Table 4-1. Tunnelman's Ground Classification for Soils (after Heuer 1974)

Classification		Behavior	Typical Soil Types
Firm		Heading can be advanced without initial support and final lining can be constructed before ground starts to move.	Loess above water table; hard clay, marl, cemented sand, and gravel when not highly overstressed.
Raveling	Slow Raveling	Chunks or flakes of material begin to drop out of the arch or walls sometime after the ground has been exposed. This is due to loosening or to overstress and *brittle* fracture (ground separates or breaks along distinct surfaces, as opposed to squeezing ground).	Residual soils or sand with small amounts of binder may be fast raveling below the water table; slow raveling above. Stiff fissured clays may be slow or fast raveling, depending upon degree of overstress.
	Fast Raveling	In fast raveling ground, the process starts within a few minutes, otherwise the ground is slow raveling.	
Squeezing		Ground squeezes or extrudes plastically into tunnel, without visible fracturing or loss of continuity, and without perceptible increase in water content. Ductile, plastic yield and flow due to overstress.	Ground with low frictional strength. Rate of squeeze depends on degree of overstress. Occurs at shallow to medium depth in clay of very soft to medium consistency. Stiff to hard clay under high cover may move in combination with raveling at excavation surface and squeezing at depth behind surface.

(Continued)

Table 4-1. Tunnelman's Ground Classification for Soils (after Heuer 1974) *(Continued)*

Classification		Behavior	Typical Soil Types
Running	Cohesive Running Running	Granular materials without cohesion are unstable at a slope greater than their angle of repose (±30 to 35°). When exposed at steeper slopes, they run like granulated sugar or dune sand until the slope flattens to the angle of repose.	Clean, dry granular materials. Apparent cohesion in moist sand or weak cementation in any granular soil may allow the material to stand for a brief period of raveling before it breaks down and runs. Such behavior is cohesive running.
Flowing		A mixture of soil and water flows into the tunnel like a viscous fluid. The material can enter the tunnel from the invert as well as from the face, crown, and walls, and can flow for great distances, completely filling the tunnel in some cases.	Below the water table in silt, sand, or gravel without enough clay content to give significant cohesion and plasticity. May also occur in highly sensitive clay when such material is disturbed.
Swelling		Ground absorbs water, increases in volume, and expands slowly into the tunnel.	Highly preconsolidated clay with a plasticity index in excess of about 30, generally containing significant percentages of montmorillonite clay.

The boundary between soil and bedrock UCS is commonly described as 140 psi (20,000 psf) (Kulhawy et al., 1991) and obviously should be considered nondisplaceable ground. Based on appropriate descriptive criteria [i.e., ASTM, International Society for Rock Mechanics (ISRM)], the field subsurface and surface site investigation strategy for projects in which bedrock is anticipated should focus on determining

- Depth and extent of bedrock;
- Rock type (e.g., lithology, classification);
- Mineralogy;
- Core recovery;
- Rock quality designation (RQD);
- Weathering/alteration index;
- Fracturing frequency;
- Discontinuity set frequency/spacing;
- Discontinuity surface characteristics (e.g., aperture, infill material, roughness, shape, joint roughness coefficient);
- Presence of fracture-controlled groundwater;
- Discontinuity orientation (e.g., dip and dip direction);
- Hardness; and
- Field-estimated UCS (e.g., point load testing, Schmidt rebound).

Conventional rock coring potentially accompanied by downhole acoustic/optical televiewer logging can be a cost-effective way to arrive at the field data outlined above, and also allows the user to collect data on discontinuity orientation.

After the field investigation phase, laboratory testing should be completed on select samples obtained in the field, to arrive at reasonable estimates of

- Hardness (e.g., Shore);
- UCS;
- Modulus of elasticity;
- Poisson's ratio;
- Tensile strength (e.g., Brazilian splitting);
- Punch penetration;
- Intact rock or joint direct shear strength;
- Mineralogy (e.g., thin sections);
- Rock mass rating system (e.g., RMR, Q, GSI);
- Abrasiveness (e.g., Cerchar, Taber, SAT);
- Cutability;
- Boreability; and
- For claystone and shale, slake durability, jar slake, and swelling tendencies.

Drilling and sampling procedures that both maximize core recovery and minimize core damage are essential to the development of a reliable rock mass characterization program. Triple-tube (e.g., HQ, NQ) coring generally provides the least sample disturbance.

When collecting rock cores, it is wise to take photographs with a scale and color guide immediately upon opening the sample. Once the sample is opened or moved it will begin to change from its in situ condition because of exposure to the atmosphere and vibration. It is also vital that photographs of each completed core box be obtained. The photos must show core intervals clearly.

Point load tests and Schmidt hammer tests can be used to supplement laboratory-determined UCS data and to rapidly obtain preliminary strength data in the field.

Weathering index, fracture frequency, joint characteristics, and overall rock mass quality are also important for estimating boreability. Estimation of block sizes can be an important factor for evaluating the potential for blocks to become wedged in the reaming head or to become separated or dislodged above the pipe and cause gouging of the pipe or couplings.

RQD is widely used as an indicator of overall rock quality. Rock quality determinations can be refined, if necessary, using various empirical rock mass classification schemes as proposed above (e.g., RMR and Q), which were developed for construction of larger tunnels (Bieniawski 1974; Barton et al. 1974).

Boreability is the ability of the rock in front of the pilot tube and cutter head to be ripped, chipped, and broken into smaller pieces to allow the advance of the pipe string. This parameter is controlled by the frequency of discontinuities of the rock; best determined based on RQD (ASTM D6032), and the following four tests performed on intact samples of rock: UCS (ASTM D7012), tensile strength (ASTM D3967), hardness (ASTM D5873), and abrasiveness. The four properties of the intact rock are determined by conducting a series of laboratory tests. The boreability of the rock also affects the tooling efficiency and the tooling survivability. Some rock may be too strong, unfractured, and abrasive to be cutable by typical tooling. Drive lengths may require modification. In some cases, other construction methods should be considered.

4.2.2.3 Mixed-Face Conditions. Mixed-face conditions are defined by distinct variations in ground conditions within the cross-sectional area of the bore, such as rock overlain by or interbedded with soft ground or very soft soil overlain by, underlain by, or interbedded with a very stiff, high-strength soil. Mixed-face conditions present significant challenges to alignment, grade control, and stability of the face, over-excavation, and stoppage of the machine advance. Mixed-face conditions should be identified during the design phase to the extent possible and should be avoided if possible.

When advancing from a full face of soft ground into a zone with a mixed face of hard and soft ground, better line-and-grade control can in some cases be achieved by advancing the pilot tube from hard ground into the softer ground.

4.2.2.4 Gravels, Cobbles, and Boulders. The extent, frequency, size distribution, maximum clast size, and physical properties of gravels, cobbles, and boulders should be determined. The pilot tube and other guided boring drives should be located to minimize the amount of gravels to be encountered, if possible. If these conditions cannot be avoided, other trenchless methods should be considered. The presence of cobbles and boulders can present a significant challenge to pilot tube and other guided boring methods and may result in a failure to complete the bore.

If rock pieces are encountered within the sampler during the geotechnical investigations, steps should be taken to determine if the rock pieces are naturally occurring gravel or were generated by the sampler encountering and fracturing cobbles and/or boulders. Where there is a potential for gravels, cobbles, and boulders, large-diameter boreholes, rotosonic borings, test pits, or trenches can be useful in obtaining representative samples for grain size analysis and determining the size and distribution of the gravels, cobbles, and boulders. Samples of the cobbles and boulders as well as the matrix material should also be obtained and tested.

One way to document the frequency of the cobbles or boulders is to determine the cobble volume ratio (CVR) and the boulder volume ratio (BVR). The CVR and BVR are the volume of cobbles or boulders to the excavation volume reported in terms of percentage. (See Hunt et al., 2013.)

4.2.2.5 Groundwater. The groundwater level in unconfined aquifers and piezometric levels in confined aquifers should be determined by installing observation wells and/or piezometers adjacent to shaft locations. Consider adding piezometers at intermediate points for longer drives. In addition, the hydraulic conductivity of water-bearing strata should also be determined.

Groundwater conditions will have a significant influence on ground behavior (see Table 4-1), the viability of the pilot tube method, and on jacking and receiving shaft design and construction. Hydraulic conductivity of water-bearing strata can be estimated using grain size correlations and preferably by borehole permeability tests. For larger projects, in which highly permeable soils are anticipated with significant groundwater control issues during construction, pumping tests may be warranted.

Dewatering in the immediate vicinity of active pilot tube and other guided boring operations can be an effective way to improve the ground and facilitate construction. It should be noted, however, that dewatering may also have unintended consequences such as increased friction on the pipe, resulting in higher jacking forces because of increases in effective stress and loss of lubrication.

4.2.2.6 Potential Obstructions. The likelihood of buried objects, their nature, and relative sizes should be established by the desktop study and site investigation. The use of pilot tube and the ability to withdraw the pilot and attempt a revised alignment is one of the many benefits of the pilot tube method. However, to avoid multiple attempts, the potential for buried objects and an understanding of their nature should be determined early in the planning phase to minimize the risk of encountering an obstruction.

4.2.2.7 Contaminated or Hazardous Ground or Groundwater. Encountering ground and/or groundwater contamination has health and safety, cost, and schedule impacts on projects. Hazardous conditions can include naturally occurring hydrocarbons and asbestos, but careful planning and execution may minimize these impacts. Determination of the potential for encountering contaminants and hazardous substances should be completed during the planning phase. If contaminants are found, then determination of the nature and extent of contaminants, if present, must be undertaken during the site investigation. Even if contaminants are not identified during the planning phase, the site investigations should screen for contaminants. One useful approach is to sample the headspace above the samples with a photo-ionizing detector during sampling and to record the readings. Consult an environmental professional for additional information regarding detecting the potential presence of containments in the ground.

4.2.3 Geotechnical Reports

All subsurface data collected during the geotechnical desktop study and site investigations, professional interpretations thereof, and design and construction considerations should be summarized in project reports. The geotechnical data report (GDR) contains all the factual geotechnical information for the project, including explorations, laboratory and field testing results, and geophysics and historical geotechnical data. The GDR typically does not include interpretation or recommendations, and should be included in the contract documents.

Geotechnical design memoranda and/or a geotechnical interpretive report (GIR) should be prepared to present summaries of the geotechnical data, interpretation of the data, earth pressures to be used for design, discussions of the expected behavior of the ground, and other geotechnical design recommendations such as appropriate tunneling and shaft types and systems. Because the GIR and design memoranda are typically prepared prior to design, there is much said in these memoranda and reports with respect to the project that may not be applicable at the time of bid. These design memoranda and GIR should be disclosed to the bidders but are typically not provided to the bidders, nor should they be in the contract documents.

Increasingly, another standalone report is prepared, known as a geotechnical baseline report (GBR). The GBR is typically prepared as the design is being completed with the owner's input and serves as the definitive geotechnical baseline for use in the resolution of disagreements, disputes, or claims relating to differing subsurface conditions. The GBR presents contractual interpretations of the data to be used for bidding and construction, as well as baseline expected behavior of the ground, and other geotechnical construction considerations, such as appropriate tunneling and shaft types and systems. See ASCE's *Geotechnical Baseline Reports for Construction: Suggested Guidelines* (ASCE 2007). The GBR should be included in the contract documents and should be prepared by a qualified geotechnical engineer experienced in underground construction.

4.2.4 Applicability of Methods Based on Subsurface Conditions and Classification

As discussed previously, the geotechnical conditions can often be grouped into displaceable and nondisplaceable categories. Rock most often classifies as nondisplaceable for obvious reasons. The information in Table 4-2 can be used to identify whether a displaceable or nondisplaceable method is more appropriate for the identified geotechnical conditions, and whether pilot tube in general is a feasible method for the project.

Because pilot tube and other guided boring methods are not considered to be a closed-face trenchless method, they are not considered applicable for use in ground conditions that classify as flowing (per terminology used in Table 4-1). Ground improvement, such as dewatering, can be implemented to modify the ground classification. Similarly, squeezing ground can result in high jacking forces, which may exceed the capacity of the chosen equipment. Identification and mitigation of the risks associated with these ground types can be key to successful completion of a drive.

4.3 UTILITY SURVEYS

It is important that the locations of existing utilities be reliably established as early as possible during planning to determine the feasibility of implementing pilot tube and other guided boring methods. Existing utilities should be dealt with in an iterative manner in which each level of survey builds on the prior study and identifies data gaps to be filled in a subsequent study.

Table 4-2. Applicability of Pilot Tube and Other Guided Boring Methods for Identified Geotechnical Conditions

SPT N-value	Geotechnical condition	Applicability (by method) Displacement	Applicability (by method) Nondisplacement
0–1[a]	Very soft clays, silt, and organic deposits	Marginal[b]	Marginal[b]
2–4	Soft clays, silt, and organic deposits or very loose sands	Yes	Yes
5–10	Medium stiff clays and silts or loose sands	Yes	Yes
11–30	Stiff to very stiff clays and silts or medium dense sands	Yes	Yes
11–30	Soil with gravels (1 to 3 in.)	Yes[c]	Yes[c]
11–30	Soils with occasional cobbles (3 to 12 in.), boulders (>12 in.)	Marginal[d]	Marginal[d]
11–30	Soils with significant cobbles, boulders, and obstructions larger than 4 in.	No	No
31–50	Hard clays or dense sands	Marginal[e]	Possible[f]
>50	Very dense sands or weak weathered rock	No	Possible[f]
>50	Weathered rocks, marls, chalks, and firmly cemented soils	No	Possible[f]
>50	Significantly weathered to unweathered rocks	No	Possible[f]

Note: Generally, larger equipment and tooling (i.e., larger-diameter augers) have a better success rate in more complicated geotechnical conditions.

[a] Also referred to as *weight of hammer material*.

[b] The ground conditions are too weak to maintain line and grade.

[c] As the gravel content increases, the success rate decreases.

[d] Total chance as to whether the drive is completed depends on hitting the buried object.

[e] Pilot tube may be able to penetrate a portion of the ground with this N-value but not for an extended distance.

[f] With the proper rock tooling on the pilot tube and reamer/cutter head.

All utility information (aerial and subsurface) should be collected in connection with the project alignment(s) and presented in accordance with ASCE/CI 38, *Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data* (2002). It is recommended to obtain Quality Level B and Quality Level A utility data, especially if the utility expectancy is complex and/or risky. Note that using a *design ticket* from a state's on-call service can only result in Quality Level C or Quality Level D information.

During the planning and design phase, it may be possible to make changes to the bored alignment and shaft locations to avoid conflict and the necessity for a potentially costly and time-consuming utility relocation. If conflicts cannot be avoided, relocation plans should be prepared. Relocation of the utilities can be done in advance of the project or as part of the project and can be of a temporary or permanent nature. The utility owner must be engaged as early as possible for input and review. Utilities should be shown on the contract drawings. Information such as utility quality level, diameter, depth, material type, owner, trenched cross section, and backfill material used (per ASCE/CI 38) should be identified if available.

Utilities that will remain in place and are in close proximity to the project may require protection and should be monitored during construction. Evaluation of settlement and heave risks may be appropriate depending on type and age of the utility, clearances, and ground conditions.

4.4 TRAFFIC FLOW AND ACCESS FOR VEHICLES AND PEDESTRIANS

It is important to collect and evaluate traffic information for the planned alignment as early as possible during planning to determine the feasibility of implementing pilot tube and other guided boring method, to develop alignment alternatives, to plan shaft locations, staging areas, and drive lengths, and to develop means to minimize disruption to vehicles and pedestrians. These traffic data may already exist for the alignments through the city or local municipality. In other cases, it will be necessary to plan and implement a project-specific study. The extent of the data requirements is largely dependent on the nature, complexity, and setting of the proposed construction. The presence of individual facilities with unique access demands, such as schools, post offices, distribution centers, and bus depots must also be considered.

During planning and route selection the alternatives analysis should include the cost and noncost effects to traffic. Cost impacts include traffic control and enforcement as well as reduced delay and fewer miles to travel. Alternative traffic management strategies through work zones may have substantial project cost consequences. For example, if a given method involves time restrictions on construction activities, such as construction during off-peak hours only, the effective workday may be reduced significantly. Thus, the overall duration of project construction increases, substantially affecting project costs. Similarly, other requirements may influence the available work area during certain phases of construction, such as work space limitations that may be due to parallel or adjacent construction activities with potential increased project cost consequences.

In this context, roadway occupancy refers to the degree to which the roadway is *occupied* by construction activities, and, therefore, unavailable for normal traffic flow. As different types of work zone activities occupy varying amounts of the roadway, they also have varying impacts on capacity of the facility.

For most projects, traffic impacts cannot be completely eliminated. Even when the route is fixed, the selection of shaft locations and work spaces can have a significant impact on traffic. Although the individual project considerations vary considerably, the following presents general guidance on shaft siting.

Although most common, the least desirable shaft location is typically within the traffic lanes at an intersection of two roadways. This location could interfere with vehicle turning movements through the intersection as well as movements that cause delays in traffic flow. Another undesirable location would be where activities completely occupy the width of the roadway, thus closing all vehicle traffic from the roadway. Roadway occupancy within 50 ft (15.2 m) of an intersection is also undesirable. This location, depending on the direction of vehicle traffic flow as well as which side of the roadway is occupied, can interfere with turning movements from and through the nearby intersection, thus causing delay to vehicle traffic flow.

A more desirable location for roadway occupancy would be an area at least 100 ft (30.5 m) from an intersection and occupying the middle of the roadway. This location would not, in general, interfere with turning movements from and through the nearby intersection. In addition, vehicle thru-traffic on the roadway could squeeze by the construction activities area with minimal delay to traffic flow. If possible, a roadway occupancy midblock between two intersections, and to one side of the roadway, would be even more preferable. This would allow vehicle traffic to occupy most of the roadway with little or no disruption to vehicle traffic.

4.5 ENVIRONMENTAL CONDITIONS

Environmental conditions can be naturally occurring or the result of human activity. Some naturally occurring conditions include naturally occurring hydrocarbons and asbestos as well as active or dormant