Chapter 39

RECENT DEVELOPMENTS IN SITE INVESTIGATION AND TESTING FOR HARD ROCK TBM PROJECTS

Bjorn Nilsen
Professor of Geological Engineering,
Norwegian University of Science and Technology (NTNU),
Norway

Levent Ozdemir
Professor of Mining/Director of Earth Mechanics Institute,
Colorado School of Mines, USA

ABSTRACT

For several recent TBM tunnel projects, unexpected ground conditions have been encountered, causing extra cost, considerable delay, and in some cases major claims. Undoubtedly, insufficient and/or irrelevant site investigation and testing are among the main causes of such incidents. The purpose of this paper is to review the main investigations and tests relevant for hard rock TBM projects, with particular emphasis on the considerable development that has taken place over the last few years. Also, guidelines for defining optimum scope and extent of site investigations and testing are discussed, as well as the importance of adjusting the investigations and tests according to complexity of the ground conditions and project type.

INTRODUCTION

For TBM-projects, as for rock engineering projects in general, site investigations and testing are crucial to obtain the basis for:

- Overall planning, including siting and design optimization.
- Analyzing stability and rock support requirements.
- Evaluating alternative excavation methods, selecting equipment and predicting performance.
- Assessing environmental impact and the disposal/use of excavated material.
- Estimating costs, schedule and preparing tender documents.

The complexity of rock mass as an engineering material and the limited possibility to actually observe the material, represent great challenges in investigation and testing, interpretation of results and characterization of the site. The geological conditions may vary within wide limits. Each site has its own characteristics, and hence there is no “standard investigation procedure” which will, in all cases, meet the project requirements.

For several recent TBM tunnel projects, unexpected ground conditions have been encountered, causing extra cost, considerable delays and in some cases major claims. Undoubtedly, such incidents in most cases have been due to insufficient or irrelevant investigation of engineering geological and rock mechanical conditions.

With this background, this paper will discuss what types of investigation and testing should be carried out for a planned TBM project, and, depending upon the complexity of the planned project and the ground conditions, what extent of investigation is reasonable.

Over the last 5-10 years, important developments in investigation and testing techniques and procedures have taken place. In this paper, particular emphasis will be placed on these developments, and on factors which are often underestimated, but are of major importance when evaluating performance and cost of TBM projects, including ground water conditions, rock stresses and petrographical factors.

INVESTIGATION STAGES

It is generally recognized that investigations for tunnels and underground openings are best organized for maximum benefit if they are linked with the progress of engineering design and construction, as indicated in **Table 1**.

Generally, the investigations can be divided into two main stages:

- *Pre-construction phase investigations - or: Pre-investigations.*
  Underground excavation has not yet started and information has to be collected on or from the surface.
- *Construction phase investigations - or: Post-investigations.*
  Through tunnels being excavated, the rock masses are accessible for inspection and sampling.

Important information undoubtedly can be obtained at the post-investigation stage, where considerable development has also taken place; for instance, on probing ahead of the face by ground penetrating radar and seismics utilizing the machine vibration as the source signal. It is, however, at the pre-investigation stage that the siting of the project is selected, and thus the ground conditions defined. Since the most serious errors and/or misinterpretations undoubtedly are made at this stage, the pre-investigations will be primary focus of this paper.

MAIN INVESTIGATIONS AND TESTS

For any planned TBM project, a variety of factors concerning ground conditions need to be addressed and investigated. The most important factors are listed in **Table 2** together with the techniques which are most commonly used to investigate the respective factors.

What factors are the most critical for the actual case, and what methods should be applied for investigation and testing, depends greatly on the local conditions. Some general guidelines can, however, be given, and will be briefly reviewed in the following.

Table 1. Site investigations versus the progress of engineering design and construction as recommended by IAEG (1981)

SITE INVESTIGATION STAGE	INVESTIGATION ACTIVITIES	DESIGN AND CONSTRUCTION PROGRESS
PROJECT CONCEPTION	Recognition of need for project ↓	
	INITIAL PROJECT CONCEPTION	
	↓	↓
	basic knowledge of ground conditions	⇒ basic project designs
	↓	↓
	recognition major problems	
	↓	
PRELIMINARY	preliminary field investigations	⇒ confirmation or amendment of design concept
	↓	⇐ preliminary detailed design
	design of main investigation	↓
	↓	
MAIN	main investigation information recovered during investigation	⇒ modifications to ⇐ detailed design
	↓	↓
	report on main investigation	⇒final design of project
CONSTRUCTION	CONSTRUCTION	
	↓	↓
	recording ground conditions as found	⇒ modifications to design
	↓	
	further investigation	⇐ modifications to design
POST CONSTRUCTION	COMPLETION OF CONSTRUCTION	
	↓	↓
	monitoring behavior in operation	⇒ maintenance works

⇒ Exchange of information

Table 2. Overview of the applicability of the main methods for investigating ground conditions

Investigation method/ factor to investigate	Desk study	Field mapping	Core drilling	Geophysics	Expl. adits	Field testing	Lab. testing
Rock types	x	x	x	(x)	x	-	x
Mechanical properties	(x)	(x)	(x)	(x)	x	x	x
Weathering	(x)	(x)	x	x	x	-	-
Soil cover	x	x	x	x	x	-	-
Jointing	(x)	x	(x)	-	x	(x)	(x)
Faults/weakness zones	x	x	x	x	x	-	(x)
Rock stresses	(x)	-	-	-	(x)	x	-
Ground water conditions	(x)	(x)	(x)	x	x	x	-

x the method is well suited
(x) the method is partly/sometimes suited
- the method is not suited

Desk Study

The importance of this initial stage of site investigation should not be underestimated, as a significant amount of valuable information often can be produced even before entering the field. This information makes planning of further investigations much easier, and also may reduce considerably the extent of required field work.

Thus, a few days spent on a desk study is always a good investment. Collection, analysis and evaluation of the following background material are the key issues of the study:

- Topographical maps.
- Geological maps and reports.
- Air and satellite photos.
- Descriptions of any previous projects in the area.

As indicated in Table 2, if good quality background material exists, valuable information can be obtained on practically every aspect of ground conditions. This is particularly true if accurate descriptions are available of the ground conditions encountered in previous projects in the same area, and even more so, if inspection of such projects is possible.

In the more general case of no nearby project, the desk study will still provide crucial information. Most importantly, geological maps and reports give information on rock type distribution, boundaries and structure, while air and satellite photos are very useful on identifying the regional pattern of faults or weakness zones.

The tools available for conducting a desk study have not changed much over the last few years, apart from satellite photos, which have become more regionally available in greatly improved quality. Undoubtedly, various background material has become much more easily accessible through the many data bases on the world wide web. Today, in many countries, databases exist on important issues like:

- Topographical maps.
- Geological maps and reports.
- Air and satellite photos.
- Ground water.
- Rock stresses.
- Seismicity.

Such databases are often organized and maintained by the geological survey of the respective country (in U.S.A, most of the data are accessible through the homepage of the U.S. Geological Survey: www.usgs.gov).

Field Mapping

Field mapping is carried out by using mainly simple tools like a geologist hammer, a compass with clinometer and a notebook, and thus, is relatively inexpensive.

Supplementary mapping of rock types and geological structures is carried out as required by the quality of the background material. In this mapping, it is more important to focus on mechanical character of the rock than sophisticated mineralogical and petrographical features (as included in some project reports). Basic information on rock can be obtained by observing and hitting the rock with the hammer, but for more detailed information, sampling for laboratory testing and analysis has to be carried out.

In the sampling, great care must be exercised so that representative specimens are collected. The fewer specimens that are analyzed, the more important is the representativity of the samples. To avoid the effect of weathering, some blasting may be necessary to retrieve fresh rock samples. If this is required, blasting should be done carefully to avoid blast-induced fractures.

Joint mapping is one of the key issues of field work, since for TBM projects, information on degree of jointing, joint orientation as well as joint continuity are crucial input data for performance prediction. For larger scale discontinuities, such as faults and weakness zones, orientation and width can be studied in more detail at this stage than during the desk study, but, as for detailed jointing, the character is still largely unknown.

The field mapping often provides good information about the degree of weathering and soil/weathering depth, but these features also can represent a considerable problem for the mapping of the other geologic factors discussed here.

Particular emphasis at this stage of investigation should be placed on factors which can dramatically influence the feasibility of a TBM project, including major faults and weakness zones, adverse stress conditions (sometimes being revealed by intense exfoliation jointing) and potential high-permeability rocks (like karstic limestone).

Field mapping, to a great extent, is a matter of experience, and thus the methodology and techniques have not changed much over the last few years. The major development probably has been the introduction of GPS (Global Positioning System) instruments, making positioning much more reliable, and thus enhancing the quality of mapping results in difficult terrain.

Core Drilling

Core drilling is among the routine methods for subsurface exploration. Most commonly, NX-size core drill is used, representing a hole diameter of 76mm (3”) and a core diameter of 54mm (2 1/8”). The drilling often has multiple purposes, of which the following are in most cases the most important:

- Verification of the geological interpretation.
- To obtain more information on rock type boundaries and degree of weathering.
- To supplement information on orientation and character of weakness zones.
- To provide samples for laboratory analyses.
- Hydrogeological and/or geophysical testing.

The drilling often is carried out as illustrated in **Figure 1**, with the prime purpose to investigate major faults or weakness zones assumed to be crucial for the stability and ground water conditions of the opening. The drillhole will also give valuable information about the adjacent rock mass. A parameter closely linked to core drilling is the RQD-value, as shown in this Figure, representing the total length of recovered core pieces greater than or equal to 10 cm (4") divided by the length of the attempted core run, expressed as a percentage.

As the poor quality sections are generally of greatest interest, and a high core recovery thus is an overall goal, contracts on core drilling should be based on time consumption, and not production. Considering the high cost of good quality core recovery, it is well worth spending a little extra to provide for good routine core examination and carefully prepared reports. The core material never should be thrown away until all aspects of the project are completed.

Apart from drillhole testing, the main recent development in this field involves directional drilling, making it possible to core drill practically in any direction, for example, along the alignment of a planned tunnel. A recent directional core drilling completed along the alignment of a Norwegian subsea tunnel is shown in **Figure 2**.

In this case, the hole length was about 225 meters and the deviation from the straight line just over 100 meters. Technically, the method is capable of producing longer and more deviated holes. The limitation is, however, mainly related to cost, since deviated holes cost several times more than conventional. Also, the core recovery may some times present problems, since smaller core diameter is obtained where the hole deviation occurs.

Geophysics

The geophysical methods most commonly used in site investigations for underground excavations are shown in **Table 3**.

As indicated in the table, the refraction seismic method is most commonly used. In most cases, it is used for logging the thickness of soil cover or weathering and for evaluating rock mass quality based on seismic velocities, as illustrated in Figure 1.

Continuous progress has been made in geophysical data processing and interpretation, making the results more accurate and reliable. However, seismic refraction or other routine geophysical methods do not automatically give high quality results in all geological environments. Particularly, there are limitations across deep clefts due to side reflection. When a high degree of accuracy is

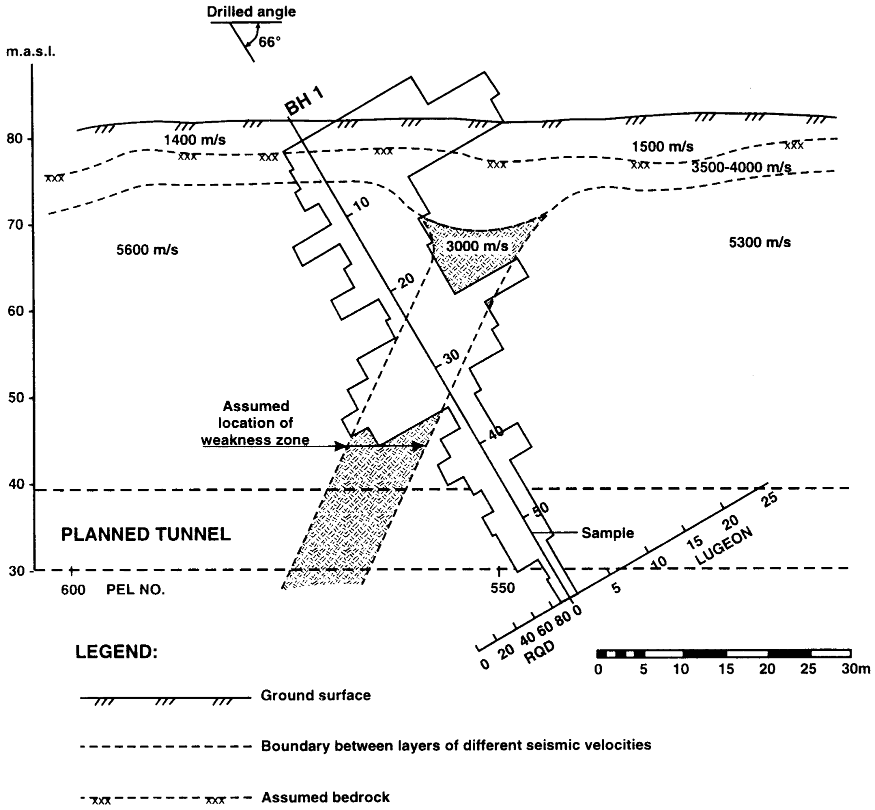

Figure 1. Results of core drilling, drillhole testing and refraction seismic investigation. RQD and Lugeon values along the hole are given.

needed in such topography, control boring should be carried out. Generally, the highest value of geophysical pre-construction investigation undoubtedly is obtained when combined with results of other investigations, as in the example shown in Figure 1.

Concerning ground quality characterization, the most important recent development probably has been in the field of seismic tomography. Since its introduction for this purpose about 15 years ago, the method has been continuously improved regarding signal source and receiver, as well as interpretation, and today can provide invaluable information on subsurface ground conditions, as illustrated by the example shown in Figure 3.

Most commonly, the tomographic method is applied between drill holes (often from core drilling) as shown in the Figure (referred to as crosshole tomography). Alternatively, it may be applied between underground openings, or between one underground opening and the surface (in subsea tunnels it is sometimes applied between a drillhole ahead of the face and the sea bottom).

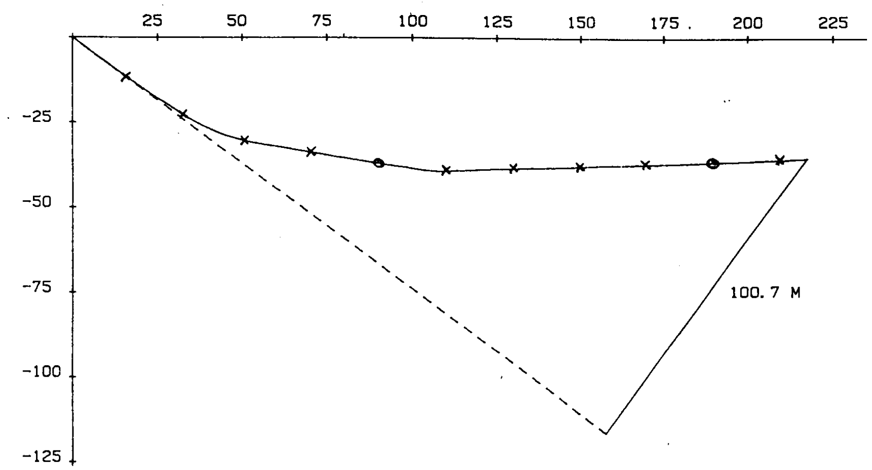

Figure 2. Directional core drilling for the Nappstraumen subsea road tunnel (figures in meters)

Table 3. Summary of relevant geophysical methods

METHOD	MAIN INFORMATION	MAIN LIMITATIONS	APPLICATION
Seismic refraction	Thickness of soil layers. Location of ground water table. Location of rock surface. Quality of rock mass.	“Blind zones” (if non-increasing velocity with depth). Side reflection.	Extensive
Seismic reflection	Locations of different layers (soil, rock, sea bottom, etc.). Soil/rock structure.	“Blind zones”. Side reflection. Interpretation for great depths.	Limited (mainly subsea tunnels)
Crosshole tomography	Rock mass quality. Karst caverns etc.	Interpretation.	Increasing
Geoelectric (resistivity)	Location of ground water table/rock surface. Character of weakness zones.	Interpretation. Stray current/buried metal.	General
Electromagnetic (radar)	Location of ground water table/soil structure. Openings.	Restricted to soft ground.	Limited
Magnetic	Structural geology.	Interpretation.	Minimal
Gravitational	Structural geology.	Interpretation.	Minimal

A method in which significant developments have taken place, but more research and improvement still need to be made, involves the geoelectric resistivity method, which undoubtedly carries a great potential for identifying water bearing zones.

Exploratory Adits

Due to the uncertainty of projecting geological information obtained from surface mapping towards the depth, excavation of adits or shafts may be required as part of the site investigation program. This is most relevant in very complex

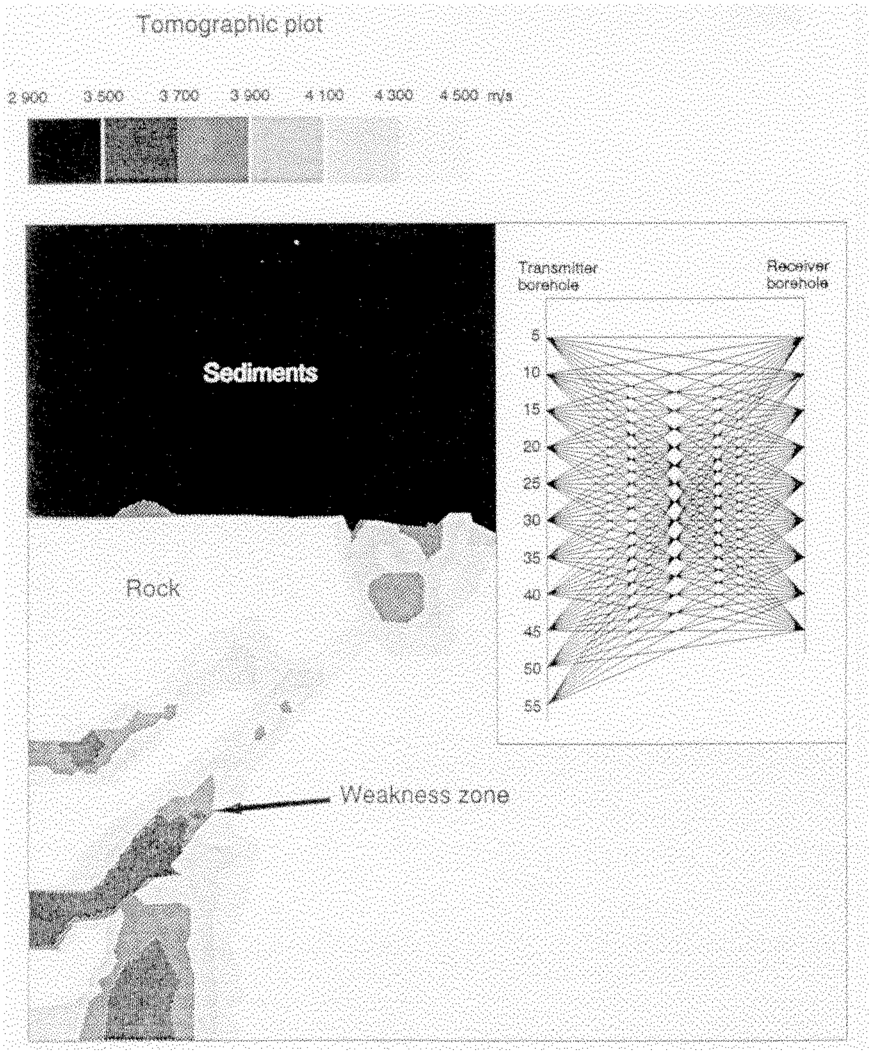

Figure 3. The principle of seismic holography and resulting tomographic plot (from By, 1987)

geology and/or when very detailed information of the rock mass conditions are required. Sometimes, the main purpose may also be in-situ measurement (for instance of rock stresses) or testing (e.g. the shear strength of discontinuities).

Field Testing

Field testing may cover many different aspects, depending upon ground conditions and the type of project. For TBM projects, it is mainly the following two factors, which may both greatly influence the project feasibility, that are investigated:

1) In-situ rock stresses.

2) Ground water conditions.

Rock Stresses. Measurement generally is carried out according to one of the following three main principles:

- The overcoring technique.
- Flatjack testing.
- Hydraulic fracturing.

The first two are normally carried out in underground openings (although triaxial overcoring in a few cases have been carried out from the surface in 10-20 m deep drillholes), and thus at the pre-construction investigation stage, are restricted mainly to exploratory adits.

As a result of the considerable development of methodology during the last decade, the hydraulic fracturing technique is, however, being applied today in drillholes to depths of 100-200 meters and more. The basic principle of the method is shown in **Figure 4**.

By recording characteristic water pressures during testing as illustrated in **Figure 5** and identifying the direction of the induced fracture, and thus the direction of minor principal stress, by using an impression packer as illustrated in Figure 4b, the magnitudes and directions of the principal stresses can be calculated according to principles described by the International Society for Rock Mechanics (ISRM).

Ground Water. For investigating ground water conditions, pumping tests are most commonly used. Although pumping gives an indication of the overall permeability and the risk of excessive water inflow into a proposed tunnel, injecting water instead of pumping provides more information on the relation between geology and permeability.

The water injection test, or the Lugeon test, as it is commonly referred to, definitely is not new, but a more reliable and improved basis for using the test for predicting water inflow in a planned tunnel has been established over the last decade. The test involves injection of water at a pressure of 1 MPa between two packers 3 meters apart in a borehole, and recording the flow-rate when constant flow is achieved. The unit 1 Lugeon (1 L) corresponds to a water loss of 1 l/min per meter of drill hole.

The results of Lugeon testing, as shown for the example in Figure 1, may represent a good basis for predicting water inflow in a planned tunnel. Since the results are markedly influenced by local features of single joints, they may, however, in some cases also be misleading.

Laboratory Testing

In all site characterization programs, and for TBM performance prediction efforts in particular, careful sampling becomes a key factor. If the test samples are not representative of the actual field conditions, the predicted performance, of course, will not be very reliable.

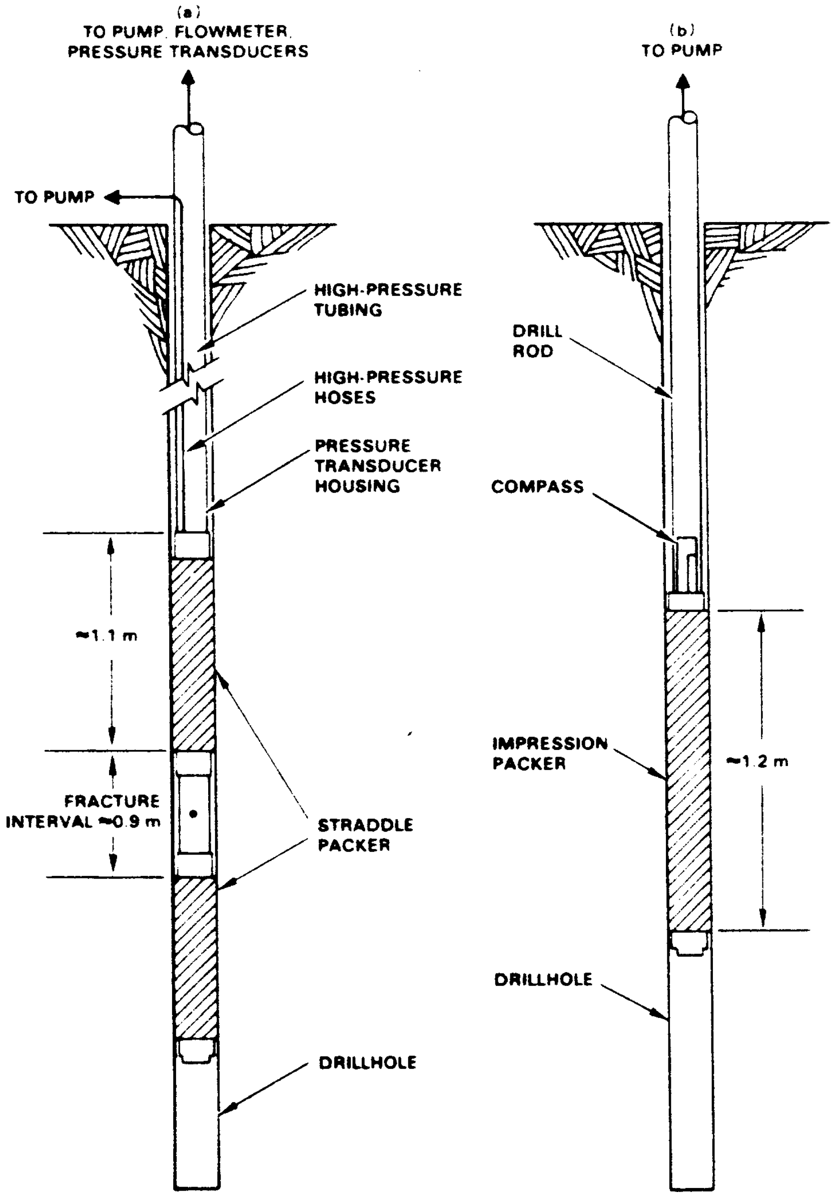

Figure 4. Schematic representation of a) hydrofracturing tool and b) impression packer (from ISRM, 1987)

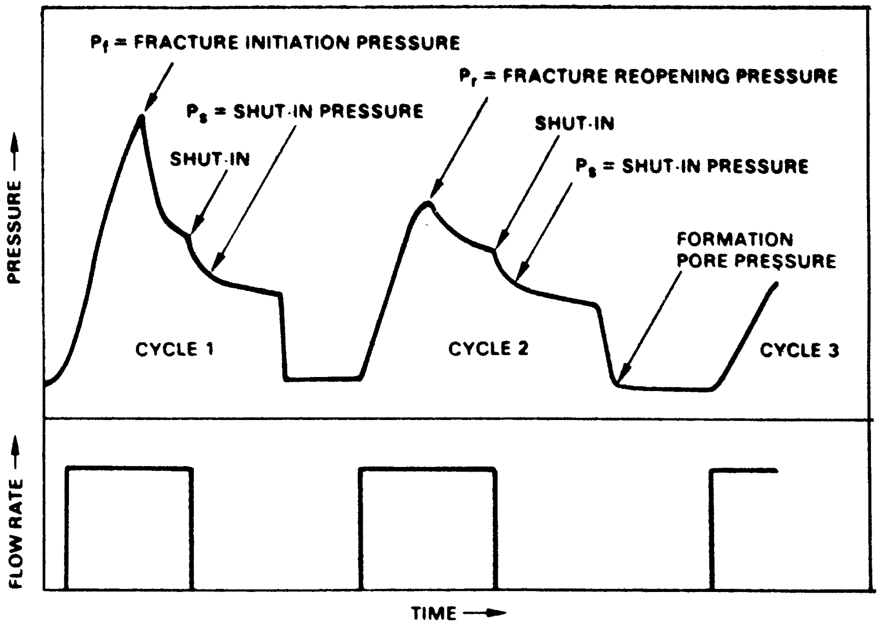

Figure 5. Idealized hydraulic fracturing record (from ISRM, 1987)

The principal tests used for TBM projects include:

- Mechanical strength tests (UCS, brittleness-value, triaxial, Brazilian and point load strength tests).
- Surface hardness tests (Vickers hardness).
- Abrasiveness tests (Cerchar and AV-tests).
- Indention (punch-penetration) tests.
- Rock cutting tests (linear and rotary).
- Miniature drill tests (Siever´s J-value).
- Fracture toughness.
- Petrographic analysis (thin section and XRD analysis).

The various tests are standardized according to the performance prediction models developed at the different organizations and institutions around the world. The most extensive and widely used performance prediction models, those developed at the Colorado School of Mines (CSM) and the Norwegian University of Science and Technology (NTNU, formerly NTH) are described in the proceedings of the 1993 RETC conference (Nilsen and Ozdemir, 1993).

Most notable recent developments in this field include the introduction of new methods and modification of existing methodology, as well as, in some cases, improved understanding of what should be emphasized in a site investigation program.

New Methods. The increased use of the punch penetration and fracture toughness tests represent the most important development. In the punch penetration test, a standard indentor is pressed into a rock sample that has been cast in a confining ring (**Figure 6**). The load and displacement of the indentor are recorded with a computer system. The particular shape and slope of the force-penetration curve provides a good basis for estimating the excavatability of the rock, i.e. the energy needed for efficient chipping. This is affected by the stiffness, brittleness and porosity of the sample. In addition, visual observations are made on how the rock fails under the indentor. All these informations combined can be used to assess rock toughness.

The fracture toughness test defines the fracturing strength of the rock sample. It uses a specimen with a notch cut perpendicular to the core axis, see **Figure 7**. The specimen rests on two support rollers, and a compressive load is applied to press apart the two notch sides, causing transverse splitting by crack growth in the un-notched part. This test can be useful for classifying intact rock with respect to its resistance to crack propagation, but further research and development is still required for this to become a routine and reliable test for TBM performance evaluation.

Modification of Methodology. A relevant example here is the modification of the NTNU-method to cover smaller size sample material. The reason for modification is that sometimes, when the bedrock is highly weathered or has a thick soil cover, sampling of material sufficient for the standard boreability testing (about 15 kg) is a problem. Modification of the standard tests for testing drill core material and drill chips therefore has been attempted (Bruland et al., 1997).

Promising correlations between modified and standard boreability test results have been established. Further development is, however, required before the reliability of the miniature drill testing can be confirmed and the method used on a routine basis.

Improved Understanding. Based on the experience from many recent TBM-projects, there are particularly two issues that should be mentioned here:

1) Rock anisotropy, such as foliation and/or bedding, can have a significant effect on TBM performance. The Brazilian tensile strength test can provide a reliable indication of the degree and extent of rock anisotropy. This information together with punch penetration and/or fracture toughness tests can be used to develop an assessment of anisotropy influence on TBM performance. It is of critical importance, however, that such tests be carried out in the same orientation as will be encountered by the machine during tunnel drivage.

2) The importance of emphasizing the most relevant factors in petrographic (thin section) analysis. For TBM performance evaluation, emphasis should

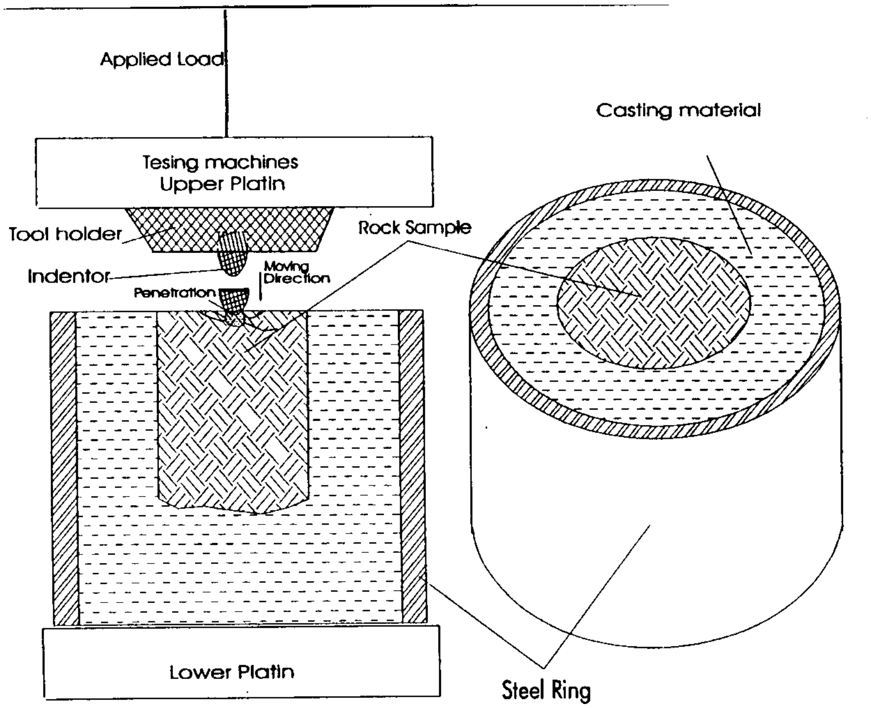

Figure 6. Schematic drawing of punch penetration test

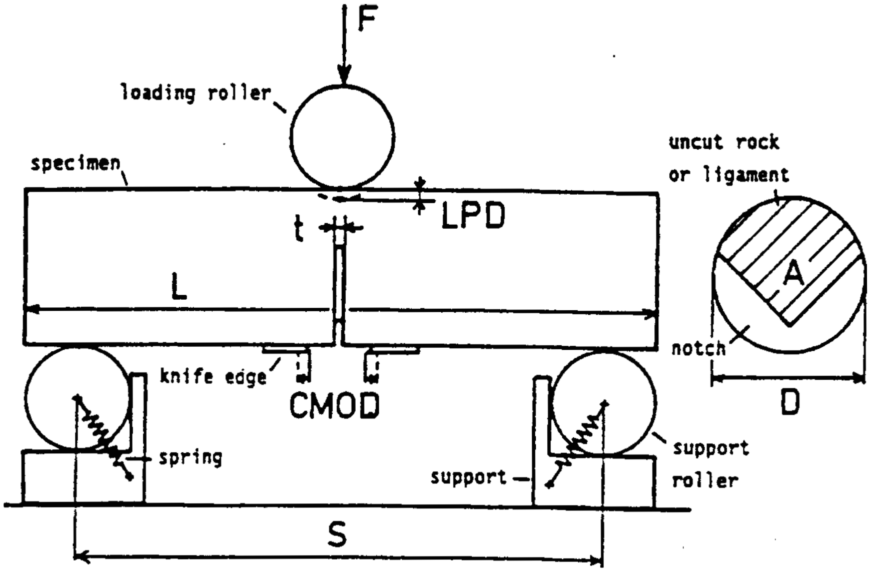

Figure 7. The principle of fracture toughness testing (ISRM, 1995)

not be placed on the traditional mineralogical and petrographic study only, or on discussing the rock name or origin, as commonly found in most geotechnical reports, but rather on factors of key importance for evaluation of TBM performance and cutter wear, such as:

- Grain suturing/interlocking.
- Microfractures.
- Orientation, directional properties.
- Grain size/shape/elongation.
- Content of particular hard minerals (such as quartz, garnet and epidote).
- Any other unusual microscopic features.

EXTENT OF INVESTIGATIONS

The scope of efforts put on site investigation and testing varies from country to country, reflecting the geological complexity of the actual region, but to some extent, traditions also. Thus, the U.S. National Committee on Tunneling Technology (USNC/TT, 1984) recommends site exploration budgets averaging 3.0 % of the estimated project cost, while in hard rock countries like Norway, site investigation costs typically have been on the order of 0.5-1 % of the total construction cost (higher for recent, urban projects).

The recent international trend has been towards tailoring the scope and extent of investigations to the complexity of the ground conditions and the nature of the project. This is reflected in the Norwegian Standard NS 3480 “Geotechnical planning” (NBR, 1988) and the European Prestandard “Eurocode 7” (CEN, 1994). The basic principle here is that the project owner and the designer jointly, based on evaluation of potential problems and the degree of difficulty, define the geotechnical category or class of the project, as shown in **Table 4**.

Potential damage consequences to be evaluated relate to life as well as property, including long term economical consequences. Degree of difficulty is to reflect uncertainty in planning and construction, and depends mainly on:

- The in-situ ground conditions.
- To what extent the ground conditions will influence the planned project.
- Whether reliable methods exist for defining the ground conditions and the input parameters for analyses.
- Whether reliable methods exist for design of the project.
- Whether experience exists from similar projects.

Table 4. Definition of geotechnical project class according to the Norwegian Standard NS 3480 (from NBR, 1988)

DAMAGE CONSEQUENCE CLASS	DEGREE OF DIFFICULTY		
	Low	Medium	High
Less serious	1	1	2
Serious	1	2	2
Very serious	2	2	3

Water tunnels in rural areas might be mentioned as an example of a project type usually belonging to geotechnical project class 1, while for instance subsea traffic tunnels, fall under Class 3.

The geotechnical category/project class, as described in more detail in CEN (1994)/NBR (1988), recommends the efforts to emphasize:

- Collection of information on ground conditions.
- Analyses and planning.
- Design supervision and control.
- Construction supervision and control.

CONCLUDING REMARKS

Undoubtedly, a variety of appropriate current methods exist for characterization of ground conditions, and a considerable amount of improvements have taken place over the last few years, making the results of site investigation and testing more reliable. Provided that relevant tools are selected and properly applied depending on geologic complexity and project requirements, a successful site investigation program can be carried out to reduce project risks and uncertainty.

However, some factors whether not properly investigated or often underestimated still cause the basis for claims in TBM projects, as follows:

- Ground water, which in cases of excessive inflow, can cause great problems and considerable extra cost.
- Rock stresses, which in worst case may cause the TBM to get stuck, particularly in squeezing ground.
- Adverse ground conditions, such as running or swelling ground.
- Geologic features, such as joints, fractures, bedding/foliation which can have a significant impact on TBM performance.
- Microscopic features of the rock such as grain suturing/interlocking which can increase the difficulty of excavation.

Based on experience, particular attention for future projects should be paid on these factors, although the others are also important, and definitely should not be omitted.

The accuracy of interpretation and description of rock and geologic conditions often will improve considerably if several investigation methods are combined in a joint effort. Always, the basic principle should be to tailor the investigation methods and the analyses to closely match the character and complexity of the geological conditions, as well as the project scope and specific requirements.

REFERENCES

Bruland, A., T.S. Dahlö, and B. Nilsen. 1997. Development of new miniature drillability tests for performance prediction. Proc. 4th Int. Symp. on Mine Mechanization and Automation, Brisbane, 2:A5.59-66.

By, T.L. 1987. Crosshole seismics including geotomography for investigation of foundations. Proc. 2nd Int. Symp. on Field Measurements in Geomechanics, Kobe, 1:335-346.

CEN. 1994. *Eurocode 7. Geotechnical design* - Part 1:General rules. European Prestandard ENV 1997-1, Comite Europeen de Normalisation.

IAEG. 1981.Commission on site investigation. *Bull. Int. Assoc. Eng. Geol.*, 24: 185-226.

ISRM. 1987. Suggested methods for rock stress determination. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* 24:53-73.

ISRM. 1995. Suggested method for determining mode I fracture toughness using cracked chevron notched Brazilian disc specimen (CCNBD). *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* 32:59-64.

NBR. 1988. *Norwegian Standard NS 3480*: Geotechnical planning. (In Norwegian). Norwegian Council for building Standardization, Oslo, Norway.

Nilsen, B. and Ozdemir, L. 1993. Hard rock tunnel boring prediction and field performance. Proc. 1993 RETC meeting, Boston, Ch.52:833-52.

USNC/TT 1984. Geotechnical site investigations for underground projects. U.S. Nat. Comm. on Tunneling Technology, National Research Council, Washington D.C.