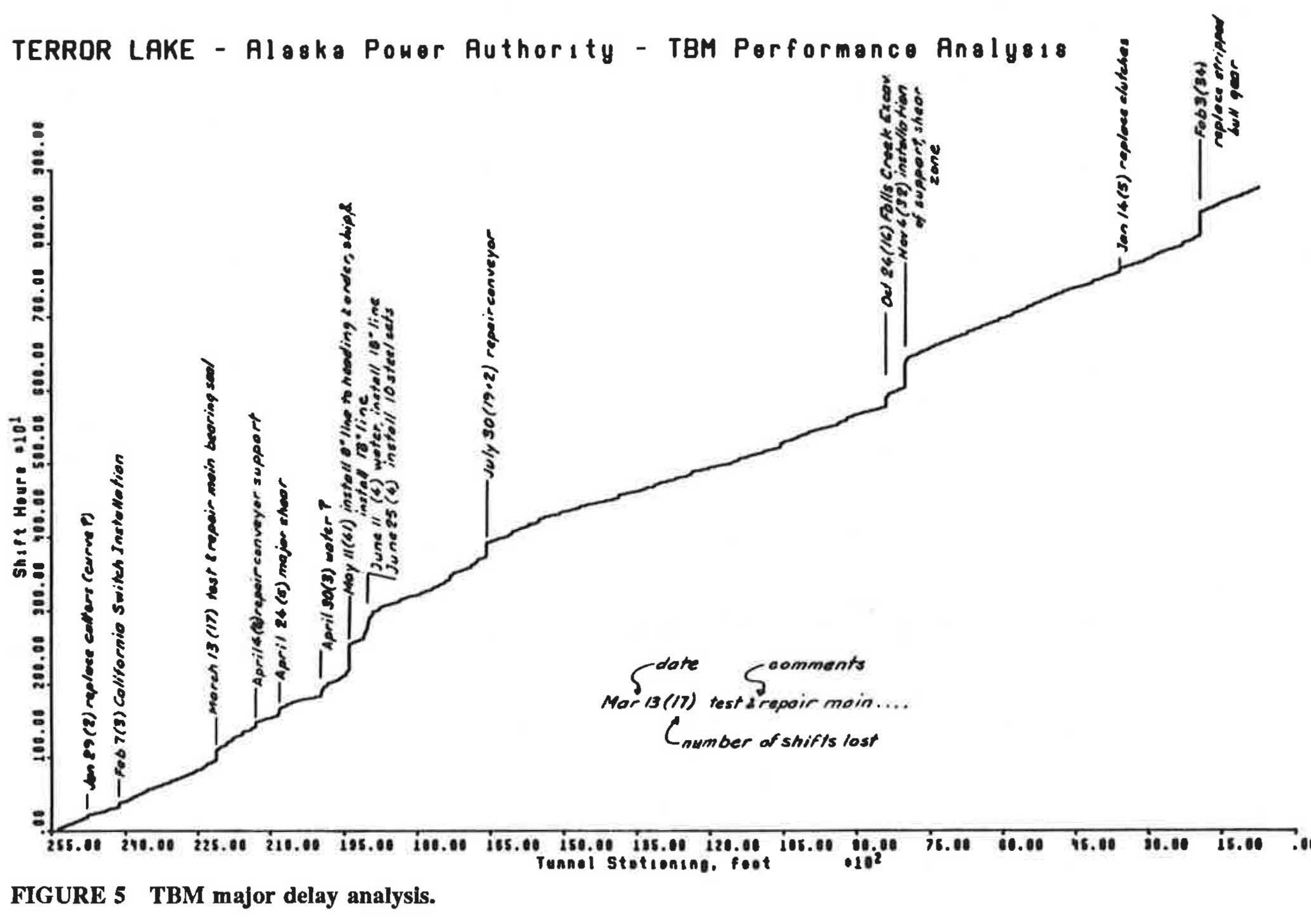

FIGURE 5 TBM major delay analysis.

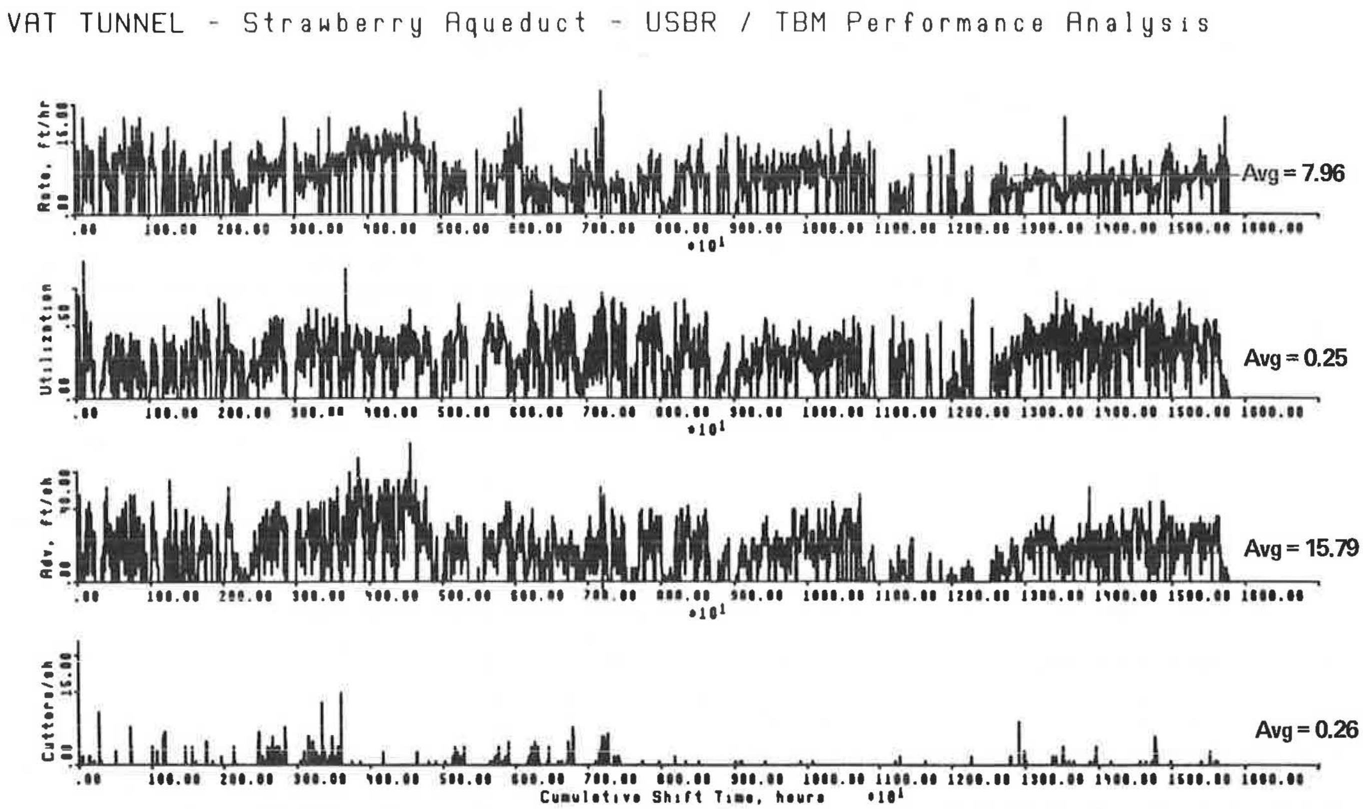

FIGURE 6 TBM performance analysis along tunnel alignment.

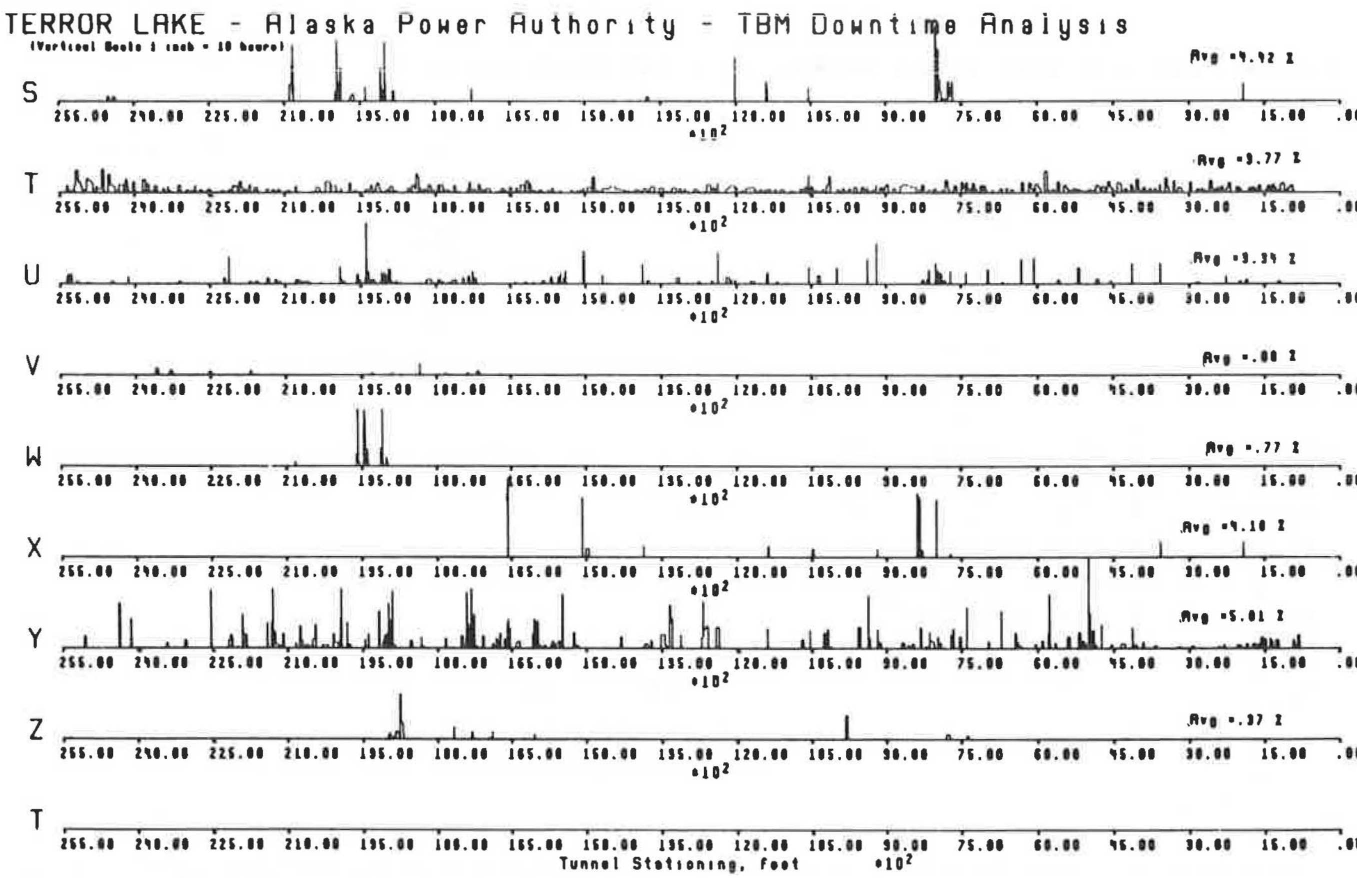

FIGURE 7 TBM downtime analysis along tunnel alignment.

average rolling path life in the early stages of the project and a subdued effect in later stages.

TBM Downtime Analysis

The analysis of downtime is used to define, identify, summarize, and illustrate the effect of specific operations and geological conditions as they relate to TBM downtime.

An example of TBM downtime sustained along a tunnel alignment is shown in Figure 7. It is easy to identify and relate geological conditions that are associated with downtime in this manner. A summary of total project downtime (in as many as 26 categories) is useful as case history data for estimating TBM downtime. It has also been used successfully to resolve differing site condition claims.

One such claim involved an 8-month delay caused by time lost to install additional and unanticipated support. Analysis of all shift records resulted in a summary of all downtime. The actual documented lost time for all support, including anticipated and unanticipated support, amounted to less than ½ month. Needless to say, the differing site condition claim was promptly resolved.

TBM Excavation Efficiency Analysis

TBM performance data in association with crew sizes and manhours worked are useful for evaluating construction efficiency during construction or later for evaluating differing site condition claims. For example, in one case it was alleged that water inflow was the cause of all delays. A plot of lineal feet of tunnel excavated per manshift illustrated that production efficiency was decreasing and continuing on a downward trend long before high water inflows were encountered in the 14th week, as shown in Figure 8.

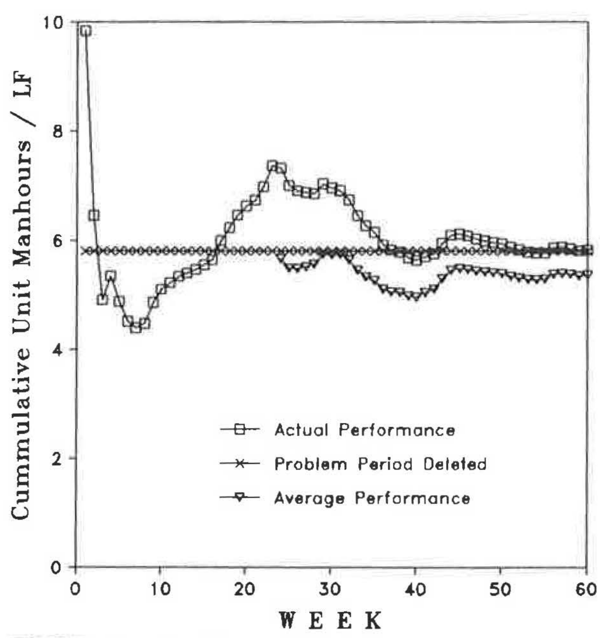

FIGURE 8 Tracking efficiency of tunnel construction.

CONCLUSIONS

Although an increasing number of projects have utilized TBMs, in many instances the design has not provided for mechanical excavation because of a lack of familiarity with TBM excavation and construction economics on the part of the designer. Similarly, many tunnel projects excavated by conventional methods could have been excavated more economically, expeditiously, and with less risk had the designers recognized the potential cost and time saving associated with a well-planned TBM excavation.

The future of TBM excavation lies in a wider application of TBMs in adverse ground conditions, an increase in backup system capacity for substantial increases in performance, ability to bore larger diameters and in harder rock, and lower cutter costs.

It is possible to increase the quantity and quality of bored tunnels by the application of state-of-the-art technology (geotechnical and TBM) at project conception and during initial planning.

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Experimental Study of Buried Fiber-Reinforced Plastic Pipe

NAFTALI GALILI AND ITZHAK SHMULEVICH

An experimental study of interaction between soil and fiberglass-reinforced plastic pipes was performed in a large laboratory soil box. Seven pipe specimens of different diameters and stiffnesses were tested at various loads and under various laying conditions. Sand and clay were the soil backfill. Five different and independent sets of measurements were taken in each test: vertical and horizontal pressures in the backfill soil, normal and tangential stresses at the pipe-soil interface, radii of curvature of the pipe, vertical and horizontal pipe deflections, and hoop strains at the internal and external perimeters of the pipes. Measurements were taken during backfilling and when superimposed pressures were applied. Short-term effects of load, soil type and density, split backfill, and installation quality on pipe performance were considered. The main findings of the study are analyzed and discussed in qualitative terms.

Flexible pipe-soil interaction has been studied extensively during the last decade. However, few experimental studies (*1*, *2*) have been done on the response of fiberglass-reinforced plastic (FRP) pipes to different loads and laying conditions. Several numerical methods, all based on finite element analysis, have been developed to predict the behavior of buried pipes. These theoretical evaluations have to be proved experimentally, especially those of the range of flexible pipes the strains and deflections of which when buried may be considerably affected by uneven soil construction.

The purpose of the present study was to obtain data in well-controlled laboratory conditions as a contribution to the knowledge of the behavior of buried FRP pipes. In particular, it was intended to provide answers to some practical questions, such as the possibility of safely replacing the usually recommended granular backfill, entirely or partly ("split backfill"), by the available in situ cohesive soil and the effects of well-compacted or poorly compacted haunches.

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METHOD

Experimental Setup

Seven pipe specimens, each 2.0 m (78.7 in.) long with outside diameters ranging from 400 to 1028 mm (15.75 to 40.47 in.), wall thicknesses of from 6.0 to 15.7 mm (0.24 to 0.62 in.), and stiffnesses ($STIS = EI/D^3$) of from 1.19 to 10.84 kPa (0.172 to 1.515 lb/in.^{2}) were tested in a large rigid laboratory soil box. A list of the tested pipes is given in Table 1. Two types of soil were used as backfill material: a fine uniform sand (SP) and a terra rossa clay (CH). Soil classifications are given in Table 2; details of the mechanical properties of the soils are given in Table 3.

TABLE 1 MECHANICAL PROPERTIES AND DIMENSIONS OF THE TESTED PIPES

Pipe Code	Outside Diameter, D_0 (mm)	Wall Thickness, t (mm)	Pipe Stiffness, *STIS* (kPa)
A	400	6.0	1.35
B	618	8.0	1.19
C	1,028	13.4	1.24
D	616	15.7	10.84
E	616	8.2	1.27
F	630	13.5	5.28

Note: 1 mm = 0.039 in.; 1 kPa = 0.145 lb/in.^{2}.

Superimposed loads were applied to the surface of the soil backfill through a rubber membrane at the bottom of a semi-cylindrical steel cupola fixed to the top of the box and filled with pressurized air. Measurements were taken close to the midway cross section of the pipes. The measuring instrumentation included