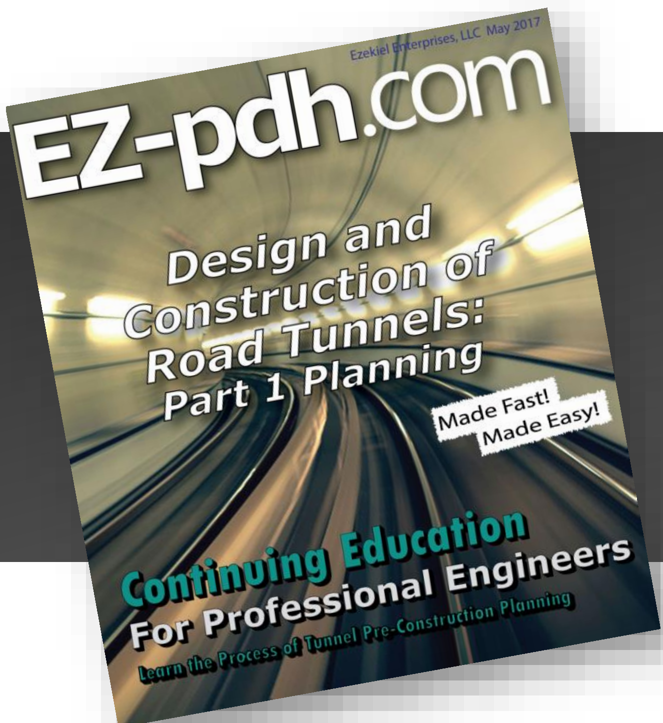

Design and Construction of Road Tunnels: Part 1 Planning

Five (5) Continuing Education Hours
Course #CV7051

Approved Continuing Education for Licensed Professional Engineers

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Course Description:

The Design and Construction of Road Tunnels: Part 1 Planning course satisfies five (5) hours of professional development.

The course is designed as a distance learning course that enables the practicing professional engineer to understand the planning process of a road tunnel project.

Objectives:

The primary objective of this course is enable the student to understand the planning process of a road tunnel project, geometrical requirements and recommendations of new road tunnels, investigative techniques and parameters required for planning, construction and design of road tunnels, and the different types of reports required for a road tunnel project.

Grading:

Students must achieve a minimum score of 70% on the online quiz to pass this course. The quiz may be taken as many times as necessary to successful pass and complete the course.

A copy of the quiz questions are attached to last pages of this document.

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CHAPTER 1
PLANNING

1.1 INTRODUCTION

Road tunnels as defined by the American Association of State Highway and Transportation Officials (AASHTO) Technical Committee for Tunnels (T-20), are enclosed roadways with vehicle access that is restricted to portals regardless of type of the structure or method of construction. The committee further defines road tunnels not to include enclosed roadway created by highway bridges, railroad bridges or other bridges. This definition applies to all types of tunnel structures and tunneling methods such as cut-and-cover tunnels (Chapter 5), mined and bored tunnels in rock (Chapter 6), soft ground (Chapter 7), and difficult ground (Chapter 8), immersed tunnels (Chapter 11) and jacked box tunnels (Chapter 12).

Road tunnels are feasible alternatives to cross a water body or traverse through physical barriers such as mountains, existing roadways, railroads, or facilities; or to satisfy environmental or ecological requirements. In addition, road tunnels are viable means to minimize potential environmental impact such as traffic congestion, pedestrian movement, air quality, noise pollution, or visual intrusion; to protect areas of special cultural or historical value such as conservation of districts, buildings or private properties; or for other sustainability reasons such as to avoid the impact on natural habit or reduce disturbance to surface land. Figure 1-1 shows the portal for the Glenwood Canyon Hanging Lake and Reverse Curve Tunnels – Twin 4,000 feet (1,219 meter) long tunnels carrying a critical section of I-70 unobtrusively through Colorado's scenic Glenwood Canyon.

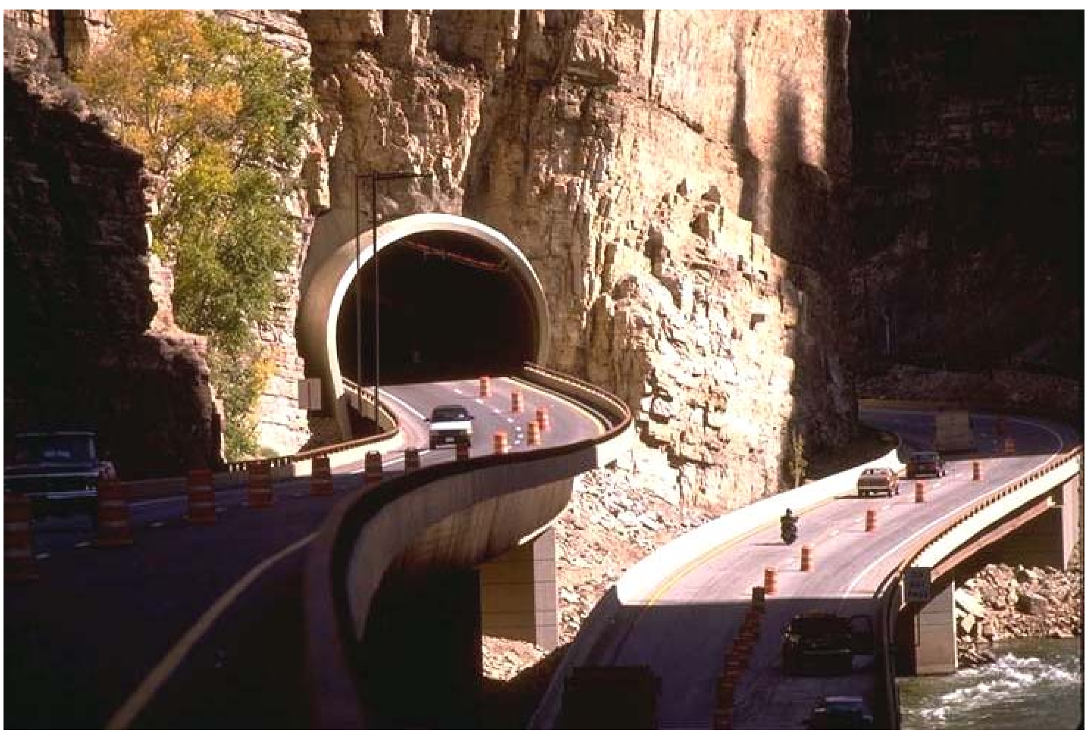


Figure 1-1 Glenwood Canyon Hanging Lake Tunnels

Planning for a road tunnel requires multi-disciplinary involvement and assessments, and should generally adopt the same standards as for surface roads and bridge options, with some exceptions as will be discussed later. Certain considerations, such as lighting, ventilation, life safety, operation and maintenance, etc should be addressed specifically for tunnels. In addition to the capital construction cost, a life cycle cost analysis should be performed taking into account the life expectancy of a tunnel. It should be noted that the life expectancies of tunnels are significantly longer than those of other facilities such as bridges or roads.

This chapter provides a general overview of the planning process of a road tunnel project including alternative route study, tunnel type and tunneling method study, operation and financial planning, and risk analysis and management.

1.1.1 Tunnel Shape and Internal Elements

There are three main shapes of highway tunnels – circular, rectangular, and horseshoe or curvilinear. The shape of the tunnel is largely dependent on the method used to construct the tunnel and on the ground conditions. For example, rectangular tunnels (Figure 1-2) are often constructed by either the cut and cover method (Chapter 5), by the immersed method (Chapter 11) or by jacked box tunneling (Chapter 12). Circular tunnels (Figure 1-3) are generally constructed by using either tunnel boring machine (TBM) or by drill and blast in rock. Horseshoe configuration tunnels (Figure 1-4) are generally constructed using drill and blast in rock or by following the Sequential Excavation Method (SEM), also as known as New Austrian Tunneling Method (NATM) (Chapter 9).

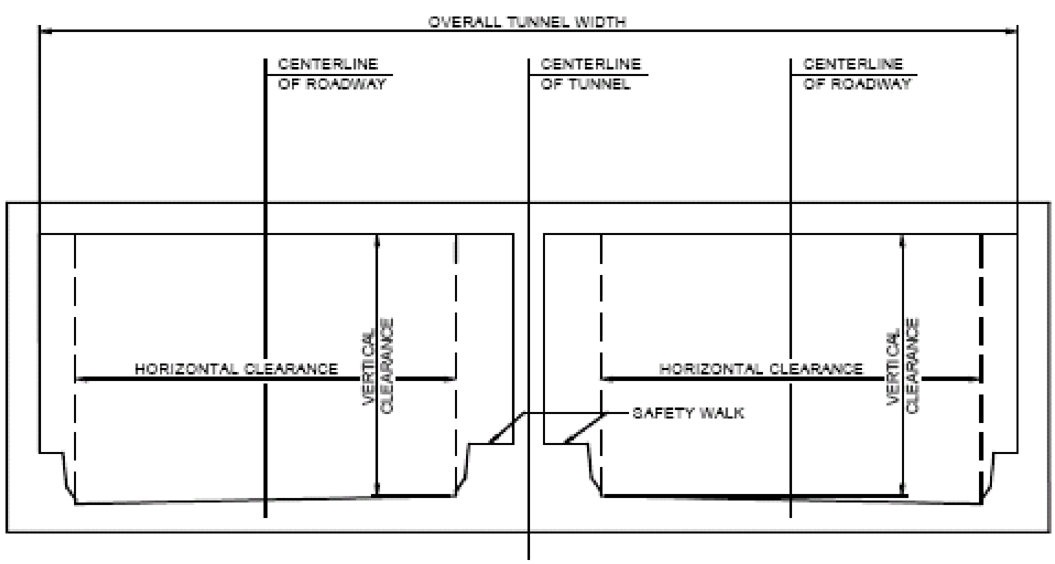


Figure 1-2 Two Cell Rectangular Tunnel (FHWA, 2005a)

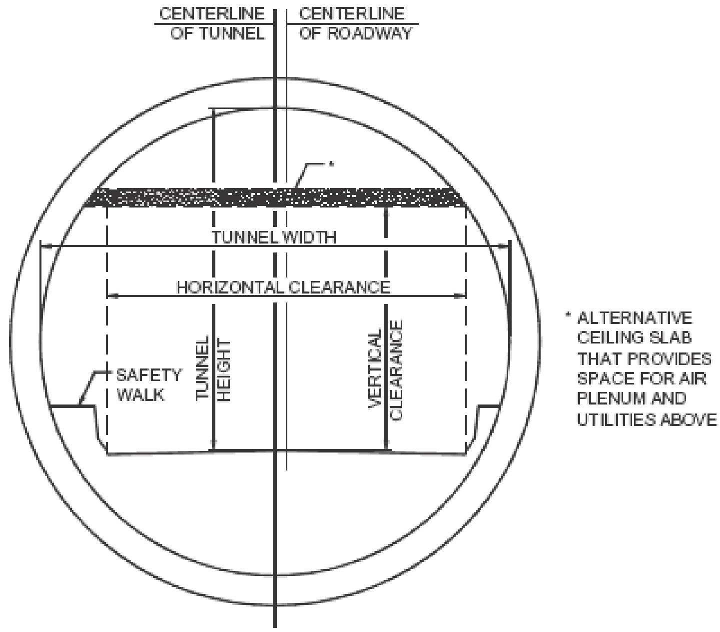
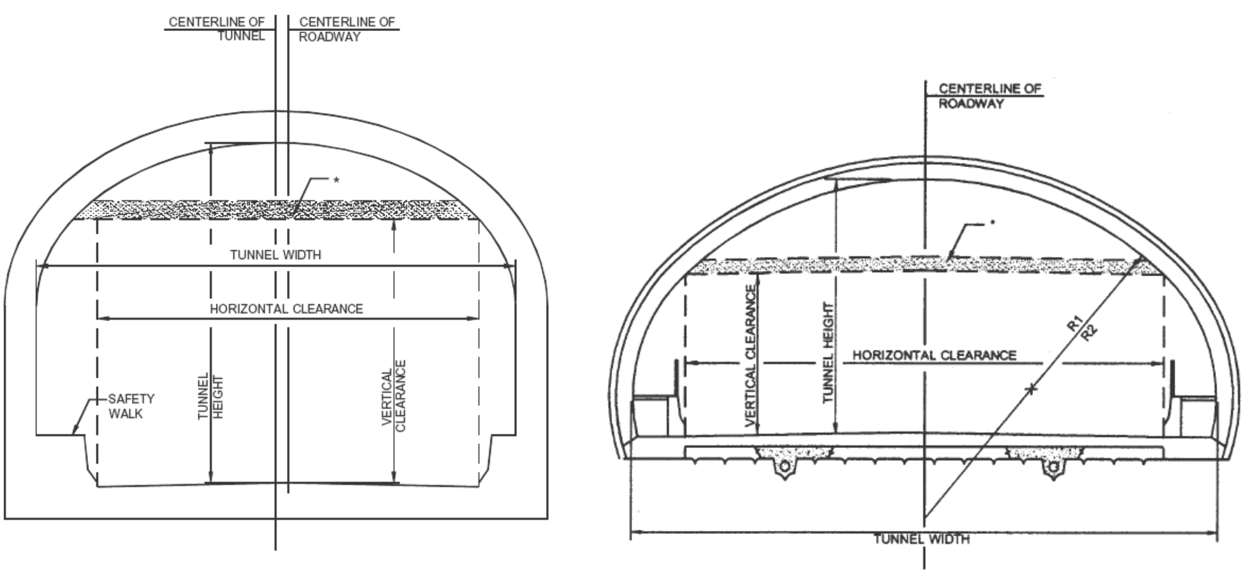


Figure 1-3 Circular Tunnel (FHWA, 2005a)



* Alternate Ceiling Slab that Provides Space for Air Plenum and Utilities Above

Figure 1-4 Horseshoe and Curvilinear (Oval) Tunnels (FHWA, 2005a)

Road tunnels are often lined with concrete and internal finish surfaces. Some rock tunnels are unlined except at the portals and in certain areas where the rock is less competent. In this case, rock reinforcement is often needed. Rock reinforcement for initial support includes the use of rock bolts with internal metal straps and mine ties, un-tensioned steel dowels, or tensioned steel bolts. To prevent small fragments of rock from spalling, wire mesh, shotcrete, or a thin concrete lining may be used. Shotcrete, or sprayed concrete, is often used as initial lining prior to installation of a final lining, or as a local solution to instabilities in a rock tunnel. Shotcrete can also be used as a final lining. It is typically placed in layers with welded wire fabric and/or with steel fibers as reinforcement. The inside surface can be finished smooth and often without the fibers. Precast segmental lining is primarily used in conjunction with a TBM in soft ground and sometimes in rock. The segments are usually erected within the tail shield of the TBM. Segmental linings have been made of cast iron, steel and concrete. Presently however, all segmental linings are made of concrete. They are usually gasketed and bolted to prevent water penetration. Precast segmental linings are sometimes used as a temporary lining within which a cast in place final lining is placed, or as the final lining. More design details are provided in the following Chapters 6 through 10.

Road tunnels are often finished with interior finishes for safety and maintenance requirements. The walls and the ceilings often receive a finish surface while the roadway is often paved with asphalt pavement. The interior finishes, which usually are mounted or adhered to the final lining, consist of ceramic tiles, epoxy coated metal panels, porcelain enameled metal panels, or various coatings. They provide enhanced tunnel lighting and visibility, provide fire protection for the lining, attenuate noise, and provide a surface easy to clean. Design details for final interior finishes are not within the scope of this Manual.

The tunnels are usually equipped with various systems such as ventilation, lighting, communication, fire-life safety, traffic operation and control including messaging, and operation and control of the various systems in the tunnel. These elements are not discussed in this Manual, however, designers should be cognizant that spaces and provisions should be made available for these various systems when planning a road tunnel. More details are provided in Chapter 2 Geometrical Configuration.

1.1.2 Classes of Roads and Vehicle Sizes

A tunnel can be designed to accommodate any class of roads and any size of vehicles. The classes of highways are discussed in *A Policy on Geometric Design of Highways and Streets* Chapter 1, AASHTO (2004). Alignments, dimensions, and vehicle sizes are often determined by the responsible authority based on the classifications of the road (i.e. interstate, state, county or local roads). However, most regulations have been formulated on the basis of open roads. Ramifications of applying these regulations to road tunnels should be considered. For example, the use of full width shoulders in the tunnel might result in high cost. Modifications to these regulations through engineering solutions and economic evaluation should be considered in order to meet the intention of the requirements.

The size and type of vehicles to be considered depend upon the class of road. Generally, the tunnel geometrical configuration should accommodate all potential vehicles that use the roads leading to the tunnel including over-height vehicles such as military vehicles if needed. However, the tunnel height should not exceed the height under bridges and overpasses of the road that leads to the tunnel. On the other hand, certain roads such as Parkways permit only passenger vehicles. In such cases, the geometrical configuration of a tunnel should accommodate the lower vehicle height keeping in mind that emergency vehicles such as fire trucks should be able to pass through the tunnel, unless special low height emergency response vehicles are provided. It is necessary to consider the cost because designing a tunnel facility to accommodate only a very few extraordinary oversize vehicles may not be economical if feasible alternative routes are available. Road tunnel A86 in Paris, for instance, is designed to accommodate two levels of passenger vehicles only and special low height emergency vehicles are provided (Figure 1-5).

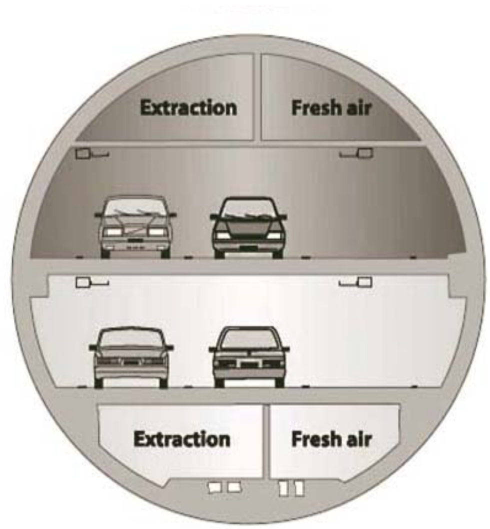


Figure 1-5 A-86 Road Tunnel in Paris, France (FHWA, 2006)

The traveled lane width and height in a tunnel should match that of the approach roads. Often, allowance for repaving is provided in determining the headroom inside the tunnel.

Except for maintenance or unusual conditions, two-way traffic in a single tube should be discouraged for safety reasons except like the A-86 Road Tunnel that has separate decks. In addition, pedestrian and cyclist use of the tunnel should be discouraged unless a special duct (or passage) is designed specifically for such use. An example of such use is the Mount Baker Ridge tunnel in Seattle, Washington.

1.1.3 Traffic Capacity

Road tunnels should have at least the same traffic capacity as that of surface roads. Studies suggest that in tunnels where traffic is controlled, throughput is more than that in uncontrolled surface road suggesting that a reduction in the number of lanes inside the tunnel may be warranted. However, traffic will slow down if the lane width is less than standards (too narrow) and will shy away from tunnel walls if insufficient lateral clearance is provided inside the tunnel. Also, very low ceilings give an impression of speed and tend to slow traffic. Therefore, it is important to provide adequate lane width and height comparable to those of the approach road. It is recommended that traffic lanes for new tunnels should meet the required road geometrical requirements (e.g., 12 ft). It is also recommended to have a reasonable edge distance between the lane and the tunnel walls or barriers (See Chapter 2 for further details).

Road tunnels, especially those in urban areas, often have cargo restrictions. These may include hazardous materials, flammable gases and liquids, and over-height or wide vehicles. Provisions should be made in the approaches to the tunnels for detection and removal of such vehicles.

1.2 ALTERNATIVE ANALYSES

1.2.1 Route Studies

A road tunnel is an alternative vehicular transportation system to a surface road, a bridge or a viaduct. Road tunnels are considered to shorten the travel time and distance or to add extra travel capacity through barriers such as mountains or open waters. They are also considered to avoid surface congestion, improve air quality, reduce noise, or minimize surface disturbance. Often, a tunnel is proposed as a sustainable alternative to a bridge or a surface road. In a tunnel route study, the following issues should be considered:

- Subsurface, geological, and geo-hydraulic conditions
- Constructability
- Long-term environmental impact
- Seismicity
- Land use restrictions
- Potential air right developments
- Life expectancy
- Economical benefits and life cycle cost
- Operation and maintenance
- Security
- Sustainability

Often sustainability is not considered; however, the opportunities that tunnels provide for environmental improvements and real estate developments over them are hard to ignore and should be reflected in term of financial credits. In certain urban areas where property values are high, air rights developments account for a significant income to public agencies which can be used to partially offset the construction cost of tunnels.

It is important when comparing alternatives, such as a tunnel versus a bridge or a bypass, that the comparative evaluation includes the same purpose and needs and the overall goals of the project, but not necessarily every single criterion. For example, a bridge alignment may not necessarily be the best alignment for a tunnel. Similarly, the life cycle cost of a bridge has a different basis than that of a tunnel.

1.2.2 Financial Studies

The financial viability of a tunnel depends on its life cycle cost analysis. Traditionally, tunnels are designed for a life of 100 to 125 years. However, existing old tunnels (over 100 years old) still operate successfully throughout the world. Recent trends have been to design tunnels for 150 years life. To facilitate comparison with a surface facility or a bridge, all costs should be expressed in terms of life-cycle costs. In evaluating the life cycle cost of a tunnel, costs should include construction, operation and maintenance, and financing (if any) using Net Present Value. In addition, a cost-benefit analysis should be performed with considerations given to intangibles such as environmental benefits, aesthetics, noise and vibration, air quality, right of way, real estate, potential air right developments, etc.

The financial evaluation should also take into account construction and operation risks. These risks are often expressed as financial contingencies or provisional cost items. The level of contingencies would be decreased as the project design level advances. The risks are then better quantified and provisions to reduce or manage them are identified. See Chapter 14 for risk management and control.

1.2.3 Types of Road Tunnels

Selection of the type of tunnel is an iterative process taking into account many factors, including depth of tunnel, number of traffic lanes, type of ground traversed, and available construction methodologies. For example, a two-lane tunnel can fit easily into a circular tunnel that can be constructed by a tunnel boring machine (TBM). However, for four lanes, the mined tunnel would require a larger tunnel, two bores or another method of construction such as cut and cover or SEM methods. The maximum size of a circular

TBM existing today is about 51 ft (15.43 m) for the construction of Chongming Tunnel, a 5.6 mile (9-kilometer) long tunnel under China's Yangtze River, in Shanghai. See Figure 1-6 showing the Chongming Tunnel. Note the scale of the machine relative to the people standing in the invert.

Figure 1-6 Chongming Tunnel under the Yangtze River

When larger and deeper tunnels are needed, either different type of construction methods, or multiple tunnels are usually used. For example, if the ground is suitable, SEM (Chapter 9) in which the tunnel cross section can be made to accommodate multiple lanes can be used. For tunnels below open water, immersed tunnels can be used. For example, the Fort McHenry Tunnel in Baltimore, Maryland accommodated eight traffic lanes of I-95 into two parallel immersed units as shown in Figure 1-7.

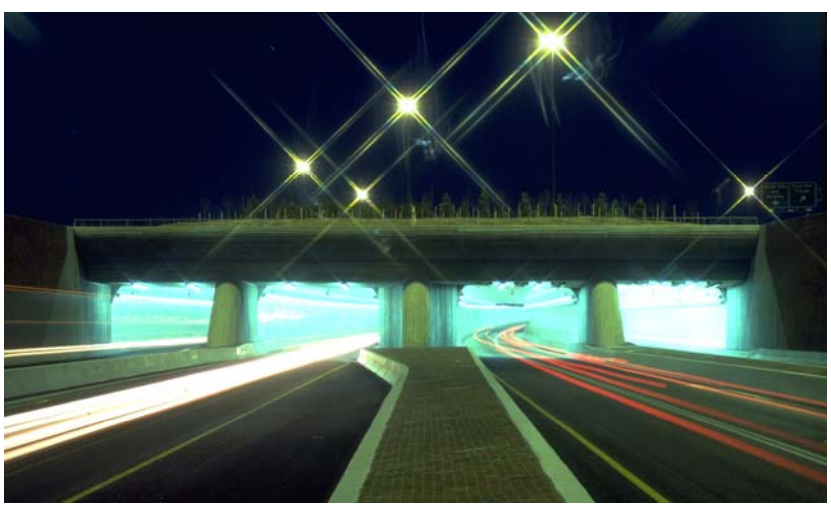


Figure 1-7 Fort McHenry Tunnel in Baltimore, MD

Shallow tunnels would most likely be constructed using cut-and-cover techniques, discussed in Chapter 5. In special circumstances where existing surface traffic cannot be disrupted, jacked precast tunnels are sometimes used. In addition to the variety of tunneling methods discussed in this manual, nonconventional techniques have been used to construct very large cross section, such as the Mt. Baker Ridge Tunnel, on I-90 in Seattle, Washington. For that project, multiple overlapping drifts were constructed and filled with concrete to form a circular envelop that provides the overall support system of the ground. Then the space within this envelop was excavated and the tunnel structure was constructed within it (Figure 1-8).

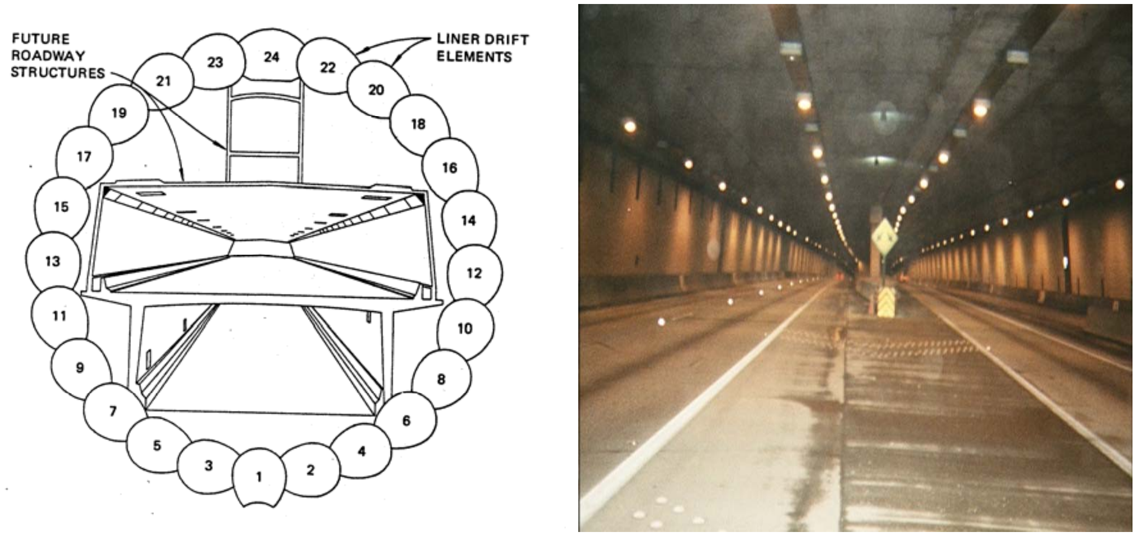


Figure 1-8 Stacked Drift and Final Mt Baker Tunnel, I-90, Seattle, WA

There are times when tunneling is required in a problematic ground such as mixed face (rock and soft ground), squeezing rock or other difficult ground conditions requiring specialized techniques, as discussed in Chapter 8.

1.2.4 Geotechnical Investigations

As discussed in Chapter 3, geotechnical investigations are critical for proper planning of a tunnel. Selection of the alignment, cross section, and construction methods is influenced by the geological and geotechnical conditions, as well as the site constraints. Good knowledge of the expected geological conditions is essential. The type of the ground encountered along the alignment would affect the selection of the tunnel type and its method of construction. For example, in TBM tunnel construction mixed ground conditions, or buried objects add complications to the TBM performance and may result in the inability of the TBM to excavate the tunnel, potential breakdown of the TBM, or potential ground failure and settlements at the surface. The selection of the tunnel profile must therefore take into account potential ground movements and avoid locations where such movements or settlements could cause surface problems to existing utilities or surface facilities and mitigation measures should be provided.

Another example of the effect of the impact of geological features on the tunnel alignment is the presence of active or inactive faults. During the planning phase, it is recommended to avoid crossing a fault zone and preferred to avoid being in a close proximity of an active fault. However, if avoidance of a fault cannot be achieved, then proper measures for crossing it should be implemented. Such measures are discussed in Chapter 13 Seismic Considerations. Special measures may also be required when tunneling in a ground that may contain methane or other hazardous gasses or fluids.

Geotechnical issues such as the soil or rock properties, the ground water regime, the ground cover over the tunnel, the presence of contaminants along the alignment, presence of underground utilities and obstructions such as boulders or buried objects, and the presence of sensitive surface facilities should be taken into consideration when evaluating tunnel alignment. Tunnel alignment is sometimes changed based on the results of the geotechnical to minimize construction cost or to reduce risks. The tunnel profile can also be adjusted to improve constructability or accommodate construction technologies as long as the road geometrical requirements are not compromised. For example, for TBM tunnels the profile would be selected to ensure that sufficient cover is maintained for the TBM to operate satisfactorily over the proposed length of bore. However, this should not compromise the maximum grade required for the road.

If the route selection is limited, then measures to deal with the poor ground in terms of construction method or ground improvement prior to excavation should be considered. It is recommended that the geotechnical investigation start as early as possible during the initial planning phase of the project. The investigation should address not just the soil and rock properties, but also their anticipated behaviors during excavation. For example in sequential excavation or NATM, ground standup time is critical for its success. If the ground does not have sufficient standup time, pre-support or ground improvement such as grouting should be provided. For soft ground TBM tunneling, the presence of boulders for example would affect the selection of TBM type and its excavation tools. Similarly, the selection of a rock TBM would require knowledge of the rock unconfined compressive strength, its abrasivity and its jointing characteristics. The investigation should also address groundwater. For example, in soft ground SEM tunneling, the stability of the excavated face is greatly dependent on control of the groundwater. Dewatering, pre-draining, grouting, or freezing are often used to stabilize the excavation. Ground behavior during tunneling will affect potential settlements on the surface. Measures to minimize settlements by using suitable tunneling methods or by preconditioning the ground to improve its characteristics would be required. Presence of faults or potentially liquefiable materials would be of concern during the planning process. Relocating the tunnel to avoid these concerns or providing measures to deal with them is critical during the planning process.

The selection of a tunnel alignment should take into consideration site specific constraints such as the presence of contaminated materials, special existing buildings and surface facilities, existing utilities, or the presence of sensitive installations such as historical landmarks, educational institutions, cemeteries, or houses of worship. If certain site constraints cannot be avoided, construction methodologies, and special provisions should be provided. For example, if the presence of contaminated materials near the surface cannot be avoided, a deeper alignment and/or the use of mined excavation (TBM or SEM) would be more suitable than cut and cover method. Similarly, if sensitive facilities exist at the surface and cannot be avoided, special provisions to minimize vibration, and potential surface settlement should be provided in the construction methods.

Risk assessment is an important factor in selecting a tunnel alignment. Construction risks include risks related the construction of the tunnel itself, or related to the impact of the tunnel construction on existing facilities. Some methods of tunneling are inherently more risky than others or may cause excessive ground movements. Sensitive existing structures may make use of such construction methods in their vicinity undesirable. Similarly, hard spots (rock, for example) beneath parts of a tunnel can also cause undesirable effects and alignment changes may obviate that. Therefore, it is important to conduct risk analysis as early as possible to identify potential risks due to the tunnel alignment and to identify measures to reduce or manage such risks. An example of risk mitigation related to tunnel alignment being close to sensitive surface facilities is to develop and implement a comprehensive instrumentation and monitoring program, and to apply corrective measures if measured movements reach certain thresholds. Chapter 15 discusses instrumentation and monitoring.

Sometimes, modifications in the tunnel structure or configurations would provide benefits for the overall tunnel construction and cost. For example, locating the tunnel ventilations ducts on the side, rather than at the top would reduce the tunnel height, raise the profile of the tunnel and consequently reduce the overall length of the tunnel.

1.2.5 Environmental and Community Issues

Road tunnels are more environmentally friendly than other surface facilities. Traffic congestion would be reduced from the local streets. Air quality would be improved because traffic generated pollutants are captured and disposed of away from the public. Similarly, noise would be reduced and visual aesthetic and land use would be improved. By placing traffic underground, property values would be improved and communities would be less impacted in the long term. Furthermore, tunnels will provide opportunities for land development along and over the tunnel alignment adding real estate properties and potential economical potential development.

In planning for a tunnel, the construction impact on the community and the environment is important and must be addressed. Issues such as impact on traffic, businesses, institutional facilities, sensitive installations, hospitals, utilities, and residences should be addressed. Construction noise, dust, vibration, water quality, aesthetic, and traffic congestion are important issues to be addressed and any potentially adverse impact should be mitigated. For example, a cut-and-cover tunnel requires surface excavation impacting traffic, utilities, and potentially nearby facilities. When completed, it leaves a swath of disturbed surface-level ground that may need landscaping and restoration. In urban situations or close to properties, cut-and-cover tunnels can be disruptive and may cut off access and utilities temporarily. Alternative access and utilities to existing facilities may need to be provided during construction or, alternatively, staged construction to allow access and to maintain the utilities would be required. Sometimes, top-down construction rather than bottom-up construction can help to ameliorate the disruption and reduce its duration. Rigid excavation support systems and ground improvement techniques may be required to minimize potential settlements and lateral ground deformations, and their impact on adjacent structures. When excavation and dewatering are near contaminated ground, special measures may be required to prevent migration of the groundwater contaminated plume into the excavation or adjacent basements. Dust suppression and wheel washing facilities for vehicles leaving the construction site are often used, especially in urban areas.

Similarly, for immersed tunnels the impact on underwater bed level and the water body should be assessed. Dredging will generate bottom disturbance and create solid turbidity or suspension in the water. Excavation methods are available that can limit suspended solids in the water to acceptable levels. Existing fauna and flora and other ecological issues should be investigated to determine whether environmentally and ecologically adverse consequences are likely to ensue. Assessment of the construction on fish migration and spawning periods should be made and measures to deal with them should be developed. The potential impact of construction wetlands should be investigated and mitigated.

On the other hand, using bored tunneling would reduce the surface impact because generally the excavation takes place at the portal or at a shaft resulting in minimum impact on traffic, air and noise quality, and utility and access disturbance.

Excavation may encounter contaminated soils or ground water. Such soils may need to be processed or disposed in a contained disposal facility, which may also have to be capped to meet the environmental regulations. Provisions would need to address public health and safety and meet regulatory requirements.

1.2.6 Operational Issues

In planning a tunnel, provisions should be made to address the operational and maintenance aspects of the tunnel and its facilities. Issues such as traffic control, ventilation, lighting, life safety systems, equipment maintenance, tunnel cleaning, and the like, should be identified and provisions made for them during the initial planning phases. For example, items requiring more frequent maintenance, such as light fixtures, should be arranged to be accessible with minimal interruption to traffic.

1.2.7 Sustainability

Tunnels by definition are sustainable features. They typically have longer life expectancy than a surface facility (125 versus 75 years). Tunnels also provide opportunities for land development for residential, commercial, or recreational facilities. They enhance the area and potentially increase property values. An example is the "Park on the Lid" in Mercer Island, Seattle, Washington where a park with recreational facilities was developed over I-90 (Figure 1-9). Tunnels also enhance communities connections and adhesion and protect residents and sensitive receptors from traffic pollutants and noise.

Figure 1-9 "Park on the Lid" Seattle, Washington

1.3 TUNNEL TYPE STUDIES

1.3.1 General Description of Various Tunnel Types

The principal types and methods of tunnel construction that are in use are:

- Cut-and-cover tunnels (Chapter 5) are built by excavating a trench, constructing the concrete structure in the trench, and covering it with soil. The tunnels may be constructed in place or by using precast sections

.

- Bored or mined tunnels (Chapters 6 through 11), built without excavating the ground surface. These tunnels are usually labeled according to the type of material being excavated. Sometimes a tunnel passes through the boundary between different types of material; this often results in a difficult construction known as mixed face (Chapter 8).

- Rock tunnels (Chapter 6) are excavated through the rock by drilled and blasting, by mechanized excavators in softer rock, or by using rock tunnel boring machines (TBM). In certain conditions, Sequential Excavation Method (SEM) is used (Chapter 9).

- Soft ground tunnels (Chapter 7) are excavated in soil using a shield or pressurized face TBM (principally earth pressure balance or slurry types), or by mining methods, known as either the sequential excavation method (SEM) (Chapter 9).

- Immersed tunnels (Chapter 11), are made from very large precast concrete or concrete-filled steel elements that are fabricated in the dry, floated to the site, placed in a prepared trench below water, and connected to the previous elements, and then covered up with backfill.

- Jacked box tunnels (Chapter 12) are prefabricated box structures jacked horizontally through the soil using methods to reduce surface friction; jacked tunnels are often used where they are very shallow but the surface must not be disturbed, for example beneath runways or railroads embankments.

Preliminary road tunnel type selection for conceptual study after the route studies can be dictated by the general ground condition as illustrated in Figure 1-10.

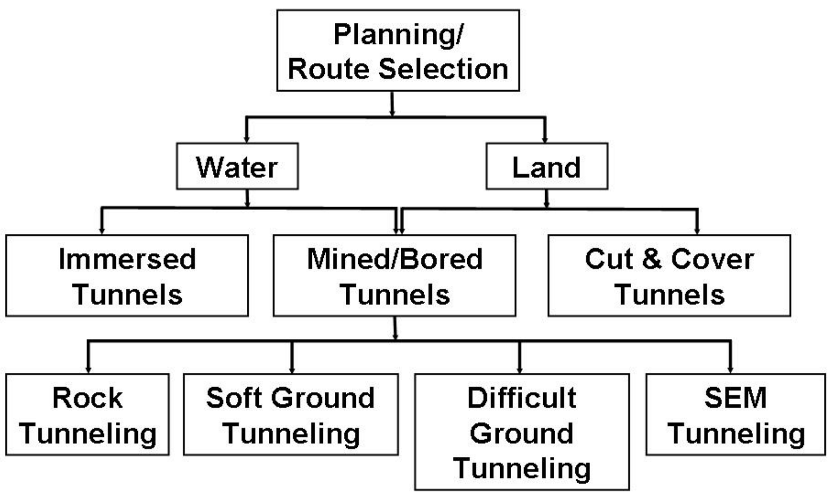


Figure 1-10 Preliminary Road Tunnel Type Selection Process

The selection of a tunnel type depends on the geometrical configurations, the ground conditions, the type of crossing, and environmental requirements. For example, an immersed tunnel may be most suitable for crossing a water body, however, environmental and regulatory requirements might make this method very expensive or infeasible. Therefore, it is important to perform the tunnel type study as early as possible in the planning process and select the most suitable tunnel type for the particular project requirements.

1.3.2 Design Process

The basic process used in the design of a road tunnel is:

- Define the functional requirements, including design life and durability requirements;
- Carry out the necessary investigations and analyses of the geologic, geotechnical and geohydrological data
- Conduct environmental, cultural, and institutional studies to assess how they impact the design and construction of the tunnel;
- Perform tunnel type studies to determine the most appropriate method of tunneling.
- Establish design criteria and perform the design of the various tunnel elements. Appropriate initial and final ground support and lining systems are critical for the tunnel design, considering both ground conditions and the proposed method of construction. Perform the design in Preliminary and Final design phases. Interim reviews should be made if indicated by ongoing design issues.
- Establish tunnel alignment, profile and cross-section
- Determine potential modes of failure, including construction events, unsatisfactory long-term performance, and failure to meet environmental requirements. Obtain any necessary data and analyze these modes of failure;
- Perform risk analysis and identify mitigation measures and implement those measures in the design
- Prepare project documents including construction plans, specifications, schedules, estimates, and geotechnical baseline report (GBR).

1.3.3 Tunnel Cross-Section

The tunnel cross section geometrical configuration must satisfy the required traffic lanes, shoulders or safety walks, suitable spaces for ventilation, lights, traffic control system, fire/life safety systems, etc. The cross section is also dictated by the method of tunnel construction. For example, bored tunnels using TBM will result in circular configuration, while cut and cover construction will result in rectangular configuration. The structural systems will also vary accordingly. The available spaces in a circular cross section can be used to house tunnel systems, such as the ventilation duct or fans, lighting, traffic control systems and signs, close circuit TV, and the like. For rectangular sections the various systems can be placed overhead, invert or adjacent to the traffic lanes if overhead space is limited. It is essential at early design stages to pay attention to detail in laying out the tunnel cross-section to permit easy inspection and maintenance not only of mechanical and electrical equipment, but also of the tunnel structure itself.

The tunnel structural systems depend on the type of tunnel, the geometrical configuration of the cross section, and method of construction. For example, in cut and cover tunnels of rectangular cross section, cast in place concrete is often the selected structural system, while for SEM/NATM tunnel, the structural system could be lattice girders and shotcrete. For soft ground tunnels using TBM, the structural system is often a precast segmental one pass lining. Sometimes, the excavation support system can be used as the final tunnel structural system such as the case in top down construction.

Chapter 2 provides detailed discussions for the geometrical configurations.

1.3.4 Groundwater Control

Building a dry tunnel is a primary concerns of the owner, user, and operator alike. A dry tunnel provides a safer and friendlier environment and significantly reduces operation and maintenance costs. Advancements in tunneling technology in the last few decades in general and in the waterproofing field in particular have facilitated the implementation of strict water infiltration criteria and the ability to build dry tunnels.

Based on criteria obtained from the International Tunneling Association (ITA), Singapore's Land Transport Authority (LTA), Singapore's Public Utilities Board (PUB), Hong Kong's Mass Transit Rail Corporation (MTRC) and the German Cities Committee, as well as criteria used by various projects in the US and abroad for both highway and transit tunnels (e.g. Washington DC, San Francisco, Atlanta, Boston, Baltimore, Buffalo, Melbourne (Australia), Tyne & Wear (UK) and Antwerp (Belgium), the following ITA ground water infiltration criteria are recommended;

Allowable Infiltration

Tunnels	≤	0.002 gal/sq. ft/day
Underground public space	≤	0.001 gal/sq. ft/day

In addition no dripping or visible leakage from a single location shall be permitted.

Tunnel waterproofing systems are used to prevent groundwater inflow into an underground opening. They consist of a combination of various materials and elements. The design of a waterproofing system is based on the understanding of the ground and geohydrological conditions, geometry and layout of the structure and construction methods to be used. A waterproofing system should always be an integrated system that takes into account intermediate construction stages, final conditions of structures and their ultimate usage including maintenance and operations.

There are two basic types of waterproofing systems: drained (open) and undrained (closed). Figures 6-40 and 6-41 illustrate drained (open) and undrained system (closed) tunnels, respectively. Various waterproofing materials are available for these systems. Open waterproofing systems allow groundwater inflow into a tunnel drainage system. Typically, the tunnel vault area is equipped with a waterproofing system forming an umbrella-like protection that drains the water seeping towards the cavity around the arch into a drainage system that is located at the bottom of the tunnel sidewalls and in the tunnel invert. The open system is commonly used in rock tunnels where water infiltration rates are low. Groundwater inflow is typically localized to distinct locations such as joints and fractures and the overall permeability is such that a groundwater draw-down in soil layers overlying the rock mass will not be affected. This system is commonly installed between an initial tunnel support (initial lining) and the secondary or final support (permanent lining). The open waterproofing system generally allows for a more economical secondary lining and invert design as the hydrostatic load is greatly reduced or eliminated.

Closed waterproofing systems (closed system), often referred to as tanked systems, extend around the entire tunnel perimeter and aim at excluding the groundwater from flowing into the tunnel drainage system completely. Thus no groundwater drainage is provided. The secondary linings therefore have to be designed for full hydrostatic water pressures. These systems are often applied in permeable soils where groundwater discharge into the tunnels would be significant and would otherwise cause a lowering of the groundwater table and possibly cause surface settlements.

For precast segmental lining, the segments are usually equipped with gaskets to seal the joints between segments and thus provide a watertight tunnel. For cut and cover tunnels under the groundwater table and for immersed tunnels, waterproofing membranes encapsulating the structures are recommended.
The waterproofing system should be addressed as early as possible and design criteria for water infiltration should be established during the process. This issue is further discussed in Chapter 10- Tunnel Linings.

1.3.5 Tunnel Portals

Portals and ventilation shafts should be located such that they satisfy environmental and air quality requirements as well as the geometrical configuration of the tunnel. At portals, it may be necessary to extend the dividing wall between traffic traveling in opposite directions to reduce recirculation of pollutants from the exit tunnel into the entry tunnel. If possible, Portals should be oriented to avoid drivers being blinded by the rising or setting sun. Special lighting requirements at the portal are needed to address the "black hole" effect (Chapter 2). The portal should be located at a point where the depth of the tunnel is suitably covered. This depends on the type of construction, the crossing configuration, and the geometry of the tunnel. For example, in a cut and cover tunnel, the portal can be as close to the surface as the roof of the tunnel can be placed with sufficient clearance for traffic. On the other hand, in TBM mined tunnels, the portal will be placed at a location where there is sufficient ground cover to start the TBM. In mountain tunnels the portal can be as close to the face of the mountain as practically constructible.

1.3.6 Fire-Life Safety Systems

Safety in the event of a fire is of paramount importance in a tunnel. The catastrophic consequences of the tunnel fires (e.g., the Mont Blanc tunnel, 1999 and the Swiss St. Gotthard tunnel, 2001) not only resulted in loss of life, severe property damages, but also great concerns of the lack of fire-life safety protection in road tunnels. During the Gotthard Tunnel October 2001 fire (Figure 1-11) that claimed 11 deaths, the temperature reportedly reached 1,832 ^{o}F (1,000 ^{o}C) in few minutes, and thick smoke and combustible product propagated over 1.5 mile (2.5km) within 15 minutes.

Figure 1-11 Gotthard Tunnel Fire in October 2001 (FHWA 2006)

For planning purposes, it is important to understand the fire-life safety issues of a road tunnel and consider their impacts on the alignments, tunnel cross section, emergency exits, ventilation provisions, geometrical configuration, right-of-way, and conceptual cost estimates, National Fire Protection Association (NFPA) 502 – Standard for Road Tunnels, Bridges, and Other Limited Access Highways provides the following fire protection and life safety requirements for road tunnels:

- Protection of Structural Elements
- Fire Detection
- Communication Systems
- Traffic Control

- Fire Protection (i.e., standpipe, fire hydrants, water supply, portable fire extinguisher, fixed water-base fire-fighting systems, etc.)
- Tunnel Drainage System
- Emergency Egress
- Electric, and
- Emergency response plan.

In 2005, the FHWA, AASHTO, and the National Cooperative Highway Research Program (NCHRP) sponsored a scanning study of equipment, systems and procedures used in European tunnels. The study concluded with nine (9) recommendations for implementation include conducting research on tunnel emergency management that includes human factors; developing tunnel design criteria that promote optimal driver performance during incidents; developing more effective visual, audible, and tactile signs for escape routes; and using a risk-management approach to tunnel safety inspection and maintenance. Appendix A presents the executive summary of the scan study. The scan study report is available entirety on the FHWA web site at http://International.fhwa.dot.gov/uts/uts.pdf (FHWA, 2006).

1.3.6.1 Emergency Egress

Emergency egress for persons using the tunnel to a place of refuge should be provided at regular intervals. Throughout the tunnel, functional, clearly-marked escape routes should be provided for use in an emergency. As shown in Figure 1-12, exits should be clearly marked, and the spacing of exits into escape routes should not exceed 1000 feet (300 m) and should comply with the latest NFPA 502 - Standard for Road Tunnels, Bridges, and Other Limited Access Highways. Emergency exits should be provided to safe, secure locations.

Figure 1-12 Emergency Exit (FHWA, 2006)

The emergency egress walkways should be a minimum of 3.6 ft wide and should be protected from oncoming traffic. Signage indicating both direction and distance to the nearest escape door should be mounted above the emergency walkways at reasonable intervals (100 to 150 ft) and be visible in an emergency. The emergency escape routes should be provided with adequate lighting level and connected to the emergency power system.

Where tunnels are provided in twin tubes, cross passages to the adjacent tube can be considered safe haven. The cross passage should be of at least two-hour fire rating construction, should be equipped with self closing fire rated doors that open in both directions or sliding doors, and the cross passages should be located not more than 656 ft (200m) apart. An emergency walkway" at least 3.6 feet (1.12 m) wide should be provided on each side of the cross-passageways.

In long tunnels, sometimes breakdown emergency alcoves (local widening) for vehicles are provided. See Figure 1-13. Some European tunnels also provide at intervals an emergency turn-around for vehicles into the adjacent roadway duct which turn-around would normally be closed by doors.

Figure 1-13 Emergency Alcove

1.3.6.2 Emergency Ventilation, Lighting and Communication

An emergency ventilation system should be provided to control smoke and to provide fresh air for the evacuation of passengers and for support to the emergency responders. The emergency ventilation system is often the normal ventilation system operated at higher speeds. Emergency ventilation scenarios should be developed and the operation of the fans would be based on the location of the fire and the direction of the tunnel evacuation. The fans should be connected to an emergency power source in case of failure of the primary power.

Emergency tunnel lighting, fire detection, fire lines, and hydrants should be provided. In certain installations, fire suppression measures such as foam or deluge system have been used. The risk of fire spreading through power cable ducts should be eliminated by dividing cable ducts into fireproof sections, placing cables in cast-in ducts, using fireproof cables where applicable, and other preventative measures. Vital installations should be supplied with fire-resistant cables. Materials used should not release toxic or aggressive gases such as chlorine. Water for fire-fighting should be protected against frost. Fire alarm buttons should be provided adjacent to every cross-passage. Emergency services should be able to approach a tunnel fire in safety.

Emergency telephones should be provided in the tunnels and connected to the emergency power supply. When such a telephone is used, the location of the caller should be identified both at the control center and by a warning light visible to rescuing personnel. Telephones should be provided at cross-passage doors and emergency exits. Communication systems should give the traveling public the possibility of summoning help and receiving instructions, and should ensure coordinated rescue. Systems should raise the alarm quickly and reliably when unusual operating conditions or emergency situations arise.

Radio coverage for police, fire and other emergency services and staff should extend throughout the tunnel. It is necessary for police, fire and emergency services to use their mobile radios within tunnels and cross-passages. Radio systems should not interfere with each other and should be connected to the emergency power supply to communicate with each other. It is also recommended that mobile telephone coverage be provided.

1.3.7 Tunnel Drainage

Good design anticipates drainage needs. Usually sump-pump systems are provided at the portals and at low points. Roadway drainage throughout the tunnel using drain inlets and drainage pipes should be provided. The drainage system should be designed to deal with surface drainage as well as any groundwater infiltration into the tunnel. Other areas of the tunnels, such as ventilation ducts and potential locations for leakage, should have provision for drainage. Accumulation of ice due to inadequate drainage provisions must be avoided for safe passage.

1.4 OPERATIONAL AND FINANCIAL PLANNING

1.4.1 Potential Funding Sources and Cash Flow Requirements

Traditionally State, Federal, and Local funds are the main funding sources for road tunnels. However, recently private enterprises and public-private partnership (PPP) are becoming more attractive potential sources for funding road tunnel projects. For example, the Port of Miami Tunnel has been developed using the PPP approach. Various forms of financing have been applied in various locations in the US and the World. Tolls are often levied on users to help repay construction costs, and to pay operating costs, especially when the roads are financed by private sources. In some cases, bond issues have been used to raise funding for the project.

In developing the funding strategy, it is important to consider and secure the cash flow required to complete the project. In assessing the cash flow analysis, escalation to the year of expenditure should be used. Various indices of escalation rates are available. It is recommended that escalation rates comparable to this type of construction and for the area of the project should be used. Factors such as work load in the area, availability of materials, availability of skilled labor, specialty equipment, and the like, should be taken into consideration. Repayment of loans and the cost of the money should be considered. They may continue for a substantial number of years while the operation and maintenance costs of the tunnel also have to be covered.

1.4.2 Conceptual Level Cost Analysis

At the conceptual level, cost analyses are often based upon the costs per unit measurement for a typical section of tunnel. The historical cost data updated for inflation and location is also commonly used as a quick check. However, such data should be used with extreme caution since in most cases, the exact content of such data and any special circumstances are not known. In addition, construction of tunnels is a specialty work and involves a significant labor component. Labor experience and productivity are critical for proper estimating of a tunnel construction cost. Furthermore, the tunnel being a linear structure, its cost is highly dependent on the advance rate of construction, which in turn is dependent on the labor force, the geological conditions, the suitability of equipment, the contractor's means and methods, and the experience of the workers. Since tunneling is highly dependent on the labor cost, issues such as advance rates, construction schedule, number of shifts, labor union requirements, local regulations such as permissible time of work, environmental factors such as noise and vibrations, and the like should be taken into considerations when construction cost estimates are made. It is recommended, even at the planning phase, to prepare a bottom up construction cost estimate using estimate materials, labor, and equipment. The use of experience from other similar projects in the area is usually done for predicting labor force and the advance rates. At the conceptual level, substantial contingencies may be required at the early stages of a project. As the design advances and the risks identified and dealt with, contingencies would be reduced gradually as the level of detail and design increases. Soft costs such as engineering, program and construction management, insurance, owner cost, third party cost, right of way costs, and the like should be considered. The cost estimate should progressively become more detailed as the design is advanced. More detailed discussions on this subject are presented in Chapter 14.

1.4.3 Project Delivery Methods

Generally, two categories of delivery methods have been used in the past for underground construction, with various levels of success. They are:

- Design-Bid-Build
- Design-Build

The contractual terms of these two delivery methods vary widely. The most common is the fixed price approach, although for tunneling, the unit prices approach is the most suitable. Other contract terms used include:

- Fixed Price lump sum
- Low bid based on unit prices
- Quality based selection
- Best and Final Offer (BAFO)
- Cost plus fixed fee

The traditional project delivery model is the design-bid-build. In this method, the client finances the project and develops an organization to deal with project definition, legal, commercial, and land access/acquisition issues. It appoints a consulting engineer under a professional services contract to act on its behalf to undertake certain design, procurement, construction supervision, and contract administration activities, in return for which the consulting engineer is paid a fee. The client places construction contracts following a competitive tendering process for a fixed price, with the selection are often based on low bid. This type of contract is simple, straight forward and familiar to public owners. However, in this process the majority of construction risk is passed to the contractor who often uses higher contingency factors to cover the potential construction risks. The client effectively pays the contractor for taking on the risk, irrespective of whether the risk actually transpires.

Whilst this type of contract has its advantages, its shortfalls particularly on large infrastructure projects could be significant. Adversarial relationships between project participants, potential cost overruns, and delays to project schedules are by no means unusual. With the traditional contract forms, there is significant potential for protracted disputes over responsibility for events, to the detriment of the progress of the physical works. The client, its agents, and the contractors are subject to different commercial risks and potentially conflicting commercial objectives.

In a design-build process, the project is awarded to a design-build entity that design and construct the project. The owner's engineer usually prepares bidding documents based on a preliminary-level design identifying the owner's requirements. Contract terms vary from fixed price to unit prices, to cost plus fee. For tunneling projects, the geotechnical and environmental investigations should be advanced to a higher level of completion to provide better information and understanding of the construction risks. The selected contractor then prepares the final design (usually with consultation with the owner's engineer) and constructs the project. This process is gaining interest among owners of underground facilities in order to reduce the overall time required to complete the project, avoid dealing with disputes over changed conditions, and avoid potential lengthy and costly litigations.

The procurement options of the design-build approach vary based on the project goals and the owners' objectives. Examples of the procurement options include:

- Competitive bid (low price)
- Competitive bid with high responsibility standards (cost and qualifications)
- Competitive bids with alternative proposals
- Price and other factors
- Price after discussion including "Best and Final Offer"
- Quality based selection
- Sole source negotiation

The allocation of risk between the owner and the contractor will have a direct relationship to the contractor contingency as part of the contractor's bid. Therefore, it is important to identify a risk sharing mechanism that is fair and equitable and that will result in a reasonable contingency by the contractor and sufficient reserve fund to be provided by the owner to address unforeseen conditions. For example unforeseen conditions due to changes in the anticipated ground conditions are paid for by the owner if certain tests are met, while the means and methods are generally the contractor's responsibility and his inability to perform under prescribed conditions are risks to be absorbed by the contractor. With proper contracting form and equitable allocation of risks between the owner and the contractor, the contractor contingency, which is part of its bid price, will be reduced. Similarly, the owner's reserve fund will be used only if certain conditions are encountered, resulting in an overall lesser cost to the owner. This is further discussed in Chapter 14 Construction Engineering.

Design-build has the advantage that the design can be tailored to fit the requirements of the contractor's means and methods since both, the designer and the constructor work through one contract. This can be particularly useful when some of the unknown risks are included in the contractor's price without major penalties that could occur if the design is inadequate. Risk sharing is especially useful if anticipated conditions can be defined within certain limits and the client takes the risk if the limits are exceeded. Examples of conditions that might not be expected include soil behavior, the hardness of rock, flood levels, extreme winds and currents. Considerable use is currently made of Geotechnical Baseline Reports to define anticipated ground conditions in this way.

Most claims in tunnel construction are related to unforeseen ground conditions. Therefore, the underground construction industry in the US tried to provide a viable trigger by means of the Differing Site Condition (DSC) clause, culminating in the use of the Geotechnical Baseline Report (GBR) and Geotechnical Data Report (GDR). It is important from a risk-sharing perspective that the contractual language in the DSC and the GBR are complementary. Chapter 4 discusses Geotechnical Baseline Reports. The contractor qualifications process is further discussed in Chapter 14-Construction Engineering

It is important to establish a selection process by which only qualified contractors can bid on tunneling projects, with fair contracts that would allocate risks equitably between the owner and the contractor, in order to have safe, on time, and high quality underground projects at fair costs.

1.4.4 Operation and Maintenance Cost Planning

Operations are divided into three main areas, traffic and systems control, toll facility (if any), and emergency services, not all of which may be provided for any particular tunnel. The staff needed in these areas would vary according to the size of the facility, the location, and the needs. For 24-hour operation, staff would be needed for three shifts and weekends; weekend and night shifts would require sufficient staff to deal with traffic and emergency situations.

The day-to-day maintenance of the tunnel generally requires a dedicated operating unit. Tunnel cleaning and roadway maintenance are important and essential for safe operation of the tunnel. Special tunnel cleaning equipment are usually employed. Mechanical, electrical, communication, ventilation, monitoring, and control equipment for the tunnel must be kept operational and in good working order, since faulty equipment could compromise public safety. Regular maintenance and 24-hour monitoring is essential, since failure of equipment such as ventilation, lights and pumps is unacceptable and must be corrected immediately. Furthermore, vehicle breakdowns and fires in the tunnel need immediate response.

Generally most work can be carried out during normal working hours including mechanical and electrical repair, traffic control, and the like. However, when the maintenance work involves traffic lane closure, such as changing lighting fixtures, roadway repairs, and tunnel washing, partial or full closure of the tunnel may be required. This is usually done at night or weekends.

Detailed discussions for the operation and maintenance issues are beyond the scope of this manual.

1.5 RISK ANALYSIS AND MANAGEMENT

Risk analysis and management is essential for any underground project. A risk register should be established as early as possible in the project development. The risk register would identify potential risks, their probability of occurrence and their consequences. A risk management plan should be established to deal with the various risks either by eliminating them or reducing their consequences by planning, design, or by operational provisions. For risks that cannot be mitigated, provisions must be made to reduce their consequences and to manage them. An integrated risk management plan should be regularly updated to identify all risks associated with the design, execution and completion of the tunnel.

The plan should include all reasonable risks associated with design, procurement and construction. It should also include risks related to health and safety, the public and to the environment.

Major risk categories include construction failures, public impact, schedule delay, environmental commitments, failure of the intended operation and maintenance, technological challenges, unforeseen geotechnical conditions, and cost escalation. This subject is discussed in detail in Chapter 14 Construction Engineering.

CHAPTER 2
GEOMETRICAL CONFIGURATION

Chapter 2 provides general geometrical requirements for planning and design of road tunnels. The topics consist of the following: horizontal and vertical alignments; clearance envelopes; and cross section elements. Geometrical requirements for the tunnel approaches and portals are also provided. In addition to the requirements addressed herein, the geometrical configurations of a road tunnel are also governed by its functionality and locality (see Chapter 1 - Planning), as well as the subsurface conditions (see Chapter 3 – Geotechnical Investigations) and its construction method (i.e. cut-and-cover (Chapter 5), mined and bored (Chapters 6-10), immersed (Chapter 11), etc.). It often takes several iterative processes from planning, environmental study, configuration, and preliminary investigation and design to eventually finalize the optimum alignment and cross section layout.

2.1 INTRODUCTION

As defined by the American Association of State Highway and Transportation Officials (AASHTO) Technical Committee for Tunnels (T-20), road tunnels are defined as enclosed roadways with vehicle access that is restricted to portals regardless of type of structure or method of construction. Road tunnels following this definition exclude enclosed roadway created by air-rights structures such as highway bridges, railroad bridges or other bridges. Figure 2-1 illustrates Tetsuo Harano Tunnels through the hillside in Hawaii as a part of the H3 highway system. The tunnels are restricted by portal access and connected to major approach freeway bridges.

Figure 2-1 H3 Tetsuo Harano Tunnels in Hawaii

In addition to the general roadway requirements, road tunnels also require special considerations including lighting, ventilation, fire protection systems, and emergency egress capacity. These considerations often impose additional geometrical requirement as discussed in the following sections.

2.1.1 Design Standards

Road tunnels discussed in this Manual cover all roadways including freeways, arterials, collectors, and local roads and streets in urban and rural locations following the functional classifications from FHWA publication "Highway Functional Classification: Concepts, Criteria, and Procedures". AASHTO's "Green Book" - A Policy on Geometric Design of Highways and Streets, which is adopted by Federal agencies, States, and most local highway agencies, provides the general design considerations used for road tunnels from the standpoint of service level, and suggests the requirements for road tunnels which should not differ materially from those used for grade separation structures. The Green Book (AASHTO, 2004) also provides general information and recommendations about cross section elements and other requirements specifically for road tunnels.

In addition to the Green Book (AASHTO, 2004), standards to be used for the design of geometrical configurations of road tunnels should generally comply with the following documents supplemented by recommendations given in this Manual. Additional criteria may include:

- AASHTO A Policy on Design Standards - Interstate System
- Standards issued by the state or states in which the tunnel is situated
- Local authority standards, where these are applicable
- National and local standards of the country where the international crossing tunnel is located

Although the geometrical requirements for roadway alignment, profile and for vertical and horizontal clearances in the above design standards generally apply to road tunnels, amid the high costs of tunneling and restricted right-of-way, minimum requirements are typically applied to planning and design of road tunnels to minimize the overall size of the tunnel yet maintain a safe operation through the tunnel. To ensure roadway safety, the geometrical design must evaluate design speed, lane and shoulder width, tunnel width, horizontal and vertical alignments, grade, stopping sight distance, cross slope, superelevation, and horizontal and vertical clearances, on a case by case basis.

In addition to the above highway design standards, geometrical design for road tunnels must consider tunnel systems such as fire life safety elements, ventilation, lighting, traffic control, fire detection and protection, communication, etc… Therefore, planning and design of the alignment and cross section of a road tunnel must also comply with National Fire Protection Association (NFPA) 502 – Standard for Road Tunnels, Bridges, and Other Limited Access Highways.

The recommendations in this Manual are provided as a guide for the engineer to exercise sound judgment in applying standards to the geometrical design of tunnels and generally base on 5th Edition (2004) of the Green Book and 2008 Edition of NFPA 502. The design standards used for a road tunnel project should equal or exceed the minimum given below in this Manual to the maximum extent feasible, taking into account costs, traffic volumes, safety requirements, right of way, socioeconomic and environmental impacts, without compromising safety considerations. The readers should always check with the latest requirements from the above references.

2.2 HORIZONTAL AND VERTICAL ALIGNMENTS

Planning and design of road tunnel alignments must consider the geological, geotechnical and groundwater conditions at the site as well as environmental constraints as discussed in Chapter 1 - Planning. Maximum grade, horizontal and vertical curves, and other requirement/constraints for road tunnel horizontal and vertical alignments are discussed in this Section.

2.2.1 Maximum Grades

Road tunnel grades should be evaluated on the basis of driver comfort while striving to reach a point of economic balance between construction costs and operating and maintenance expenses.

Maximum effective grades in main roadway tunnels preferably should not exceed 4%; although grades up to 6% have been used where necessary. Long or steep uphill grades may result in a need for climbing lanes for heavy vehicles. However, for economic and ventilation reasons, climbing lanes should be avoided within tunnels; the addition of a climbing lane part-way through a tunnel may also complicate construction considerably, particularly in a bored tunnel.

2.2.2 Horizontal and Vertical Curves

Horizontal and vertical curves shall satisfy Green Book's geometrical requirements. The horizontal alignment for a road tunnel should be as short as practical and maintain as much of the tunnel length on tangent as possible, which will limit the numbers of curves, minimize the length and improve operating efficiency. However, slight curves may be required to accommodate ventilation/access shafts location, portal locations, construction staging areas, and other ancillary facilities as discussed in Chapter 1 – Planning. A slight horizontal curve at the exit of the tunnel may be required to allow drivers to adjust gradually to the brightness outside the tunnel.

When horizontal curves are needed, the minimum acceptable horizontal radii should consider traffic speed, sight distances, and the super-elevation provided. In general, for planning purpose, the curve radii should be as large as possible and no less than 850 to 1000-ft radius. A tighter curve may be considered at the detailed design stage based on the selected tunneling method.

Super elevation rate, which is the rise in the roadway surface elevation from the inside to the outside edge of the road, should preferably lie in the range 1% to 6%.

When chorded construction is used for walls where alignments are curved, chord lengths should not exceed 25 feet (7.6 m) for radii below 2,500 feet (762 m), and 50 feet (15 m) elsewhere.

2.2.3 Sight and Braking Distance Requirements

Sight and braking distance requirements cannot be relaxed in tunnels. On horizontal and vertical curves, it may be necessary to widen the tunnel locally to meet these requirements by providing a "sight shelf". When designing a tunnel with extreme curvature, sight distance should be carefully examined, otherwise it may result in limited stopping sight distance.

2.2.4 Other Considerations

Road tunnels with more than one traffic tube should be designed so that in the event that one tube is shut down, traffic can be carried in the other. For reasons of safety, it is not recommended that tunnels be constructed for bi-directional traffic; however, they should be designed to be capable of handling bi-directional traffic during maintenance work, which should be carried out at times of low traffic volume such as at night or weekends. When operating in a bi-directional mode, appropriate signage must be provided. In addition, suitable cross-over areas are required, usually provided outside the tunnel entrances, and the ventilation system and signage must be designed to handle bi-directional traffic.

For bored and mined tunnels, it is probable that separate tunnels are constructed for traffic in each direction. For cut-and-cover, jacked and immersed tunnels, it is preferable for the traffic tubes for the two directions to be constructed within a single structure so that emergency egress by vehicle occupants into a neighboring traffic tube can be provided easily. Note that NFPA 502-2008 requires that the two tubes be divided by a minimum of 2-hour fire rated construction in order to consider cross-passageways between the tunnels to be utilized in lieu of emergency egress.

In addition to structural requirements, inundation of the tunnel by floods, surges, tides and waves, or combinations thereof resulting from storms must be prevented. The height and shape of walls surrounding tunnel entrances, the elevation of access road surfaces and any entrances, accesses and holes must be designed such that entry of water is prevented. It is recommended that water level with the probability of being exceeded no more than 0.005 times in any one year (the 500-year flood level) be used as the design water level.

2.3 TRAVEL CLEARANCE

Clearance diagram of all potential vehicles traversing the tunnel shall be established using dynamic vehicle envelopes which consider not just the maximum allowable static envelope, but also other dynamic factors such as bouncing, suspension failure, overhang on curves, lateral motion, resurfacing, etc.

The clearance diagram should take into consideration potential future vehicle heights, vehicle mounting on curbs, construction tolerances, and any potential ground and structure settlement. Ventilation equipment, lighting, guide signs, and other equipment should not encroach within the clearance diagram.

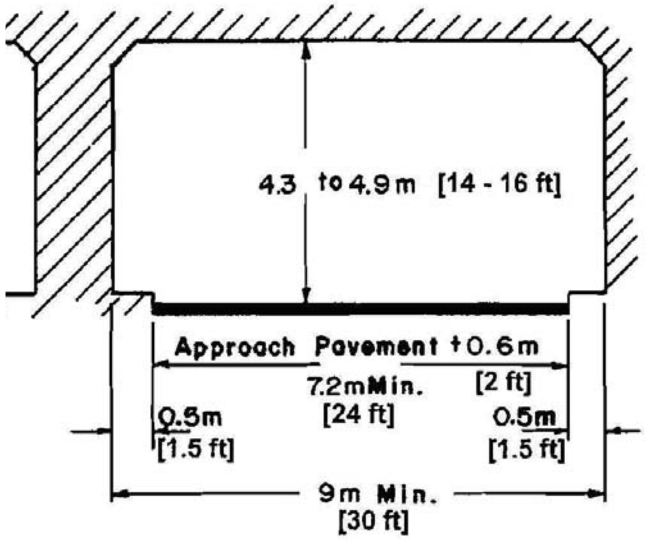
Vertical clearance should be selected as economical as possible consistent with the vehicle size (see Chapter 1). The 5th Edition of AASHTO Green Book (2004) recommends that the minimum vertical clearance to be 16 feet (4.9 m) for highways and 14 feet (4.3 m) for other roads and streets. Note that the minimum clear height should not be less than the maximum height of load that is legal in a particular state.

Figure 2-2 illustrates the minimum and desirable clearance diagrams for two lane tunnels as recommended by the 5th Edition of the Green Book (AASHTO, 2004).

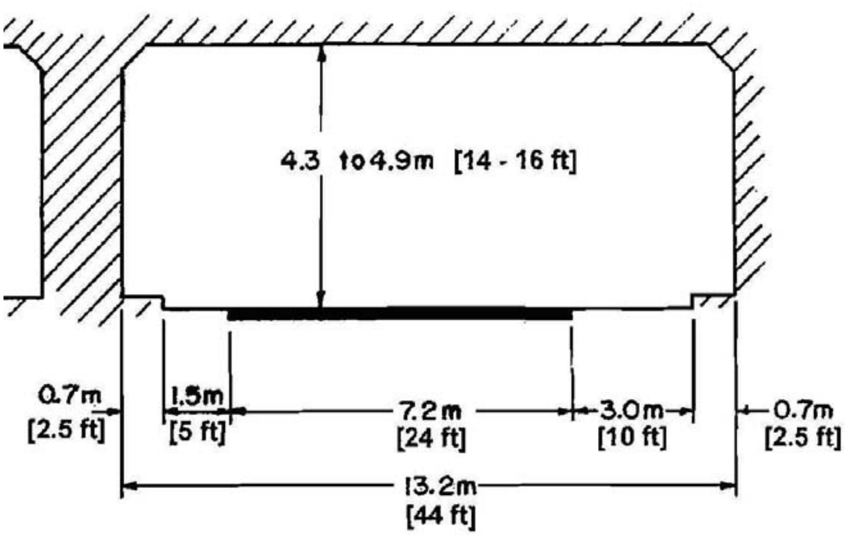
Figure 2-2(a) illustrates the minimum clearance diagram for a two-lane tunnel which indicates the minimum horizontal curb-to-curb and wall-to-wall clearances to be no less than 24 ft (7.2-m) and 30 ft (9-m), respectively. The curb-to-curb (including shoulders) clearance is also required to be 2 ft (0.6m) greater than the lane widths of the approach traveled way. Therefore, for an approach structure with two standard 12-ft lane widths, the minimum horizontal curb-to-curb clearance for the connecting two-lane tunnel should be no less than 26 ft (7.8 m).

Figure 2-2 (b) illustrates the desirable curb-to-curb and wall-to-wall clearances for a two-lane tunnel to be 39 ft (11.7m) and 44 ft (13.2m), respectively.

The vertical clearance shall also take into consideration for future resurfacing of the roadway. Although it is recommended to resurface roadways in tunnels only after the previous surface has been removed, it is prudent to provide limited allowances for resurfacing once without removal of the old pavement. Consideration should also be given for potential truck mounting on the barrier in the tunnel or on low sidewalk and measures shall be used to prevent such mounting from damaging the tunnel ceiling or tunnel system components mounted on the ceiling or the walls. The designer must follow the latest edition of the Green Book.



Minimum (a)



Desirable (b)

Figure 2-2 Typical Two-Lane Tunnel Clearance Requirements - Minimum (a) and Desirable (b) (After AASHTO, 2004)

Tunnel ventilation ducts, if required, can be provided above or below the traffic lanes, or to the sides of them. Where clearances to the outside of the tunnel at a particular location are such that by moving ventilation from overhead to the sides can reduce the tunnel gradients or reduce its length, such an option should be considered.

Over-height warning signals and diverging routes should be provided before traffic can reach the tunnel entrances. The designated traffic clearance should be provided throughout the approaches to the tunnel.

2.4 CROSS SECTION ELEMENTS

2.4.1 Typical Cross Section Elements

Although many road tunnels appear rectangular from inside bordered by the walls, ceiling and pavement (Figure 2-3), the actual tunnel shapes may not be rectangular. As described in Chapter 1, there are generally three typical shapes of tunnels – circular, rectangular, and horseshoe/ curvelinear. The shape of a tunnel section is mainly decided by the ground condition and construction methods as discussed in Chapter 1.

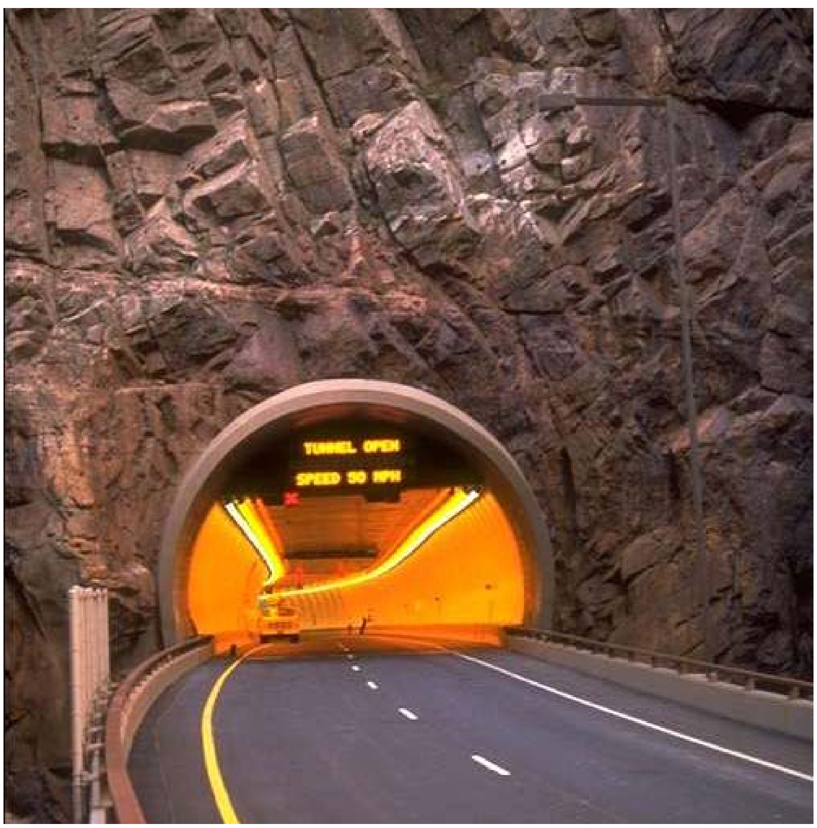


Figure 2-3 A Typical Horseshoe Section for a Two-lane Tunnel (Glenwood Canyon, Colorado)

A road tunnel cross section must be able to accommodate the horizontal and vertical traffic clearances (Section 2.3), as well as the other required elements. The typical cross section elements (Figure 2-4) include:

- Travel lanes
- Shoulders
- Sidewalks/Curbs
- Tunnel drainage
- Tunnel ventilation
- Tunnel lighting
- Tunnel utilities and power
- Water supply pipes for firefighting
- Cabinets for hose reels and fire extinguishers
- Signals and signs above roadway lanes
- CCTV surveillance cameras
- Emergency telephones
- Communication antennae/equipment
- Monitoring equipment of noxious emissions and visibility
- Emergency egress illuminated signs at low level (so that they are visible in case of a fire or smoke condition)

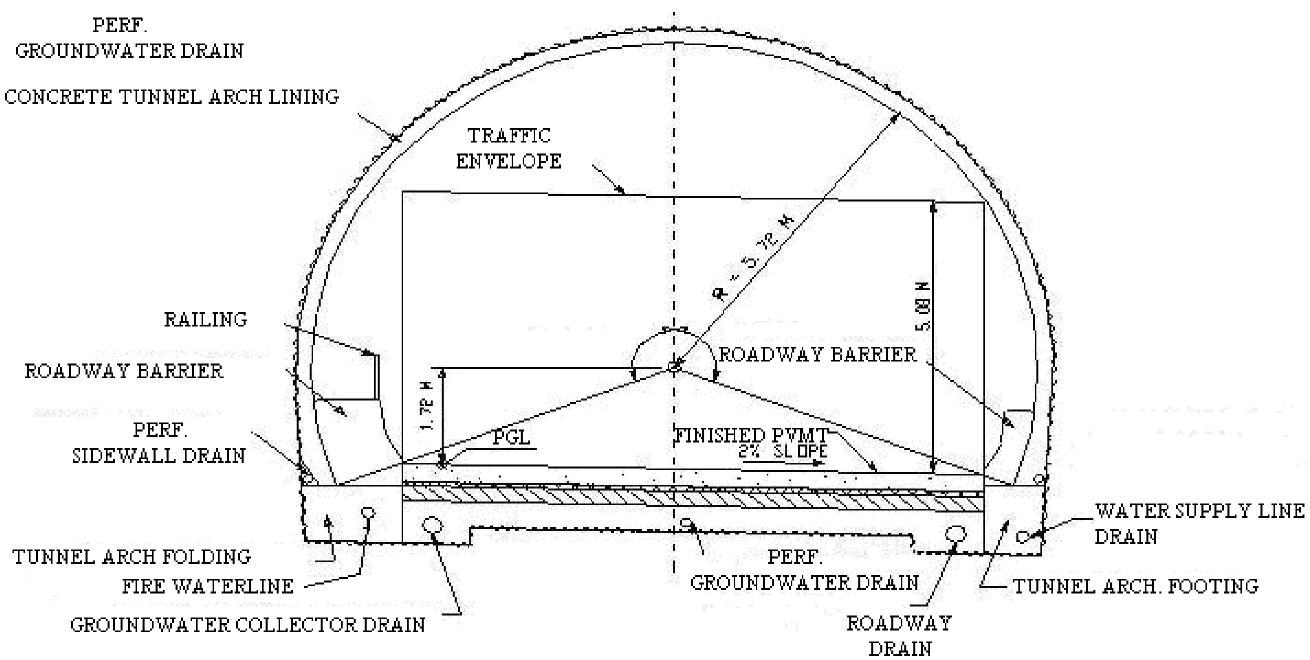


Figure 2-4 Typical Two-Lane Road Tunnel Cross Section and Elements

Additional elements may be needed under certain design requirements and should be taken into consideration when developing the tunnel geometrical configuration. The requirements for travel lane and shoulder width, sidewalks/emergency egress, drainage, ventilation, lighting, and traffic control are discussed in the following sections. Other elements cited above are required for fire and safety protection for tunnels longer than 1000 ft (300m) or 800 ft (240m) long if the maximum distance from any point within the tunnel to a point of safety exceeds 400 ft (120m) (NFPA, the latest). Fire and safety protection requirements are not within the scope of this manual. Refer to Appendix A, and the latest NFPA 502 Standard for requirement for fire and safety protection elements.

2.4.2 Travel Lane and Shoulder

As discussed previously, for planning and design purposes, each lane width within a road tunnel should be no less than 12 feet (3.6 m) as recommended in the 5th Edition of Green Book (AASHTO, 2004).

Although the Green Book states that it is preferable to carry the full left- and right-shoulder widths of the approach freeway through the tunnel, it also recognizes that the cost of providing full shoulder widths may be prohibitive. Reduction of shoulder width in road tunnels is usual. In certain situations narrow shoulders are provided on one or both sides. Sometimes shoulders are eliminated completely and replaced by barriers. Based on a study conducted by World Road Association (PIARC) and published a report entitled "Cross Section Geometry in Unidirectional Road Tunnels" 2001; shoulder widths vary from country to country and they range from 0 to 2.75 m (9 ft). They are generally in the range of 1 m (3.3 ft). It is suggested for unidirectional road tunnels that the right shoulder be at 4 ft (1-2 m) and left shoulder at least 2 ft (0.6 m).

Figure 2-2(A) does not show a minimum requirement for a shoulder in a tunnel, except it requires that a minimum 2 feet (0.6m) be added to the travel lane width of the approach structure. The Green Book also recommends that the determination of the width of shoulders be established on an in-depth analysis of all aspects involved. Where it is not realistic (for economic or constructability considerations) to provide shoulders at all in a tunnel, travel delays may occur when vehicle(s) become inoperative during periods of heavy traffic. In long tunnels, emergency alcoves are sometimes provided to accommodate disabled vehicles.

To prevent errant vehicles from hitting the walls of the tunnel, a deflecting concrete barrier with a sloping or partially sloping face is commonly used. The height of the barrier should not be so great that it is perceived by drivers of low vehicles to be narrowing the width to the wall nor should it be too low to allow vehicles to mount it. A barrier of 3.3 ft (1 m) is common. A reduced shoulder width from a traveled way to the face of the adjacent barrier ranging between 2 and 4 feet (between 0.6 and 1.2 m) has been found to be acceptable.

Figure 2-5 illustrates an example of a typical tunnel roadway section including and two standard 12 ft lane widths and two reduced shoulder widths. Refer to Section 2.4.3 for the requirements for the barriers when used as the raised sidewalks or emergency egress walkways.

2.4.3 Sidewalks/Emergency Egress Walkway

Although pedestrians are typically not permitted in road tunnels, sidewalks are required in road tunnels to provide emergency egress and access by maintenance personnel. The 5th Edition of Green Book recommends that raised sidewalks or curbs with a width of 2.5 ft (0.7 m) or wider beyond the shoulder area are desirable to be used as an emergency egress, and that a raised barrier to prevent the overhang of vehicles from damaging the wall finish or the tunnel lighting fixtures be provided.

In addition, NFPA 502 requires an emergency egress walkway within the cross-passageways be of a minimum clear width of 3.6 ft (1.12 m).

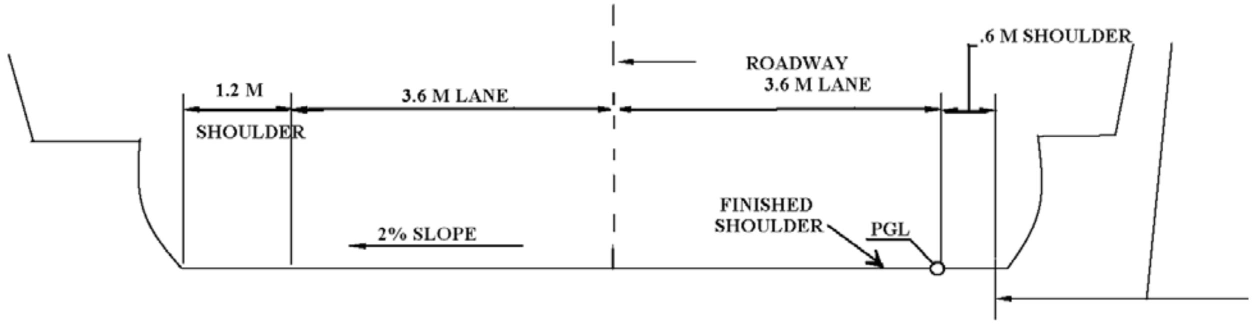


Figure 2-5 Typical Tunnel Roadway with Reduced Shoulder Widths

2.4.4 Tunnel Drainage Requirements

Road tunnels must be equipped with a drainage system consisting of pipes, channels, sump/pump, oil/water separators and control systems for the safe and reliable collection, storage, separation and disposal of liquid/ effluent from the tunnels that might otherwise collect. Drainage must be provided in tunnels to deal with surface water as well as water leakage. However, drainage lines and sump-pumps should be sized to accommodate water intrusion and/or fire fighting requirements. They should be designed so that fire would not spread through the drainage system into adjacent tubes by isolating them. For the safety reason, PVC, fiberglass pipe, or other combustible materials should not be used.

Sumps should be provided with traps to collect and remove solids. Sand traps should be provided, as well as oil and fuel separators. It may be assumed in sizing sumps that fires and storms do not happen simultaneously. Sumps and pumps should be located at low points of a tunnel and at portals to handle water that might otherwise flow into the tunnel. Sumps should be sized to match the duty cycle of the discharge pumps such that inflow does not cause sump capacity to be exceeded. Sumps should be designed to be capable of being cleaned regularly.

2.4.5 Ventilation Requirements

The ventilation system of a tunnel operates to maintain acceptable air quality levels for short-term exposure within the tunnel. The design may be driven either by fire/safety considerations or by air quality; which one governs depends upon many factors including traffic, size and length of the tunnel, and any special features such as underground interchanges.

Ventilation requirements in a highway tunnel are determined using two primary criteria, the handling of noxious emissions from vehicles using the tunnel and the handling of smoke during a fire. Computational fluid dynamics (CFD) analyses are often used to establish an appropriate design for the ventilation under fire conditions. An air quality analysis should also be conducted to determine whether air quality might govern the design. Air quality monitoring points in the tunnel should be provided and the ventilation should be adjusted based on the traffic volume to accommodate the required air quality.

Environmental impacts and air quality may affect the locations of ventilation structures/buildings, shafts and portals. Analyses should take into account current and future development, ground levels, the heights and distances of sensitive receptors near such locations and the locations of operable windows and terraces of adjacent buildings to minimize impacts. Ventilation buildings have also been located below grade and exhaust stacks hidden within other structures.

The two main ventilation system options used for tunnels are longitudinal ventilation and transverse ventilation. A longitudinal ventilation system introduces air into, or removes air from a road tunnel, with the longitudinal flow of traffic, at a limited number of points such as a ventilation shaft or a portal. It can be sub-classified as either using a jet fan system or a central fan system with a high-velocity (Saccardo) nozzle. The use of jet fan based longitudinal system was approved by the FHWA in 1995 based on the results of the Memorial Tunnel Fire Ventilation Test Program (NCHRP, 2006). Generally, it includes a series of axial, high-velocity jet fans mounted at the ceiling level of the road tunnel to induce a longitudinal air-flow through the length of the tunnel as shown in Figure 2-6.

Figure 2-6 Ventilation System with Jet Fans at Cumberland Gap Tunnel

A transverse ventilation system can be either a full or semi-full transverse type. With full transverse ventilation, air supply ducts are located above, below or to the side of the traffic tube and inject fresh air into the tunnel at regular intervals. Exhaust ducts are located above or to the side of the traffic tube and remove air and contaminants. With semi-transverse ventilation, the supply duct is eliminated with its "duties" taken over by the traffic opening. When supply or exhaust ducts are used, the flow is generated by fans grouped together in ventilation buildings. Local noise standards generally would require noise attenuators at the fans or nozzles.

Selection of the appropriate ventilation system obviously has a profound impact on the tunnel alignment, layout, and cross section design. Detailed discussion of tunnel ventilation design is not within the scope of this manual.

2.4.6 Lighting Requirements

Lighting in tunnels assists the driver in identifying hazards or disabled vehicles within the tunnel while at a sufficient distance to safely react or stop. High light levels (Portal light zone) are usually required at the beginning of the tunnel during the daytime to compensate for the “Black Hole Effect” that occurs by the tunnel structure shadowing the roadway as shown on Figure 2-7. These high light levels will be used only during daytime. Tunnel light fixtures are usually located in the ceiling, or mounted on the walls near the ceiling. Tunnel lighting methods and guidelines are not within the scope of this manual. However, the location, size, type, and number of light fixtures impact the geometrical requirements of the tunnel and should be taken into consideration.

Figure 2-7 “Black Hole” (Left) and Proper Lighting (Right)

The tunnel lighting documents issued by the IESNA (ANSI/IESNA RP-22 Recommended Practice for Tunnel Lighting) and the CIE (CIE-88 Guide for the Lighting of Road Tunnels and Underpasses) offer comprehensive approaches to tunnel lighting. The AASHTO Roadway Lighting Design Guide provides some recommendations for road tunnels as well.

For improved safety during a fire, it is suggested that strobe lights be placed to identify exit routes. If used they should be placed around exit doors, especially at lower levels which might then be under the smoke level. The strobe lights would be activated only during tunnel fires. Emergency lighting in tunnels including wiring methods and other requirements are included in NFPA 502 “Standard for Road Tunnels, Bridges and Other Limited Access Highways”, PIARC “Fire and Smoke Control in Road Tunnels”, and in the findings of the 2005 FHWA/AASHTO European Scan Tour (Appendix A) .

2.4.7 Traffic Control Requirements

The latest NFPA 502 Standard mandates that tunnels 300 ft (90 m) in length should be provided with a means to stop traffic approaching portals (external). In addition, the NFPA 502 also specifies that traffic control means within the tunnel 800 feet (240 m) in length are required. These should include lane control signals, over-height warning signals, changeable message signs (CMS), etc. Traffic control may be required to close and open lanes for maintenance and handling accidents, and for monitoring of vehicles carrying prohibited materials. Incident control systems linked to CCTV cameras should be installed. It is recommended that 100% coverage of the tunnel with CCTV be provided. Refer to the latest NFPA 502 for more detailed requirements. Traffic control requirements should be taken into consideration when developing the cross sectional geometry.

2.4.8 Portals and Approach

Tunnel portals may require special design considerations. Portal sites need to be located in stable ground with sufficient space. Orientation of the portals should avoid if possible direct East and West to avoid blinding sunlight. Ameliorating measures should be taken where drivers might otherwise be blinded by the rising or setting sun. Intermittent cross members are sometimes provided across the approach structure above the traffic lanes as an amelioration measure. A central dividing wall sometime is extended some distance out from the portal to prevent recirculation of polluted air, i.e. vented polluted air from one traffic duct is prevented from entering an adjacent duct as "clean" air.

Tunnels with a high traffic volume and long tunnels should be equipped with emergency vehicles at each end with potential access to all traffic tubes. Wrecker trucks should be capable of pushing a disabled vehicle as well as the more traditional method of towing. These vehicles should preferably be equipped with some fire-fighting equipment, the extent of which depending upon the distance to the nearest fire department. At least, they should carry dry chemical fire extinguishers.

If the tunnel is in a remote rural area where responses of nearby fire companies and emergency squads are not available in a timely matter, a larger portal structure as shown in Figure 2-8 may be required to host the operation control center, as well as the fire-fighting and emergency-responding personnel, equipment and vehicles.

In determining portal locations and where to end the approach structure and retaining walls, protection should be provided against flooding resulting from high water levels near bodies of water and tributary watercourses, or from storm runoff. The height of the portal end wall and the approach retaining walls should be set to a level at least 2 ft (0.6m) higher than the design flood level. Alternatively a flood gate can be provided. Adequate provision should be made for immediate and effective removal of water from rainfall, drainage, groundwater seepage, or any other source. Portal cross drain and sump-pump should be provided.

Figure 2-8 Portal Structure for Cumberland Gap Tunnel

CHAPTER 3
GEOTECHNICAL INVESTIGATIONS

3.1 INTRODUCTION

To successfully plan, design and construct a road tunnel project requires various types of investigative techniques to obtain a broad spectrum of pertinent topographic, geologic, subsurface, geo-hydrological, and structure information and data. Although most of the techniques and procedures are similar to those applied for roadway and bridge projects, the specific scope, objectives and focuses of the investigations are considerably different for tunnel and underground projects, and can vary significantly with subsurface conditions and tunneling methods.

A geotechnical investigation program for a tunnel project must use appropriate means and methods to obtain necessary characteristics and properties as basis for planning, design and construction of the tunnel and related underground facilities, to identify the potential construction risks, and to establish realistic cost estimate and schedule. The extent of the investigation should be consistent with the project scope (i.e., location, size, and budget), the project objectives (i.e., risk tolerance, long-term performance), and the project constraints (i.e., geometry, constructability, third-party impacts, aesthetics, and environmental impact). It is important that the involved parties have a common understanding of the geotechnical basis for design, and that they are aware of the inevitable risk of not being able to completely define existing subsurface conditions or to fully predict ground behavior during construction.

Generally, an investigation program for planning and design of a road tunnel project may include the following components:

- Existing Information Collection and Study
- Surveys and Site Reconnaissance
- Geologic Mapping
- Subsurface Investigations
- Environmental Studies
- Seismicity
- Geospatial Data Management

It is beyond the scope of this manual to discuss each of the above components in details. The readers are encouraged to review the FHWA and AASHTO references provided in this Chapter for more details. Similar investigations and monitoring are often needed during and after the construction to ensure the problems that occurred during construction are rectified or compensated, and short term impacts are reversed. Geotechnical investigations after construction are not discussed specifically in this Chapter.

3.1.1 Phasing of Geotechnical Investigations

Amid the higher cost of a complete geotechnical investigation program for a road tunnel projects (typically about 3% to 5% of construction cost), it is more efficient to perform geotechnical investigations in phases to focus the effort in the areas and depths that matter. Especially for a road tunnel through mountainous terrain or below water body (Figure 3-1), the high cost, lengthy duration, limited access, and limited coverage of field investigations may demand that investigations be carried out in several phases to obtain the information necessary at each stage of the project in a more cost-efficient manner.

Figure 3-1 Water Boring Investigation from a Barge for the Port of Miami Tunnel, Miami, FL

Furthermore, it is not uncommon to take several decades for a road tunnel project to be conceptualized, developed, designed, and eventually constructed. As discussed in Chapter 1, typical stages of a road tunnel project from conception to completion are:

- Planning
- Feasibility Study
- Corridor and Alignment Alternative Study
- Environmental Impact Studies (EIS) and Conceptual Design
- Preliminary Design
- Final Design
- Construction

Throughout the project development, the final alignment and profile may often deviate from those originally anticipated. Phasing of the geotechnical investigations provides an economical and rational approach for adjusting to these anticipated changes to the project.

The early investigations for planning and feasibility studies can be confined to information studies and preliminary reconnaissance. Geological mapping and minimum subsurface investigations are typically required for EIS, alternative studies and conceptual design. EIS studies may also include limited topographical and environmental investigations to identify potential "fatal flaws" that might stop the project at a later date. A substantial portion of the geotechnical investigation effort should go into the Preliminary Design Phase to refine the tunnel alignment and profile once the general corridor is selected, and to provide the detailed information needed for design. As the final design progresses, additional test borings might be required for fuller coverage of the final alignment and for selected shaft and portal locations. Lastly, depending on the tunneling method selected, additional investigations may be required to confirm design assumptions, or to provide information for contractor design of temporary works. Figure 3-2 illustrates the flow process of the phases of investigations.

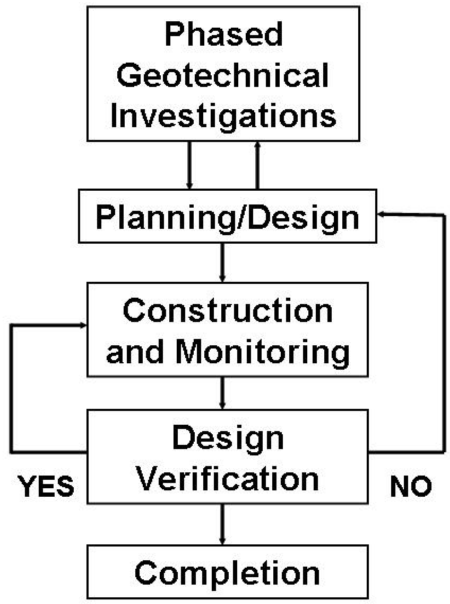


Figure 3-2 Phased Geotechnical Investigations with Project Development Process

This Chapter discusses the subsurface investigation techniques typically used for planning, design and construction of road tunnels. Additional information on this subject is available from FHWA Geotechnical Engineering Circular No. 5 (FHWA, 2002a), FHWA Reference Manual for Subsurface Investigations – Geotechnical Site Characterization (FHWA, 2002b), FHWA Reference Manual for Rock Slopes (FHWA, 1999), and AASHTO Manual on Subsurface Investigations (AASHTO, 1988).

3.2 INFORMATION STUDY

3.2.1 Collection and Review of Available Information

The first phase of an investigation program for a road tunnel project starts with collection and review of available information to develop an overall understanding of the site conditions and constraints at little cost. Existing data can help identify existing conditions and features that may impact the design and construction of the proposed tunnel, and can guide in planning the scope and details of the subsurface investigation program to address these issues.

Published topographical, hydrological, geological, geotechnical, environmental, zoning, and other information should be collected, organized and evaluated. In areas where seismic condition may govern or influence the project, historical seismic records are used to assess earthquake hazards. Records of landslides caused by earthquakes, documented by the USGS and some State Transportation Departments, can be useful to avoid locating tunnel portals and shafts at these potentially unstable areas.

In addition, case histories of underground works in the region are sometimes available from existing highway, railroad and water tunnels. Other local sources of information may include nearby quarries, mines, or water wells. University publications may also provide useful information.

Table 3-1 presents a summary list of potential information sources and the type of information typically available.

Today, existing data are often available electronically, making them easier to access and manage. Most of the existing information such as aerial photos, topographical maps, etc. can be obtained in GIS format at low or no cost. Several state agencies are developing geotechnical management systems (GMS) to store historical drilling, sampling, and laboratory test data for locations in their states. An integrated project geo-referenced (geospatial) data management system will soon become essential from the initiation of the project through construction to store and manage these extensive data instead of paper records. Such an electronic data management system after the project completion will continue to be beneficial for operation and maintenance purposes. Geospatial data management is discussed in Section 3.9.

3.2.2 Topographical Data

Topographic maps and aerial photographs that today can be easily and economically obtained, are useful in showing terrain and geologic features (i.e., faults, drainage channels, sinkholes, etc.). When overlapped with published geological maps they can often, by interpretation, show geologic structures. Aerial photographs taken on different dates may reveal the site history in terms of earthwork, erosion and scouring, past construction, etc.

U.S. Geological Survey (USGS) topographic maps (1:24,000 series with 10 ft or 20 ft contours) may be used for preliminary route selection. However, when the project corridor has been defined, new aerial photography should be obtained and photogrammetric maps should be prepared to facilitate portal and shaft design, site access, right-of-way, drainage, depth of cover, geologic interpretation and other studies.

3.3 SURVEYS AND SITE RECONNAISSANCE

3.3.1 Site Reconnaissance and Preliminary Surveys

As discussed previously, existing lower-resolution contour maps published by USGS or developed from photogrammetric mapping, are sufficient only for planning purposes. However, a preliminary survey will be needed for concept development and preliminary design to expand existing topographical data and include data from field surveys and an initial site reconnaissance. Initial on-site studies should start with a careful reconnaissance over the tunnel alignment, paying particular attention to the potential portal and shaft locations. Features identified on maps and air photos should be verified. Rock outcrops, often exposed in highway and railroad cuts, provide a source for information about rock mass fracturing and bedding and the location of rock type boundaries, faults, dikes, and other geologic features. Features identified during the site reconnaissance should be photographed, documented and if feasible located by hand-held GPS equipment.

Table 3-1 Sources of Information Data (After FHWA, 2002a)

Source	Functional Use	Location	Examples
Aerial Photographs	• Identifies manmade structures • Provides geologic and hydrological information which can be used as a basis for site reconnaissance • Track site changes over time	Local Soil Conservation Office, United States Geological Survey (USGS), Local Library, Local and National aerial survey companies	Evaluating a series of aerial photographs may show an area on site which was filled during the time period reviewed
Topographic Maps	• Provides good index map of the site • Allows for estimation of site topography • Identifies physical features and structures • Can be used to assess access restrictions • Maps from multiple dates indicate changes in land use	USGS and State Geological Survey	Engineer identifies access areas/restrictions, identifies areas of potential slope instability; and can estimate cut/fill capacity before visiting the site
Geologic Maps and Reports	• Provides information on local soil/rock type and characteristics; hydrogeological issues, environmental concerns	USGS and State Geological Survey	A twenty year old report on regional geology identifies rock types, fracture and orientation and groundwater flow patterns
Prior Subsurface Investigation Reports	• Provides information on local soil/rock type; strength parameters; hydrogeological issues; foundation types previously used; environmental concerns	State DOTs, USGS, United States Environmental Protection Agency (US EPA)	A five year old report for a nearby roadway widening project provides geologic, hydrogeologic, and geotechnical information for the area, reducing the scope of the investigation
Prior Underground and Foundation Construction Records	• Provides information on local soil/rock type; strength parameters; hydrogeological issues; environmental concerns; tunnel construction methods and problems	State DOTs, US EPA Utility agencies; Railroads	Construction records from a nearby railroad tunnel alerted designer to squeezing rock condition at shear zone
Water Well Logs	• Provide stratigraphy of the site and/or regional areas • Yield rate and permeability • Groundwater levels	State Geological Survey; Municipal Governments; Water Boards	A boring log of a water supply well two miles from the proposed tunnel shows site stratigraphy facilitating interpretation of local geology
Flood Insurance Maps	• Identifies 100 to 500 yr. Floodplains near water bodies • May prevent construction in a floodplain • Provide information for evaluation of scour potential	Federal Emergency Management Agency (FEMA), USGS, State/Local Agencies	Prior to investigation, the flood map shows that the site is in a 100 yr floodplain and the proposed structure is moved to a new location
Sanborn Fire Insurance Maps	• Useful in urban areas • For many cities provides continuous record for over 100 yrs. • Identifies building locations and type • Identifies business type at a location (e.g., chemical plant) • May highlight potential environmental problems at an urban site	State Library/Sanborn Company (www. Sanborncompany.com)	A 1929 Sanborn map of St. Louis shows that a lead smelter was on site for 10 years. This information helps identify a local contaminated area.

The reconnaissance should cover the immediate project vicinity, as well as a larger regional area so that regional geologic, hydrologic and seismic influences can be accounted for.

A preliminary horizontal and vertical control survey may be required to obtain general site data for route selection and for design. This survey should be expanded from existing records and monuments that are based on the same horizontal and vertical datum that will be used for final design of the structures. Additional temporary monuments and benchmarks can be established, as needed, to support field investigations, mapping, and environmental studies.

3.3.2 Topographic Surveys

As alternatives are eliminated, detailed topographic maps, plans and profiles must be developed to establish primary control for final design and construction based on a high order horizontal and vertical control field survey. On a road tunnel system, centerline of the roadway and centerline of tunnel are normally not identical because of clearance requirements for walkways and emergency passages as discussed in Chapter 2. A tunnel centerline developed during design should be composed of tangent, circular, and transition spiral sections that approximate the complex theoretical tunnel centerline within a specified tolerance (0.25 in.). This centerline should be incorporated into the contract drawings of the tunnel contract, and all tunnel control should be based on this centerline. During construction, survey work is necessary for transfer of line and grade from surface to tunnel monuments, tunnel alignment control, locating and monitoring geotechnical instrumentation (particularly in urban areas), as-built surveys, etc. Accurate topographic mapping is also required to support surface geology mapping and the layout of exploratory borings, whether existing or performed for the project. The principal survey techniques include:

- Conventional Survey
- Global Positioning System (GPS)
- Electronic Distance Measuring (EDM) with Total Stations.
- Remote Sensing
- Laser Scanning

The state-of-art surveying techniques are discussed briefly below. Note that the accuracies and operation procedures of these techniques improve with time so the readers should seek out up-to-date information when applying these techniques for underground projects.

<u>Global Positioning System (GPS)</u> utilizes the signal transit time from ground station to satellites to determine the relative position of monuments in a control network. GPS surveying is able to coordinate widely spaced control monuments for long range surveys, as well as shorter range surveys. The accuracy of GPS measurement is dependent upon the number of satellites observed, configuration of the satellite group observed, elapsed time of observation, quality of transmission, type of GPS receiver, and other factors including network design and techniques used to process data. The drawback for GPS survey is its limitation in areas where the GPS antenna cannot establish contact with the satellites via direct line of sight, such as within tunnels, downtown locations, forested areas, etc.

<u>Electronic Distance Measuring (EDM)</u> utilizes a digital theodolite with electronic microprocessors, called a "total station" instrument, which determines the distance to a remote prism target by measuring the time required for a laser or infrared light to be reflected back from the target. EDM can be used for accurate surveys of distant surfaces that would be difficult or impractical to monitor by conventional survey techniques. EDM can be used for common surveying applications, but is particularly useful for

economically monitoring displacement and settlement with time, such as monitoring the displacement and settlement of an existing structure during tunneling operations.

Remote Sensing can effectively identify terrain conditions, geologic formations, escarpments and surface reflection of faults, buried stream beds, site access conditions and general soil and rock formations. Remote sensing data can be easily obtained from satellites (i.e. LANDSAT images from NASA), and aerial photographs, including infrared and radar imagery, from the USGS or state geologists, U.S. Corps of Engineers, and commercial aerial mapping service organizations. State DOT aerial photographs, used for right-of-way surveys and road and bridge alignments, may also be available.

Laser Scanning utilizes laser technology to create 3D digital images of surfaces. Laser scanning equipment can establish x, y and z coordinates of more than one thousand points per second, at a resolution of about 0.25 inch over a distance of more than 150 feet. Laser scanning can be used to quickly scan and digitally record existing slopes to determine the geometry of visible features, and any changes with time. These data may be useful in interpreting geologic mapping data, for assessing stability of existing slopes, or obtaining as-built geometry for portal excavations. In tunnels, laser scanning can efficiently create cross sections at very close spacing to document conditions within existing tunnels (Figure 3-3), verify geometry and provide as-built sections for newly constructed tunnels, and to monitor tunnel deformations with time.

Figure 3-3 3D Laser Scanning Tunnel Survey Results in Actual Scanned Points

3.3.3 Hydrographical Surveys

Hydrographic surveys are required for subaqueous tunnels including immersed tunnel (Chapter 11), shallow bored tunnel, jacked box tunnel, and cofferdam cut-and-cover river crossings to determine bottom topography of the water body, together with water flow direction and velocity, range in water level, and potential scour depth. In planning the hydrographic survey, an investigation should be made to determine the existence and location of submarine pipelines, cables, natural and sunken obstructions, rip rap, etc. that may impact design or construction of the immersed tunnel or cofferdam cut-and-cover tunnel. Additional surveys such as magnetometer, seismic sub-bottom scanning, electromagnetic survey, side scan sonar, etc., may be required to detect and locate these features. These additional surveys may be done simultaneously or sequentially with the basic hydrographic survey. Data generated from the hydrographic survey should be based on the same horizontal coordinate system as the project control surveys, and should be compatible with the project GIS database. The vertical datum selected for the hydrographic survey should be based on the primary monument elevations, expressed in terms of National Geodetic Vertical Datum of 1929 (NGVD), Mean Lower Low Water Datum, or other established project datum.

3.3.4 Utility Surveys

Utility information is required, especially in the urban areas, to determine the type and extent of utility protection, relocation or reconstruction needed. This information is obtained from surveys commissioned for the project, and from existing utility maps normally available from the owners of the utilities (utility companies, municipalities, utility districts, etc.). Utility surveys are performed to collect new data, corroborate existing data, and composite all data in maps and reports that will be provided to the tunnel designer. The requirement for utility information varies with tunneling methods and site conditions. Cut-and-cover tunnel and shallow soft ground tunnel constructions, particularly in urban areas, extensively impacts overlying and adjacent utilities. Gas, steam, water, sewerage, storm water, electrical, telephone, fiber optic and other utility mains and distribution systems may require excavation, rerouting, strengthening, reconstruction and/or temporary support, and may also require monitoring during construction.

The existing utility maps are mostly for informational purposes, and generally do not contain any warranty that the utility features shown actually exist, that they are in the specific location shown on the map, or that there may be additional features that are not shown. In general, surface features such as manholes and vaults tend to be reasonably well positioned on utility maps, but underground connections (pipes, conduits, cables, etc.) are usually shown as straight lines connecting the surface features. During original construction of such utilities, trenching may have been designed as a series of straight lines, but, in actuality, buried obstructions such as boulders, unstable soil or unmapped existing utilities necessitated deviation from the designed trench alignment. In many instances, as-built surveys were never done after construction, and the design map, without any notation of as-constructed alignment changes, became the only map recording the location of the constructed utilities.

In well-developed areas, it may not be realistic to attempt to locate all utilities during the design phase of a project without a prohibitive amount of investigation, which is beyond the time and cost limitations of the designer's budget. However, the designer must perform a diligent effort to minimize surprises during excavation and construction. Again, the level of due diligence depends on the method of excavation (cut-and-cover, or mined tunnel), the depth of the tunnel, and the number, size and location of proposed shafts.

3.3.5 Identification of Underground Structures and Other Obstacles

Often, particularly in dense urban areas, other underground structures may exist that may impact the alignment and profile of the proposed road tunnel, and will dictate the need for structure protection measures during construction. These existing underground structures may include transit and railroad tunnels, other road tunnels, underground pedestrian passageways, building vaults, existing or abandoned marine structures (bulkheads, piers, etc.), and existing or abandoned structure foundations. Other underground obstructions may include abandoned temporary shoring systems, soil treatment areas, and soil or rock anchors that were used for temporary or permanent support of earth retaining structures. Initial surveys for the project should therefore include a survey of existing and past structures using documents from city and state agencies, and building owners. In addition, historical maps and records should be reviewed to assess the potential for buried abandoned structures.

3.3.6 Structure Preconstruction Survey

Structures located within the zone of potential influence may experience a certain amount of vertical and lateral movement as a result of soil movement caused by tunnel excavation and construction in close proximity (e.g. cut-and-cover excavation, shallow soft ground tunneling, etc.). If the anticipated movement may induce potential damage to a structure, some protection measures will be required, and a detailed preconstruction survey of the structure should be performed. Preconstruction survey should ascertain all pertinent facts of pre-existing conditions, and identify features and locations for further monitoring. Refer to Chapter 15 for detailed discussions of structural instrumentation and monitoring.

3.4 GEOLOGIC MAPPING

After collecting and reviewing existing geologic maps, aerial photos, references, and the results of a preliminary site reconnaissance, surface geologic mapping of available rock outcrops should be performed by an experienced engineering geologist to obtain detailed, site-specific information on rock quality and structure. Geologic mapping collects local, detailed geologic data systematically, and is used to characterize and document the condition of rock mass or outcrop for rock mass classification (Chapter 6) such as:

- Discontinuity type
- Discontinuity orientation
- Discontinuity infilling
- Discontinuity spacing
- Discontinuity persistence
- Weathering

The International Society of Rock Mechanics (ISRM) (www.isrm.net) has suggested quantitative measures for describing discontinuities (ISRM 1981). It provides standard descriptions for factors such as persistence, roughness, wall strength, aperture, filling, seepage, and block size. Where necessary, it gives suggested methods for measuring these parameters so that the discontinuity can be characterized in a constant manner that allows comparison.

By interpreting and extrapolating all these data, the geologist should have a better understanding of the rock conditions likely to be present along the proposed tunnel and at the proposed portal and shaft excavations. The collected mapping data can be used in stereographic projections for statistical analysis using appropriate computer software (e.g., DIPS), in addition to the data obtained from the subsurface investigations.

In addition, the following surface features should also be observed and documented during the geologic mapping program:

- Slides, new or old, particularly in proposed portal and shaft areas
- Faults
- Rock weathering
- Sinkholes and karstic terrain
- Groundwater springs

- Volcanic activity
- Anhydrite, gypsum, pyrite, or swelling shales
- Stress relief cracks
- Presence of talus or boulders
- Thermal water (heat) and gas

The mapping data will also help in targeting subsurface investigation borings and in situ testing in areas of observed variability and anomalies. Section 4 of AASHTO Subsurface Investigations Manual (1988) provides details of commonly used field geologic mapping techniques and procedures.

Geologic mapping during and after tunnel excavation is briefly discussed in Section 3.8. For details of in-tunnel peripheral geologic mapping refer to US Army Corps of Engineers - Engineering Manual EM-1110-1-1804 for Geotechnical Investigations (USACE, Latest).

3.5 SUBSURFACE INVESTIGATIONS

3.5.1 General

Ground conditions including geological, geotechnical, and hydrological conditions, have a major impact on the planning, design, construction and cost of a road tunnel, and often determine its feasibility and final route. Fundamentally, subsurface investigation is the most important type of investigations to obtain ground conditions, as it is the principal means for:

- Defining the subsurface profile (i.e. stratigraphy, structure, and principal soil and rock types)(Figure 3-4)
- Determining soil and rock material properties and mass characteristics;
- Identify geological anomalies, fault zones and other hazards (squeezing soils, methane gas, etc.)
- Defining hydrogeological conditions (groundwater levels, aquifers, hydrostatic pressures, etc.); and
- Identifying potential construction risks (boulders, etc.).

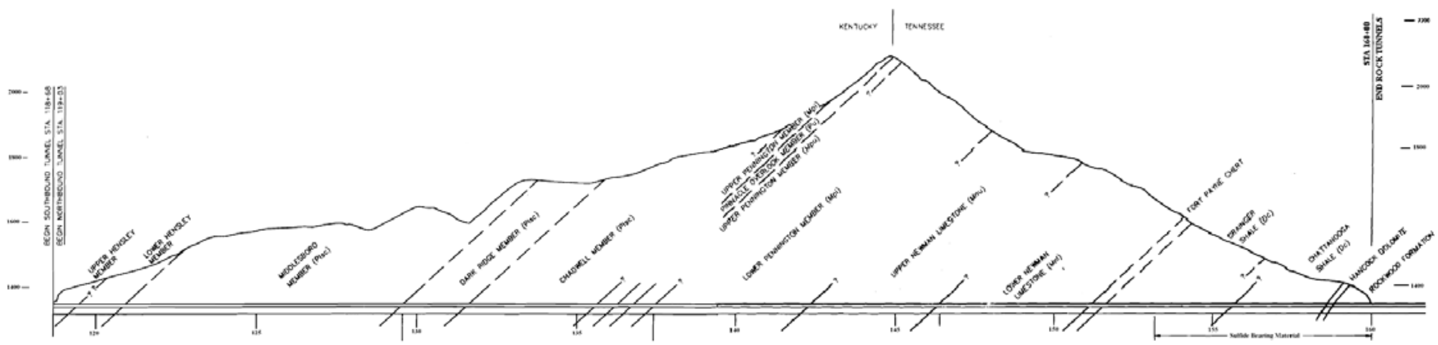


Figure 3-4 Cumberland Gap Tunnel Geological Profile

Subsurface investigations typically consist of borings, sampling, in situ testing, geophysical investigations, and laboratory material testing. The principal purposes of these investigation techniques are summarized below:

- Borings are used to identify the subsurface stratigraphy, and to obtain disturbed and undisturbed samples for visual classification and laboratory testing;
- In situ tests are commonly used to obtain useful engineering and index properties by testing the material in place to avoid the disturbance inevitably caused by sampling, transportation and handling of samples retrieved from boreholes; in situ tests can also aid in defining stratigraphy;
- Geophysical tests quickly and economically obtain subsurface information (stratigraphy and general engineering characteristics) over a large area to help define stratigraphy and to identify appropriate locations for performing borings; and
- Laboratory testing provides a wide variety of engineering properties and index properties from representative soil samples and rock core retrieved from the borings.

Unlike other highway structures, the ground surrounding a tunnel can act as a supporting mechanism, or loading mechanism, or both, depending on the nature of the ground, the tunnel size, and the method and sequence of constructing the tunnel. Thus, for tunnel designers and contractors, the rock or soil surrounding a tunnel is a construction material, just as important as the concrete and steel used on the job. Therefore, although the above subsurface investigative techniques are similar (or identical) to the ones used for foundation design as specified in Section 10 of AASHTO 2006 Interim and in accordance with appropriate ASTM or AASHTO standards, the geological and geotechnical focuses for underground designs and constructions can be vastly different.

In addition to typical geotechnical, geological, and geo-hydrological data, subsurface investigation for a tunnel project must consider the unique needs for different tunneling methods, i.e. cut-and-cover, drill-and-blast, bored, sequential excavation, and immersed. Table 3-2 shows other special considerations for various tunneling methods.

As discussed in Section 3.1.1, subsurface investigations must be performed in phases to better economize the program. Nonetheless, they are primarily performed during the design stage of the project, with much of the work typically concentrated in the preliminary design phase of a project. These investigations provide factual information about the distribution and engineering characteristics of soil, rock and groundwater at a site, allowing an understanding of the existing conditions sufficient for developing an economical design, determining a reliable construction cost estimate, and reducing the risks of construction. The specific scope and extent of the investigation must be appropriate for the size of the project and the complexity of the existing geologic conditions; must consider budgetary constraints; and must be consistent with the level of risk considered acceptable to the client. To ensure the collected data can be analyzed correctly throughout the project, the project coordinate system and vertical datum should be established early on and the boring and testing locations must be surveyed, at least by hand-held GPS equipment. Photographs of the locations should be maintained as well.

Since unanticipated ground conditions are most often the reason for costly delays, claims and disputes during tunnel construction, a project with a more thorough subsurface investigation program would likely have fewer problems and lower final cost. Therefore, ideally, the extent of an exploration program should be based on specific project requirements and complexity, rather than strict budget limits. However, for most road tunnels, especially tunnels in mountainous areas or for water crossings, the cost for a comprehensive subsurface investigation may be prohibitive. The challenge to geotechnical professionals is to develop an adequate and diligent subsurface investigation program that can improve the predictability of ground conditions within a reasonable budget and acceptable level of risk. It is important that the involved parties have a common understanding of the limitations of geotechnical investigations, and be aware of the inevitable risk of not being able to completely define existing geological conditions.

Special considerations for various geological conditions are summarized in Table 3-3 (Bickel, et al., 1996).

Table 3-2 Special Investigation Needs Related to Tunneling Methods (after Bickel et al, 1996)

Cut and Cover (Ch 5)	Plan exploration to obtain design parameters for excavation support, and specifically define conditions closely enough to reliably determine best and most cost-effective location to change from cut-and-cover to true tunnel mining construction.
Drill and Blast (Ch 6)	Data needed to predict stand-up time for the size and orientation of tunnel.
Rock Tunnel Boring Machine (Ch 6)	Data required to determine cutter costs and penetration rate is essential. Need data to predict stand-up time to determine if open-type machine will be ok or if full shield is necessary. Also, water inflow is very important.
Roadheader (Ch 6)	Need data on jointing to evaluate if roadheader will be plucking out small joint blocks or must grind rock away. Data on hardness of rock is essential to predict cutter/pick costs.
Shielded Soft Ground Tunnel Boring Machine (Ch 7)	Stand-up time is important to face stability and the need for breasting at the face as well as to determine the requirements for filling tail void. Need to fully characterize all potential mixed-face conditions.
Pressurized-Face Tunnel Boring Machine (Ch 7)	Need reliable estimate of groundwater pressures and of strength and permeability of soil to be tunneled. Essential to predict size, distribution and amount of boulders. Mixed-face conditions must be fully characterized.
Compressed Air (Ch 7)	Borings must not be drilled right on the alignment and must be well grouted so that compressed air will not be lost up old bore hole in case tunnel encounters old boring
Solution-Mining (Ch 8)	Need chemistry to estimate rate of leaching and undisturbed core in order to conduct long-term creep tests for cavern stability analyses.
Sequential Excavation Method/NATM (Ch 9)	Generally requires more comprehensive geotechnical data and analysis to predict behavior and to classify the ground conditions and ground support systems into four or five categories based on the behavior.
Immersed Tube (Ch 11)	Need soil data to reliably design dredged slopes and to predict rebound of the dredged trench and settlement of the completed immersed tube structure. Testing should emphasize rebound modulus (elastic and consolidation) and unloading strength parameters. Usual softness of soil challenges determination of strength of soil for slope and bearing evaluations. Also need exploration to assure that all potential obstructions and/or rock ledges are identified, characterized, and located. Any contaminated ground should be fully characterized.
Jacked Box Tunneling (Ch 12)	Need data to predict soil skin friction and to determine the method of excavation and support needed at the heading
Portal Construction	Need reliable data to determine most cost-effective location of portal and to design temporary and final portal structure. Portals are usually in weathered rock/soil and sometimes in strain-relief zone.
Construction Shafts	Should be at least one boring at every proposed shaft location.
Access, Ventilation, or Other Permanent Shafts	Need data to design the permanent support and groundwater control measures. Each shaft deserves at least one boring.

Table 3-3 Geotechnical Investigation Needs Dictated by (Modified After Bickel et al, 1996)

Hard or Abrasive Rock	• Difficult and expensive for TBM or roadheader. Investigate, obtain samples, and conduct lab tests to provide parameters needed to predict rate of advance and cutter costs.
Mixed Face	• Especially difficult for wheel type TBM • Particularly difficult tunneling condition in soil and in rock. Should be characterized carefully to determine nature and behavior of mixed-face and approximately length of tunnel likely to be affected for each mixed-face condition.
Karst	• Potentially large cavities along joints, especially at intersection of master joint systems; small but sometimes very large and very long caves capable of undesirably large inflows of groundwater.
Gypsum	• Potential for soluble gypsum to be missing or to be removed because of change of groundwater conditions during and after construction.
Salt or Potash	• Creep characteristics and, in some cases, thermal-mechanical characteristics are very important
Saprolite	• Investigate for relict structure that might affect behavior • Depth and degree of weathering; important to characterize especially if tunneling near rock-soil boundary • Different rock types exhibit vastly differing weathering profiles
High In-Situ Stress	• Could strongly affect stand-up time and deformation patterns both in soil and rock tunnels. Should evaluate for rock bursts or popping rock in particularly deep tunnels
Low In-Situ Stress	• Investigate for open joints that dramatically reduce rock mass strength and modulus and increase permeability. Often potential problem for portals in downcut valleys and particularly in topographic "noses" where considerable relief of strain could occur. • Conduct hydraulic jacking and hydrofracture tests.
Hard Fissured or Slickensided Soil	• Lab tests often overestimate mass physical strength of soil. Large-scale testing and/or exploratory shafts/adits may be appropriate
Gassy Ground-always test for hazardous gases	• Methane (common) • H_2S

Adverse Geological Features	• Faults
	  ▪ Known or suspected active faults. Investigate to determine location and estimate likely ground motion
	  ▪ Inactive faults but still sources of difficult tunneling condition
	    o Faults sometimes act as dams and other times as drainage paths to groundwater
	      - Fault gouge sometimes a problem for strength and modulus
	  ▪ High temperature groundwater
	• Always collect samples for chemistry tests
	• Sedimentary Formations
	  ▪ Frequently highly jointed
	  ▪ Concretions could be problem for TBM

Continued on next page	

Table 3-3 (Continued) Geotechnical Investigation Needs Dictated by Geology (Modified after Bickel et al, 1996)

Adverse Geological Features (Continued)	▪ Groundwater o Groundwater is one of the most difficult and costly problems to control. Must investigate to predict groundwater as reliably as possible o Site characterization should investigate for signs of and nature of: - Groundwater pressure - Groundwater flow - Artesian pressure - Multiple aquifers - Higher pressure in deeper aquifer - Groundwater perched on top of impermeable layer in mixed face condition - Ananalous or abrupt o Aggressive groundwater - Soluble sulfates that attack concrete and shotcrete - Pyrites - Acidic • Lava or Volcanic Formation ▪ Flow tops and flow bottoms frequently are very permeable and difficult tunneling ground ▪ Lava Tubes ▪ Vertical borings do not disclose the nature of columnar jointing. Need inclined borings ▪ Potential for significant groundwater flows from columnar jointing • Boulders (sometimes nests of boulders) frequently rest at base of strata ▪ Cobbles and boulders not always encountered in borings which could be misleading. ▪ Should predict size, number, and distribution of boulders on basis of outcrops and geology • Beach and Fine Sugar Sands ▪ Very little cohesion. Need to evaluate stand-up time. • Glacial deposits ▪ Boulders frequently associated with glacial deposits. Must actively investigate for size, number, and distribution of boulders. ▪ Some glacial deposits are so hard and brittle that they are jointed and ground behavior is affected by the joining as well as properties of the matrix of the deposit • Permafrost and frozen soils ▪ Special soil sampling techniques required ▪ Thermal-mechanical properties required
Manmade Features	• Contaminated groundwater/soil ▪ Check for movement of contaminated plume caused by changes in groundwater regime as a result of construction • Existing Obstructions ▪ Piles ▪ Previously constructed tunnels ▪ Tiebacks extending out into sheet • Existing Utilities • Age and condition of overlying or adjacent utilities within zone of influence

A general approach to control the cost of subsurface investigations while obtaining the information necessary for design and construction would include a) phasing the investigation, as discussed in Section 3.1.1, to better match and limit the scope of the investigation to the specific needs for each phase of the project, and b) utilizing existing information and the results of geologic mapping and geophysical testing to more effectively select locations for investigation. Emphasis can be placed first on defining the local geology, and then on increasingly greater detailed characterization of the subsurface conditions and predicted ground behavior. Also, subsurface investigation programs need to be flexible and should include an appropriate level of contingency funds to further assess unexpected conditions and issues that may be exposed during the planned program. Failure to resolve these issues early may lead to costly redesign or delays, claims and disputes during construction.

Unless site constraints dictate a particular alignment, such as within a confined urban setting, few projects are constructed precisely along the alignment established at the time the initial boring program is laid out. This should be taken into account when developing and budgeting for geotechnical investigations, and further illustrates the need for a phased subsurface investigation program.

3.5.2 Test Borings and Sampling

3.5.2.1 Vertical and Inclined Test Borings

Vertical and slightly inclined test borings (Figure 3-5) and soil/rock sampling are key elements of any subsurface investigations for underground projects. The location, depth, sample types and sampling intervals for each test boring must be selected to match specific project requirements, topographic setting and anticipated geological conditions. Various field testing techniques can be performed in conjunction with the test borings as well. Refer to FHWA Reference Manual for Subsurface Investigations (FHWA, 2002b) and GEC 5 (FHWA, 2002a) for guidance regarding the planning and conduct of subsurface exploration programs.

Figure 3-5 Vertical Test Boring/Rock Coring on a Steep Slope

Table 3-4 presents general guidelines from AASHTO (1988) for determining the spacing of boreholes for tunnel projects:

Table 3-4 Guidelines for Vertical/Inclined Borehole Spacing (after AASHTO, 1988)

Ground Conditions	Typical Borehole Spacing (feet)
Cut-and-Cover Tunnels (Ch 5)	100 to 300
Rock Tunneling (Ch 6)	
Adverse Conditions	50 to 200
Favorable Conditions	500 to 1000
Soft Ground Tunneling (Ch 7)	
Adverse Conditions	50 to 100
Favorable Conditions	300 to 500
Mixed Face Tunneling (Ch 8)	
Adverse Conditions	25 to 50
Favorable Conditions	50 to 75

The above guideline can be used as a starting point for determining the number and locations of borings. However, especially for a long tunnel through a mountainous area, under a deep water body, or within a populated urban area, it may not be economically feasible or the time sufficient to perform borings accordingly. Therefore, engineering judgment will need to be applied by a licensed and experienced geotechnical professional to adapt the investigation program.

In general, borings should be extended to at least ***1.5 tunnel diameters*** below the proposed tunnel invert. However, if there is uncertainty regarding the final profile of the tunnel, the borings should extend at least two or three times the tunnel diameter below the preliminary tunnel invert level. Borings at shafts should extend at least ***1.5 times the depth of the shaft*** for design of the shoring system and shaft foundation, especially in soft soils.

3.5.2.2 Horizontal and Directional Boring/Coring

Horizontal boreholes along tunnel alignments provide a continuous record of ground conditions and information which is directly relevant to the tunnel alignment. Although the horizontal drilling and coring cost per linear feet may be much higher than the conventional vertical/inclined borings, a horizontal borings can be more economical, especially for investigating a deep mountainous alignment, since one horizontal boring can replace many deep vertical conventional boreholes and avoid unnecessary drilling of overburden materials and disruption to the ground surface activities, local community and industries.

A deep horizontal boring will need some distance of inclined drilling through the overburden and upper materials to reach to the depth of the tunnel alignment. Typically the inclined section is stabilized using drilling fluid and casing and no samples are obtained. Once the bore hole reached a horizontal alignment, coring can be obtained using HQ triple tube core barrels.

Figure 3-6 Horizontal Borehole Drilling in Upstate New York

3.5.2.3 Sampling - Overburden Soil

Standard split spoon (disturbed) soil samples (ASTM D-1586) are typically obtained at intervals not greater than 5 feet and at changes in strata. Continuous sampling from one diameter above the tunnel crown to one diameter below the tunnel invert is advised to better define the stratification and materials within this zone if within soil or intermediate geomaterial. In addition, undisturbed tube samples should be obtained in each cohesive soil stratum encountered in the borings; where a thick stratum of cohesive soil is present, undisturbed samples should be obtained at intervals not exceeding 15 ft. Large diameter borings or rotosonic type borings (Figure 3-7) can be considered to obtain special samples for classification and testing.

Figure 3-7 Rotosonic Sampling for a CSO Tunnel Project at Portland, Oregon.

3.5.2.4 Sampling – Rock Core

In rock, continuous rock core should be obtained below the surface of rock, with a minimum NX-size core (diameter of 2.16 inch or 54.7 mm). Double and triple tube core barrels should be used to obtain higher quality core more representative of the in situ rock. For deeper holes, coring should be performed with the use of wire-line drilling equipment to further reduce potential degradation of the recovered core samples. Core runs should be limited to a maximum length of 10 ft in moderate to good quality rock, and 5 ft in poor quality rock.

The rock should be logged soon after it was extracted from the core barrel. Definitions and terminologies used in logging rock cores are presented in Appendix B. Primarily, the following information is recommended to be noted for each core run on the rock coring logs:

- Depth of core run
- Core recovery in inches and percent
- Rock Quality Designation (RQD) percent
- Rock type, including color texture, degree of weathering and hardness
- Character of discontinuities, joint spacing, orientation, roughness and alteration
- Nature of joint infilling materials

In addition, drilling parameters, such as type of drilling equipment, core barrel and casing size, drilling rate, and groundwater level logged in the field can be useful in the future. Typical rock coring logs for tunnel design purpose are included in Appendix B.

3.5.2.5 Borehole Sealing

All borings should be properly sealed at the completion of the field exploration, if not intended to be used as monitoring wells. This is typically required for safety considerations and to prevent cross contamination of soil strata and groundwater. However, boring sealing is particularly important for tunnel projects since an open borehole exposed during tunneling may lead to uncontrolled inflow of water or escape of slurry from a slurry shield TBM or air from a compressed air tunnel.

In many parts of the country, methods used for sealing of boreholes are regulated by state agencies. FHWA-NHI-035 "Workbook for Subsurface Investigation Inspection Qualification" (FHWA, 2006a) offers general guidelines for borehole sealing. National Cooperative Highway Research Program Report No. 378 (Lutenegger et al., 1995), titled "Recommended Guidelines for Sealing Geotechnical Holes," contains extensive information on sealing and grouting boreholes.

Backfilling of boreholes is generally accomplished using a grout mixture by pumping the grout mix through drill rods or other pipes inserted into the borehole. In boreholes where groundwater or drilling fluid is present, grout should be tremied from the bottom of the borehole. Provision should be made to collect and dispose of all drill fluid and waste grout. Holes in pavement and slabs should be patched with concrete or asphaltic concrete, as appropriate.

3.5.2.6 Test Pits

Test pits are often used to investigate the shallow presence, location and depth of existing utilities, structure foundations, top of bedrock and other underground features that may interfere or be impacted by the construction of shafts, portals and cut-and-cover tunnels. The depth and size of test pits will be dictated by the depth and extent of the feature being exposed. Except for very shallow excavations, test pits will typically require sheeting and shoring to provide positive ground support and ensure the safety of individuals entering the excavation in compliance with OSHA and other regulatory requirements.

The conditions exposed in test pits, including the existing soil and rock materials, groundwater observations, and utility and structure elements are documented by written records and photographs, and representative materials are sampled for future visual examination and laboratory testing. The excavation pits are then generally backfilled with excavation spoil, and the backfill is compacted to avoid excessive future settlement. Tampers and rollers may be used to facilitate compaction of the backfill. The ground surface or pavement is then typically restored using materials and thickness dimension matching the adjoining areas.

3.5.3 Soil and Rock Identification and Classification

3.5.3.1 Soil Identification and Classification

It is important to distinguish between visual identification and classification to minimize conflicts between general visual identification of soil samples in the field versus a more precise laboratory evaluation supported by index tests. Visual descriptions in the field are often subjected to outdoor elements, which may influence results. It is important to send the soil samples to a laboratory for accurate visual identification by a geologist or technician experienced in soils work, as this single operation will provide the basis for later testing and soil profile development.

During progression of a boring, the field personnel should describe the sample encountered in accordance with the ASTM D 2488, Practice for Description and Identification of Soils (Visual-Manual Procedure), which is the modified Unified Soil Classification System (USCS). For detailed field identification procedures for soil samples readers are referred to FHWA-NHI-035 “Workbook for Subsurface Investigation Inspection Qualification”.

For the most part, field classification of soil for a tunnel project is similar to that for other geotechnical applications except that special attention must be given to accurately defining and documenting soil grain size characteristics and stratification features since these properties may have greater influence on the ground and groundwater behavior during tunneling than they may have on other types of construction, such as for foundations, embankments and cuts. Items of particular importance to tunnel projects are listed below:

- Groundwater levels (general and perched levels), evidence of ground permeability (loss of drilling fluid; rise or drop in borehole water level; etc.), and evidence of artesian conditions
- Consistency and strength of cohesive soils
- Composition, gradation and density of cohesionless soils
- Presence of lenses and layers of higher permeability soils
- Presence of gravel, cobbles and boulders, and potential for nested boulders
- Maximum cobble/boulder size from coring and/or large diameter borings (and also based on understanding of local geology), and the unconfined compressive strength of cobbles/boulders (from field index tests and laboratory testing of recovered samples)
- Presence of cemented soils
- Presence of contaminated soil or groundwater

All of the above issues will greatly influence ground behavior and groundwater inflow during construction, and the selection of the tunneling equipment and methods.

3.5.3.2 Rock Identification and Classification

In rock, rock mass characteristics and discontinuities typically have a much greater influence on ground behavior during tunneling and on tunnel loading than the intact rock properties. Therefore, rock classification needs to be focused on rock mass characteristics, as well as its origin and intact properties for typical highway foundation application. Special intact properties are important for tunneling application particularly for selecting rock cutters for tunnel boring machines and other types of rock excavators, and to predict cutter wear.

Typical items included in describing general rock lithology include:

- General rock type
- Color
- Grain size and shape
- Texture (stratification, foliation, etc.)
- Mineral composition
- Hardness
- Abrasivity
- Strength
- Weathering and alteration

Rock discontinuity descriptions typically noted in rock classification include:

- Predominant joint sets (with strike and dip orientations)
- Joint roughness
- Joint persistence
- Joint spacing
- Joint weathering and infilling

Other information typically noted during subsurface rock investigations include:

- Presence of faults or shear zones
- Presence of intrusive material (volcanic dikes and sills)
- Presence of voids (solution cavities, lava tubes, etc.)
- Groundwater levels, and evidence of rock mass permeability (loss of drilling fluid; rise or drop in borehole water level; etc.)

Method of describing discontinuities of rock masses is in accordance with International Society of Rock Mechanics (ISRM)'s "Suggested Method of Quantitative Description of Discontinuities of Rock Masses" (ISRM 1981) as shown in Appendix B. Chapter 6 presents the J values assigned to each condition of rock discontinuities for Q System (Barton 2001).

Index properties obtained from inspection of the recovered rock core include core recovery (i.e., the recovered core length expressed as a percentage of the total core run length), and Rock Quality Designation or RQD (the combined length of all sound and intact core segments equal to or greater than 4 inches in length, expressed as a percentage of the total core run length).

For detailed discussions of rock identification and classification readers are referred to Mayne et al. (2001) and the AASHTO "Manual on Subsurface Investigations" (1988). Another useful reference for rock classification is "Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses" from the International Society of Rock Mechanics (1977). For detailed field identification procedures readers are referred to FHWA-NHI-035 "Workbook for Subsurface Investigation Inspection Qualification" and "Rock and Mineral Identification for Engineer Guide."

Often, materials encountered during subsurface investigations represent a transitional (intermediate) material formed by the in place weathering of rock. Such conditions may sometimes present a complex condition with no clear boundaries between the different materials encountered. Tunneling through the intermediate geomaterial (IGM), in some cases referred as mixed-face condition, can be extremely difficult especially when groundwater is present. In the areas where tunnel alignment must cross this transition zone, the subsurface investigation is conducted much as for rock, and when possible cores are retrieved and classified, and representative intact pieces of rock should be tested. More discussions are included in Chapter 8.

3.5.4 Field Testing Techniques (Pre-Construction)

Field testing for subsurface investigations includes two general categories of tests:

a) In situ tests
b) Geophysical testing

In situ tests are used to directly obtain field measurements of useful soil and rock engineering properties. Geophysical tests, the second general category of field tests, are indirect methods of exploration in which changes in certain physical characteristics such as magnetism, density, electrical resistivity, elasticity, or a combination of these are used as an aid in developing subsurface information. There are times that two testing methods can be performed from a same apparatus, such as using seismic CPT

3.5.4.1 In situ Testing

In situ tests are used to directly obtain field measurements of useful soil and rock engineering properties. In soil, in situ testing include both index type tests, such as the Standard Penetration Test (SPT) and tests that determine the physical properties of the ground, such as shear strength from cone penetration Tests (CPT) and ground deformation properties from pressure meter tests (PMT). In situ test methods in soil commonly used in the U.S. and their applications and limitations are summarized in Table 3-5.

Common in situ tests used in rock for tunnel applications are listed in Table 3-6. One significant property of interest in rock is its in situ stress condition. Horizontal stresses of geological origin are often locked within the rock masses, resulted in a stress ratio (K) often higher than the number predicted by elastic theory. Depending on the size and orientation of the tunneling, high horizontal stresses may produce favorable compression in support and confinement, or induce popping or failure during and after excavation. Principally, two different general methods are common to be employed to measure the in situ stress condition: hydraulic fracturing and overcoring. Note that in situ stress can only be measured accurately within a fair or better rock condition. However, since weak rocks are unable to support large deviatoric stress differences, the lateral and vertical stresses tend to equalize over geologic time.

3.5.4.2 Geophysical Testing

Geophysical tests are indirect methods of exploration in which changes in certain physical characteristics such as magnetism, density, electrical resistivity, elasticity, or a combination of these are used as an aid in developing subsurface information. Geophysical methods provide an expeditious and economical means of supplementing information obtained by direct exploratory methods, such as borings, test pits and in situ testing; identifying local anomalies that might not be identified by other methods of exploration; and defining strata boundaries between widely spaced borings for more realistic prediction of subsurface profiles. Typical uses of geophysical tests include determination of the top of bedrock, the ripability of rock, the depth to groundwater, the limits of organic deposits, the presence of voids, the location and depth of utilities, the location and depth of existing foundations, and the location and depth of other obstruction, to note just a few. In addition, geophysical testing can also obtain stiffness and dynamic properties which are required for numerical analysis.

Geophysical testing can be performed on the surface, in boreholes (down or cross hole), or in front of the TBM during construction. Typical applications for geophysical tests are presented in Table 3-7.

Table 3-8 briefly summarizes the procedures used to perform these geophysical tests, and notes their limitations.

Table 3-5 In-situ Testing Methods Used in Soil (After FHWA, 2002a)

Method	Procedure	Applicable Soil Types	Applicable Soil Properties	Limitations / Remarks
Electric Cone Penetrometer (CPT)	A cylindrical probe is hydraulically pushed vertically through the soil measuring the resistance at the conical tip of the probe and along the steel shaft; measurements typically recorded at 2 to 5 cm intervals	Silts, sands, clays, and peat	Estimation of soil type and detailed stratigraphy Sand: ϕ', D_r, σ_{ho}' Clay: s_u, σ_p'	No soil sample is obtained; The probe may become damaged if testing in gravelly soils is attempted; Test results not particularly good for estimating deformation characteristics
Piezocone Penetrometer (CPTu)	Same as CPT; additionally, penetration porewater pressures are measured using a transducer and porous filter element	Silts, sands, clays, and peat	Same as CPT, with additionally: Sand: u_o / water table elevation Clay: σ_p', c_h, k_h OCR	If the filter element and ports are not completely saturated, the pore pressure response may be misleading; Compression and wear of a mid-face (u_1) element will effect readings; Test results not particularly good for estimating deformation characteristics
Seismic CPTu (SCPTu)	Same as CPTu; additionally, shear waves generated at the surface are recorded by a geophone at 1-m intervals throughout the profile for calculation of shear wave velocity	Silts, sands, clays, and peat	Same as CPTu, with additionally: V_s, G_{max}, E_{max}, ρ_{tot}, e_o	First arrival times should be used for calculation of shear wave velocity (if first crossover times are used, the error in shear wave velocity will increase with depth)
Flat Plate Dilatometer (DMT)	A flat plate is hydraulically pushed or driven through the soil to a desired depth; at approximately 20 to 30 cm intervals, the pressure required to expand a thin membrane is recorded; Two to three measurements are typically recorded at each depth.	Silts, sands, clays, and peat	Estimation of soil type and stratigraphy Total unit weight Sand: ϕ', E, D_r, m_v Clays: σ_p', K_o, s_u, m_v, E, c_h, k_h	Membranes may become deformed if over-inflated; Deformed membranes will not provide accurate readings; Leaks in tubing or connections will lead to high readings; Good test for estimating deformation characteristics at small strains
Pre-bored Pressure meter (PMT)	A borehole is drilled and the bottom is carefully prepared for insertion of the equipment; The pressure required to expand the cylindrical membrane to a certain volume or radial strain is recorded.	Clays, silts, and peat; marginal response in some sands and gravels	E, G, m_v, s_u	Preparation of the borehole most important step to obtain good results; Good test for calculation of lateral deformation characteristics
Continued on next page				

Table 3-5 (Continued) In situ Testing Methods Used in Soil

Method	Procedure	Applicable Soil Types	Applicable Soil Properties	Limitations / Remarks
Full Displacement Pressure meter (PMT)	A cylindrical probe with a pressure meter attached behind a conical tip is hydraulically pushed through the soil and paused at select intervals for testing; The pressure required to expand the cylindrical membrane to a certain volume or radial strain is recorded	Clays, silts, and peat	E, G, m_v, s_u	Disturbance during advancement of the probe will lead to stiffer initial modulus and mask liftoff pressure (p_o); Good test for calculation of lateral deformation characteristics
Vane Shear Test (VST)	A 4 blade vane is hydraulically pushed below the bottom of a borehole, then slowly rotated while the torque required to rotate the vane is recorded for calculation of peak undrained shear strength; The vane is rapidly rotated for 10 turns, and the torque required to fail the soil is recorded for calculation of remolded undrained shear strength	Clays, Some silts and peats if undrained conditions can be assumed; not for use in granular soils	s_u, S_t, σ_p'	Disturbance may occur in soft sensitive clays, reducing measured shear strength; Partial drainage may occur in fissured clays and silty materials, leading to errors in calculated strength; Rod friction needs to be accounted for in calculation of strength; Vane diameter and torque wrench capacity need to be properly sized for adequate measurements in various clay deposits

Symbols used in Table 3-5:

ϕ':	Effective stress friction angle	G_{max}:	Small-strain shear modulus
D_r:	Relative density	G:	Shear modulus
σ_{ho}':	In-situ horizontal effective stress	E_{max}:	Small-strain Young's modulus
s_u:	Undrained shear strength	E:	Young's modulus
σ_p':	Preconsolidation stress	ρ_{tot}:	Total density
c_h:	Horizontal coefficient of consolidation	e_o:	In-situ void ratio
k_h:	Horizontal hydraulic conductivity	m_v:	Volumetric compressibility coefficient
OCR:	Overconsolidation ratio	K_o:	Coefficient of at-rest earth pressure
V_s:	Shear wave velocity	S_t:	Sensitivity

Table 3-6 Common in situ Test Methods for Rock (after USACE, 1997)

Parameter	Test Method	Procedure / Limitations / Remarks
In situ Stress	Hydraulic Fracturing	Typically conducted in vertical boreholes. A short segment of the hole is sealed off using a straddle packer. This is followed by the pressurization by pumping in water. The pressure is raised until the rock surrounding the hole fails in tension at a critical pressure. Following breakdown, the shut-in pressure, the lowest test-interval pressure at which the hydrofrac closes completely under the action of the stress acting normal to the hydrofractures. In a vertical test hole the hydrofractures are expected to be formed in vertical and perpendicular to the minimum horizontal stress.
	Overcoring	Drills a small diameter borehole and sets into it an instrument to respond to changes in diameter. Rock stresses are determined indirectly from measurements of the dimensional changes of a borehole, occurring when the rock volume surrounding the hole is isolated from the stresses in the host rock
	Flat Jack Test	This method involves the use of flat hydraulic jacks, consisting of two plates of steel welded around their edges and a nipple for introducing oil into the intervening space. Flat jack is inserted into the slot, cemented in place, and pressurized. When the pins have been returned to the initial separation, the pressure in jack approximates the initial stress normal to the jack.
Modulus of Deformation	Plate Bearing Test	A relatively flat rock surface us sculptured and level with mortar to receive circular bearing plates 20 to 40 inches in diameter. Loading a rock surface and monitoring the resulting displacement. This is easily arranged in the underground gallery. The site may be selected carefully to exclude loose, highly fractured rock.
	Borehole Dilatometer Test	A borehole expansion experiment conducted with a rubber sleeve. The expansion of borehole is measured by the oil or gas flow into the sleeve as the pressure raised, or by potentiometers or linear variable differential transformers built inside the sleeve. One problem with borehole deformability test is that it affect a relatively small volume of rock and therefore contains an incomplete sample of the fracture system.
	Flat Jack Test	This method involves the use of flat hydraulic jacks, consisting of two plates of steel welded around their edges and a nipple for introducing oil into the intervening space. Provide measurement points on the face of the rock and deep slot (reference points). Modulus of deformation could be calculated from the measured pin displacements.
	Radial jacking test	Loads are applied to the circumference of a tunnel by a series of jacks reacting against circular steel ring members. This test allows the direction of load to be varied according to the plan for pressuring the jacks.
	Pressuremeter	The pressure required to expand the cylindrical membrane to a certain volume or radial strain is recorded in a borehole. It is applicable for soft rocks.

Parameter	Test Method	Procedure / Limitations / Remarks
	Dynamic Measurement	The velocity of stress waves is measured in the field. The wave velocity can be measured by swinging a sledgehammer against an outcrop and observing the travel time to a geophone standing on the rock at a distance of up to about 150 ft. The stress loadings sent through the rock by this method are small and transient. Most rock mass departs significantly from the ideal materials, consequently, elastic properties calculated from these equations are often considerably larger than elastic properties calculated from static loading tests, particularly in the case of fractured rocks.
Imaging and Discontinuities	Acoustic Televiewing	Acoustic Televiewers (ATV) produce images of the borehole wall based on the amplitude and travel time of acoustic signals reflected from the borehole wall. A portion of the reflected energy is lost in voids or fractures, producing dark bands on the amplitude log. Travel time measurements allow reconstruction of the borehole shape, making it possible to generate a 3-D representation of a borehole.
	Borehole Video Televiewing	The Borehole Video System (BVS) is lowered down boreholes to inspect the geology and structural integrity. The camera view of fractures and voids in boreholes provides information.
Permeability (Section 3.5.6)	Slug Test	Slug tests are applicable to a wide range of geologic settings as well as small-diameter piezometers or observation wells, and in areas of low permeability where it would be difficult to conduct a pumping test. A slug test is performed by injecting or withdrawing a known volume of water or air from a well and measuring the aquifer’s response by the rate at which the water level returns to equilibrium. Permeability values derived relate primarily to the horizontal conductivity. Slug tests have a much smaller zone of infiltration than pumping tests, and thus are only reliable at a much smaller scale.
	Packer Test	It is conducted by pumping water at a constant pressure into a test section of a borehole and measuring the flow rate. Borehole test sections are sealed off by packers, with the use of one or two packers being the most widely used techniques. The test is rapid and simple to conduct, and by performing tests within intervals along the entire length of a borehole, a permeability profile can be obtained. The limitation of the test is to affect a relatively small volume of the surrounding medium, because frictional losses in the immediate vicinity of the test section are normally extremely large.
	Pumping Tests	In a pumping test, water is pumped from a well normally at a constant rate over a certain time period, and the drawdown of the water table or piezometric head is measured in the well and in piezometers or observation wells in the vicinity. Since pumping tests involve large volumes of the rock mass, they have the advantage of averaging the effects of the inherent discontinuities. Most classical solutions for pump test data are based on the assumptions that the aquifers are homogeneous and isotropic, and that the flow is governed by Darcy's law. The major disadvantage is the period of time required to perform a test. Test durations of one week or longer are not unusual when attempting to approach steady-state flow conditions. Additionally, large diameter boreholes or wells are required since the majority of the conditions encountered require the use of a downhole pump.

Table 3-7 Applications for Geophysical Testing Methods (after AASHTO, 1988)

Geological Conditions to be Investigated	Useful Geophysical Techniques	
	SURFACE	**SUBSURFACE**
Stratified rock and soil units (depth and thickness of layers)	Seismic Refraction	Seismic Wave Propagation
Depth to Bedrock	Seismic Refraction Electrical Resistivity Ground Penetrating Radar	Seismic Wave Propagation
Depth to Groundwater Table	Seismic Refraction Electrical Resistivity Ground Penetrating Radar	
Location of Highly Fractured Rock and/or Fault Zone	Electrical Resistivity	Borehole TV Camera
Bedrock Topography (troughs, pinnacles, fault scarp)	Seismic Refraction Gravity	
Location of Planar Igneous Intrusions	Gravity, Magnetics Seismic Refraction	
Solution Cavities	Electrical Resistivity Ground Penetrating Radar Gravity	Borehole TV Camera
Isolated Pods of Sand, Gravel, or Organic Material	Electrical Resistivity	Seismic Wave Propagation
Permeable Rock and Soil Units	Electrical Resistivity	Seismic Wave Propagation
Topography of Lake, Bay or River Bottoms	Seismic Reflection (acoustic sounding)	
Stratigraphy of Lake, Bay or River Bottom Sediments	Seismic Reflection (acoustic sounding)	
Lateral Changes in Lithology of Rock and Soil Units	Seismic Refraction Electrical Resistivity	

Table 3-8 Geophysical Testing Methods

Method	Procedure	Limitations / Remarks
Seismic Refraction	Detectors (geophones) are positioned on the ground surface at increasing distance from a seismic impulse source, also at the ground surface. The time required for the seismic impulse to reach each geophone is recorded.	Distance between closest and furthest geophone must be 3 to 4 times the depth to be investigated. Reflection from hard layer may prevent identification of deeper layers. Other conditions affecting interpretation: insufficient density contrast between layers; presence of low-density layer; irregular surface topography.
Seismic Reflection	Performed for offshore applications from a boat using an energy source and receiver at the water surface. The travel time for the seismic wave to reach the receiver is recorded and analyzed.	The position and direction of the boat must be accurately determined by GPS or other suitable method. Reflection from hard layer may prevent identification of deeper layers.
Electrical Resistivity /Conductivity	Wenner Four Electrode Method is type most commonly used test in the U.S. Four electrodes are placed partially in the soil, in line and equidistant from each other. A low magnitude current is passed between the outer electrodes, and the resulting potential drop is measured at the inner electrodes. A number of traverses are used, and electrode spacing is varied to better define changes in deposits and layering.	Results may be influenced by presence of underground obstructions, such as pipelines, tanks, etc.
Seismic Wave Propagation:		
Cross-Hole	At least 2 boreholes are required: a source borehole within which a seismic pulse is generated, and a receiver borehole in which a geophone records generated compression and shear waves. For increased accuracy additional receiver boreholes are used.	Receivers must be properly oriented and securely in contact with the side of the borehole. Boreholes deeper than about 30 ft should be surveyed using an inclinometer or other device to determine the travel distance between holes.
Up-Hole or Down-Hole	Performed in a single borehole. In up-hole method, a sensor is placed at the ground surface and shear waves are generated at various depths in the borehole. In down-hole method, seismic wave is generated at the surface and one or more sensors are placed at different depths within the hole.	Data limited to area in immediate vicinity of the borehole.
Parallel Seismic	Used to determine the depth of existing foundations, an impulse wave is generated at the top of the foundation, and a sensor in an adjacent borehole records arrival of the stress wave at set depth increments.	Requires access to top of foundation.
Ground Penetrating Radar	Repetitive electromagnetic impulses are generated at the ground surface and the travel time of the reflected pulses to return to the transmitter are recorded.	The presence of a clay layer may mask features below that layer.

Continued on Next Page

Table 3-8 (Continued) Geophysical Testing Methods

Method	Procedure	Limitations / Remarks
Gravity	A sensitive gravimeter is used at the ground surface to measure variations in the local gravitational field in the earth caused by changes in material density or cavities.	May not identify small changes in density. May be influenced by nearby surface or subsurface features, such as mountains, solution cavities, buried valleys, etc. not directly in area of interest.
Magnetics	Magnetic surveys can be performed using either ground-based or airborne magnetometers. With ground equipment, measurements of changes in the earth's magnetic field are taken along an established survey line.	Monitoring locations should not be located near man-made objects that can change the magnitude of the earth's magnetic field (pipelines, buildings, etc.). Corrections need to be made for diurnal variations in the earth's magnetic field.

It is important to note that the data from geophysical exploration must always be correlated with information from direct methods of exploration that allow visual examination of the subsurface materials, direct measurement of groundwater levels, and testing of physical samples of soil and rock. Direct methods of exploration provide valuable information that can assist not only in the interpretation of the geophysical data, but also for extrapolating the inferred ground conditions to areas not investigated by borings. Conversely, the geophysical data can help determine appropriate locations for borings and test pits to further investigate any anomalies that are found. Readers are also referred to FHWA publication "Application of Geophysical Methods to Highway Related Problems" for more detailed information.

3.5.5 Laboratory Testing

Detailed laboratory testing is required to obtain accurate information for design and modeling purposes.

Soil Testing Detailed soil laboratory testing is required to obtain accurate information including classification, characteristics, stiffness, strength, etc. for design and modeling purposes. Testing are performed on selected representative samples (disturbed and undisturbed) in accordance with ASTM standards. Table 3-9 shows common soil laboratory testing for tunnel design purposes.

Rock Testing Standard rock testing evaluate physical properties of the rock included density and mineralogy (thin-section analysis). The mechanical properties of the intact rock core included uniaxial compressive strength, tensile strength, static and dynamic elastic constants, hardness, and abrasitivity indices.

In addition, specialized tests for assessing TBM performance rates are required including three drillability and boreability testing, namely, Drilling Rate Index (DRI), Bit Wear Index (BWI), and Cutter Life Index (CLI). Table 3-9 summarizes common rock laboratory testing for tunnel design purposes.

It is desirable to preserve the rock cores retrieved from the field properly for years until the construction is completed and disputes/claims are settled. Common practice is to photograph the rock cores in core boxes and possibly scan the core samples for review by designers and contractors. Figure 3-8 shows a roc core scanning equipment and result.

Table 3-9 Common Laboratory Tests for Rock (after USACE 1997)

Parameter	Test Method
Index properties	• Density • Porosity • Moisture Content • Slake Durability • Swelling Index • Point Load Index • Hardness • Abrasivity
Strength	• Uniaxial compressive strength • Triaxial compressive strength • Tensile strength (Brazilian) Shear strength of joints
Deformability	• Young’s modulus Poisson's ratio
Time dependence	• Creep characteristics
Permeability	• Coefficient of permeability
Mineralogy and grain sizes	• Thin-sections analysis • Differential thermal analysis • X-ray diffraction

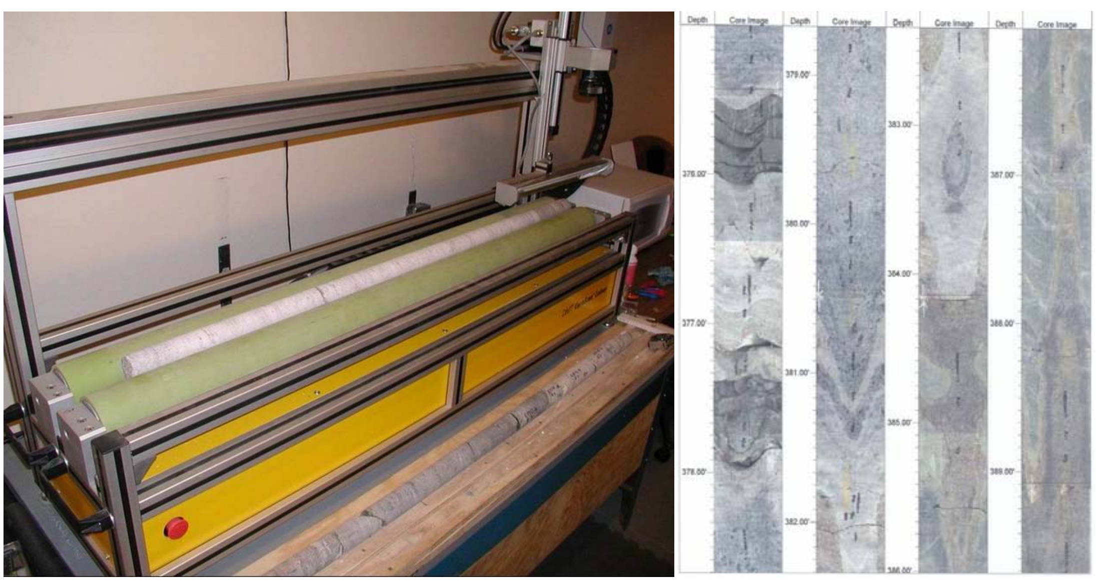


Figure 3-8 Rock Core Scanning Equipment and Result

3.5.6 Groundwater Investigation

Groundwater is a major factor for all types of projects, but for tunnels groundwater is a particularly critical issue since it may not only represent a large percentage of the loading on the final tunnel lining, but also it largely determines ground behavior and stability for soft ground tunnels; the inflow into rock tunnels; the method and equipment selected for tunnel construction; and the long-term performance of the completed structure. Accordingly, for tunnel projects, special attention must be given to defining the groundwater regime, aquifers, and sources of water, any perched or artesian conditions, water quality and temperature, depth to groundwater, and the permeability of the various materials that may be encountered during tunneling. Related considerations include the potential impact of groundwater lowering on settlement of overlying and nearby structures, utilities and other facilities; other influences of dewatering on existing structures (e.g., accelerated deterioration of exposed timber piles); pumping volumes during construction; decontamination/treatment measures for water discharged from pumping; migration of existing soil and groundwater contaminants due to dewatering; the potential impact on water supply aquifers; and seepage into the completed tunnel; to note just a few:

Groundwater investigations typically include most or all of the following elements:

- Observation of groundwater levels in boreholes
- Assessment of soil moisture changes in the boreholes
- Groundwater sampling for environmental testing
- Installation of groundwater observation wells and piezometers
- Borehole permeability tests (rising, falling and constant head tests; packer tests, etc.)
- Geophysical testing (see Section 3.5.4)
- Pumping tests

During subsurface investigation drilling and coring, it is particularly important for the inspector to note and document any groundwater related observations made during drilling or during interruptions to the work when the borehole has been left undisturbed. Even seemingly minor observations may have an important influence on tunnel design and ground behavior during construction.

Groundwater observation wells are used to more accurately determine and monitor the static water table. Since observation wells are generally not isolated within an individual zone or stratum they provide only a general indication of the groundwater table, and are therefore more suitable for sites with generally uniform subsurface conditions. In stratified soils with two or more aquifers, water pressures may vary considerably with depth. For such variable conditions, it is generally more appropriate to use piezometers. Piezometers have seals that isolate the screens or sensors within a specific zone or layer within the soil profile, providing a measurement of the water pressure within that zone. Readers are referred to Chapter 15 Geotechnical and Structural Instrumentation for detailed illustrations and descriptions about the wells and piezometers.

Observation wells and piezometers should be monitored periodically over a prolonged period of time to provide information on seasonal variations in groundwater levels. Monitoring during construction provides important information on the influence of tunneling on groundwater levels, forming an essential component of construction control and any protection program for existing structures and facilities. Local and state jurisdictions may impose specific requirements for permanent observation wells and piezometers, for documenting both temporary and permanent installations, and for closure of these installations.

3.5.6.1 Borehole Permeability Testing

Borehole permeability tests provide a low cost means for assessing the permeability of soil and rock. The principal types of tests include falling head, rising head and constant head tests in soil, and packer tests in rock, as described below. Additional information regarding the details and procedures used for performing and interpreting these borehole permeability tests are presented by FHWA (2002b). Borehole tests are particularly beneficial in sands and gravels since samples of such materials would be too disturbed to use for laboratory permeability tests. A major limitation of these tests, however, is that they assess soil conditions only in the immediate vicinity of the borehole, and the results do not reflect the influence of water recharge sources or soil stratification over a larger area.

Borehole permeability tests are performed intermittently as the borehole is advanced. Holes in which permeability tests will be performed should be drilled with water to avoid the formation of a filter cake on the sides of the borehole from drilling slurry. Also, prior to performing the permeability test the hole should be flushed with clear water until all sediments are removed from the hole (but not so much as would be done to establish a water well).

In soil, either rising head or falling head tests would be appropriate if the permeability is low enough to permit accurate determination of water level versus time. In the falling head test, where the flow is from the hole to the surrounding soil, there is risk of clogging of the soil pores by sediments in the test water. In the rising head tests, where water flows from the surrounding soil into the hole, there is a risk of the soil along the test length becoming loosened or quick if the seepage gradient is too large. If a rising head test is used, the hole should be sounded at the end of the test to determine if the hole has collapsed or heaved. Generally, the rising head test is the preferred test method. However, in cases where the permeability is so high as to preclude accurate measurement of the rising or falling water level, the constant head test should be used.

Pressure, or “Packer,” tests are performed in rock by forcing water under pressure into the rock surrounding the borehole. Packer tests determine the apparent permeability of the rock mass, and also provide a qualitative assessment of rock quality. These tests can also be used before and after grouting to assess the effectiveness of grouting on rock permeability and the strength of the rock mass. The test is performed by selecting a length of borehole for testing, then inflating a cylindrical rubber sleeve (“packer”) at the top of the test zone to isolate the section of borehole being tested. Packer testing can thus be performed intermittently as the borehole is advanced. Alternatively, testing can be performed at multiple levels in a completed borehole by using a double packer system in which packers are positioned and inflated at both the top and bottom of the zone being tested, as illustrated in Figure 3-9. Once the packer is inflated to seal off the test section, water is pumped under pressure to the test zone, while the time and volume of water pumped at different pressures are recorded. Guidelines for performing and evaluating packer tests are presented by Mayne et al. (FHWA, 2002b), and by Lowe and Zaccheo (1991).

3.5.6.2 Pumping Tests

Continuous pumping tests are used to determine the water yield of individual wells and the permeability of subsurface materials in situ over an extended area. These data provide useful information for predicting inflows during tunneling; the quantity of water that may need to be pumped to lower groundwater levels; and the radius of influence for pumping operations; among others. The test consists of pumping water from a well or borehole and observing the effect on the water table with distance and time by measuring the water levels in the hole being pumped as well as in an array of observation wells at various distances around the pumping well. The depth of the test well will depend on the depth and thickness of the strata being investigated, and the number, location and depth of the observation wells or piezometers will depend on the anticipated shape of the groundwater surface after drawdown. Guidelines for performing and evaluating pumping tests are presented by Mayne et al. (FHWA, 2002b).

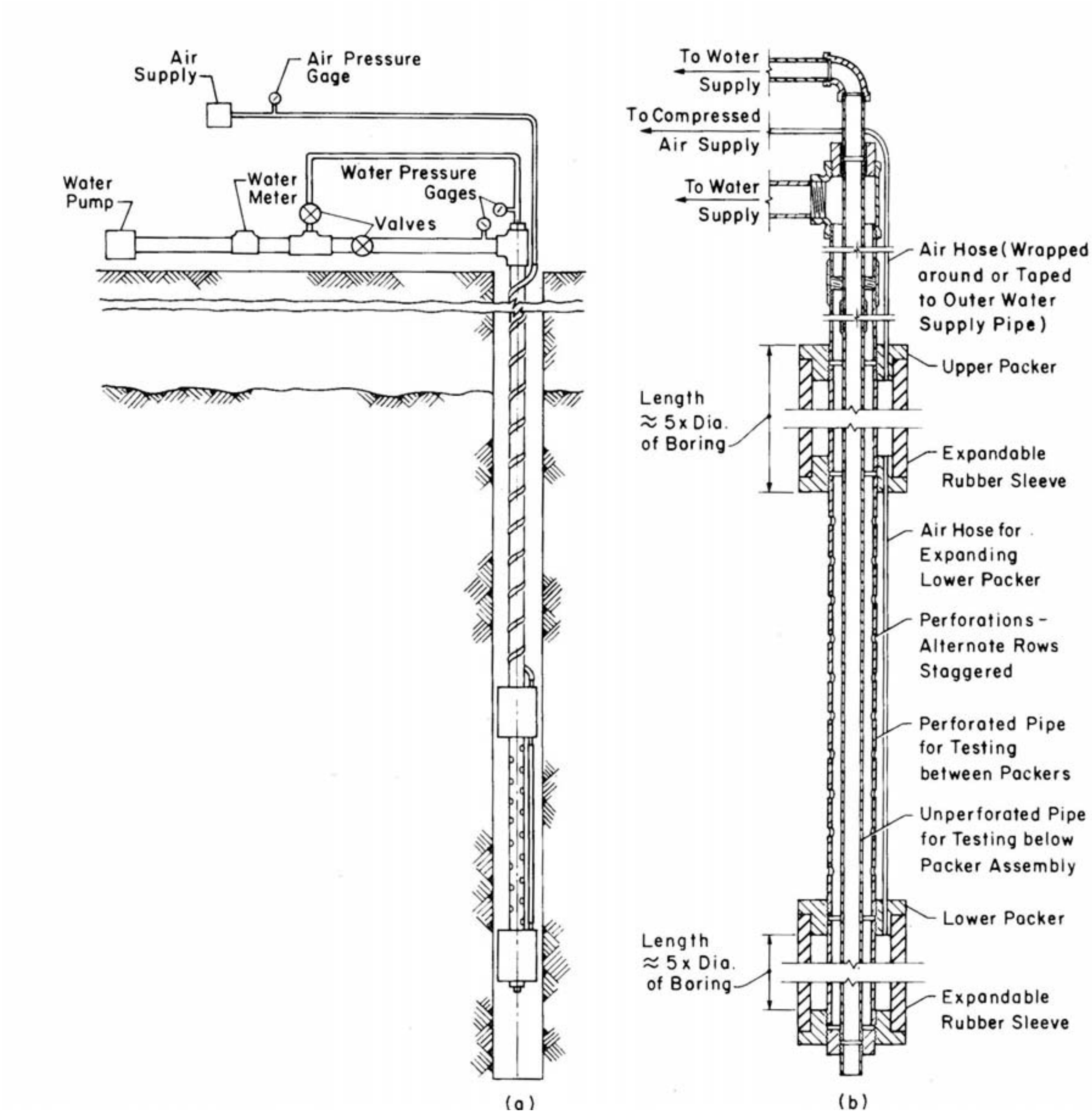


Figure 3-9 Packer Pressure Test Apparatus for Determining the Permeability of Rock (a) Schematic Diagram; (b) Detail of Packer Unit (Lowe and Zaccheo, 1991)

3.6 ENVIRONMENTAL ISSUES

Although tunnels are generally considered environmentally-friendly structures, certain short-term environmental impacts during construction are unavoidable. Long-term impacts from the tunnel itself, and from portals, vent shafts and approaches on local communities, historic sites, wetlands, and other aesthetically, environmentally, and ecologically sensitive areas must be identified and investigated thoroughly during the project planning and feasibility stages, and appropriately addressed in environmental studies and design. Early investigation and resolution of environmental issues is an essential objective for any underground project since unanticipated conditions discovered later during design or construction could potentially jeopardize the project.

The specific environmental data needed for a particular underground project very much depend on the geologic and geographic environment and the functional requirement of the underground facility. Some common issues can be stated, however, and are identified below in the form of a checklist:

- Existing infrastructure, and obstacles underground and above
- Surface structures within area of influence
- Land ownership and uses (public and private)
- Ecosystem habitat impacts
- Contaminated ground or groundwater
- Long-term impacts to groundwater levels, aquifers and water quality
- Control of runoff and erosion during construction
- Naturally gassy ground, or groundwater with deleterious chemistry
- Access constraints for potential work sites and transport routes
- Sites for muck transport and disposal
- Noise and vibrations from construction operations, and from future traffic at approaches to the completed tunnel
- Air quality during construction, and at portals, vent shafts and approaches of the completed tunnel
- Maintenance of vehicular traffic and transit lines during construction
- Maintenance of utilities and other existing facilities during construction
- Access to residential and commercial properties
- Pest control during construction
- Long-term community impacts
- Long-term traffic impacts
- Temporary and permanent easements
- Tunnel fire life safety and security
- Legal and environmental constraints, enumerated in environmental statements or reports, or elsewhere

3.7 SEISMICITY

The release of energy from earthquakes sends seismic acceleration waves traveling through the ground. Such transient dynamic loading instantaneously increases the shear stresses in the ground and decreases the volume of voids within the material which leads to an increase in the pressure of fluids (water) in pores and fractures. Thus, shear forces increase and the frictional forces that resist them decrease. Other factors also can affect the response of the ground during earthquakes.

- Distance of the seismic source from the project site.
- Magnitude of the seismic accelerations.
- Earthquake duration.
- Subsurface profile.
- Dynamic characteristics and strengths of the materials affected.

In addition to the distance of the seismic source to the project site, and the design (anticipated) time history, duration and magnitude of the bedrock earthquake, the subsurface soil profile can have a profound effect on earthquake ground motions including the intensity, frequency content, and duration of earthquake shaking. Amplification of peak bedrock acceleration by a factor of four or more has been attributed to the response of the local soil profile to the bedrock ground motions (Kavazanjian et.al, 1998).

Chapter 13 discusses the seismic considerations for the design of underground structures and the parameters required.

The ground accelerations associated with seismic events can induce significant inertial forces that may lead to instability and permanent deformations (both vertically and laterally) of tunnels and portal slopes. In addition, during strong earthquake shaking, saturated cohesionless soils may experience a sudden loss of strength and stiffness, sometime resulting in loss of bearing capacity, large permanent lateral displacements, landslides, and/or seismic settlement of the ground. Liquefaction beneath and in the vicinity of a portal slope can have severe consequences since global instability in forms of excessive lateral displacement or lateral spreading failure may occur as a result. Readers are referred to FHWA publication "Geotechnical Earthquake Engineering" by Kavazanjian, et al. (1998) for a detailed discussion of this topic.

3.8 ADDITIONAL INVESTIGATIONS DURING CONSTRUCTION

3.8.1 General

For tunneling projects it is generally essential to perform additional subsurface investigations and ground characterization during construction. Such construction phase investigations serve a number of important functions, providing information for:

- Contractor design and installation of temporary works
- Further defining anomalies and unanticipated conditions identified after the start of construction
- Documenting existing ground conditions for comparison with established baseline conditions, thereby forming the basis of any cost adjustments due to differing site conditions
- Assessing ground and groundwater conditions in advance of the tunnel heading to reduce risks and improve the efficiency of tunneling operations
- Determining the initial support system to be installed, and the locations where the support system can be changed
- Assessing the response of the ground and existing structures and utilities to tunneling operations
- Assessing the groundwater table response to dewatering and tunneling operations
- Determining the location and depth of existing utilities and other underground facilities

A typical construction phase investigation program would likely include some or all of the following elements:

- Subsurface investigation borings and probings from the ground surface
- Test pits
- Additional groundwater observation wells and/or piezometers
- Additional laboratory testing of soil and rock samples
- Geologic mapping of the exposed tunnel face
- Geotechnical instrumentation
- Probing in advance of the tunnel heading from the face of the tunnel
- Pilot Tunnels

- Environmental testing of soil and groundwater samples suspected to be contaminated or otherwise harmful

Some of the above investigation elements, such as geotechnical instrumentation, may be identified as requirements of the contract documents, while others, such as additional exploratory borings, may be left to the discretion of the contractor for their benefit and convenience. Tunnel face mapping and groundwater monitoring should be required elements for any tunnel project since the information obtained from these records will form the basis for evaluating the merits of potential differing site condition claims.

3.8.2 Geologic Face Mapping

With open-face tunneling methods, including the sequential excavation method (SEM), open-face tunneling shield in soil, and the drill-and-blast method in rock, all or a large portion of the tunnel face will be exposed, allowing a visual assessment of the existing ground and groundwater conditions. In such cases, the exposed face conditions are documented in cross-section sketches (face mapping) drawn at frequent intervals as the tunnel advances. Information typically included in these face maps include the station location for the cross-section; the date and time the face mapping was prepared; the name of the individual who prepared the face map; classification of each type of material observed; the location of interface boundaries between these materials; rock jointing including orientation of principal joints and joint descriptions; shear zones; observed seepage conditions and their approximate locations on the face; observed ground behavior noting particularly the location of any instability or squeezing material at the face; the location of any boulders, piling or other obstructions; the location of any grouted or cemented material; and any other significant observations. In rock tunnels where the perimeter rock is left exposed, sketches presenting similar information can be prepared for the tunnel walls and roof. All mapping should be prepared by a geologist or geological engineer knowledgeable of tunneling and with soil and rock classification.

The face maps can be used to accurately document conditions exposed during tunneling, and to develop a detailed profile of subsurface conditions along the tunnel horizon. However, there are limitations and considerable uncertainty in any extrapolation of the observed conditions beyond the perimeter of the tunnel.

When used in conjunction with nearby subsurface investigation data and geotechnical instrumentation records, the face maps may be used to develop general correlations between ground displacement, geological conditions and other factors (depth of tunnel, groundwater conditions, etc.).

3.8.3 Geotechnical Instrumentation

Geotechnical instrumentation is used during construction to monitor ground and structure displacements, surface settlement above and near the tunnel, deformation of the initial tunnel supports and final lining, groundwater levels, loads in structural elements of the excavation support systems, and ground and structure vibrations, among others. Such instrumentation is a key element of any program for maintenance and protection of existing structures and facilities. In addition, it provides quantitative information for assessing tunneling procedures during the course of construction, and can be used to trigger modifications to tunneling procedures in a timely manner to reduce the impacts of construction. Instrumentation is also used to monitor the deformation and stability of the tunnel opening, to assess the adequacy of the initial tunnel support systems and the methods and sequencing of tunneling, particularly for tunnels constructed by the Sequential Excavation Method (SEM) and tunnels in shear zones or squeezing ground. Chapter 16 provides a further discussion of geotechnical instrumentation for tunnel projects.

3.8.4 Probing

If applicable, such as for SEM and hard rock tunneling projects, probing ahead of the tunnel face is used to determine general ground conditions in advance of excavation, and to identify and relieve water pressures in any localized zones of water-bearing soils or rock joints. For tunnels constructed by SEM, probing also provides an early indication of the type of ground supports that may be needed as the excavation progresses. Advantages of probing are a) it reduces the risks and hazards associated with tunneling, b) it provides continuous site investigation data directly along the path of the tunnel, c) it provides information directly ahead of the tunnel excavation, allowing focus on ground conditions of most immediate concern to tunneling operations, and d) it can be performed quickly, at relatively low cost. However, disadvantages include a) the risk of missing important features by drilling only a limited number of probe holes from the face, and b) the interruption to tunneling operations during probing. Probing from within the tunnel must be considered as a supplementary investigation method, to be used in conjunction with subsurface investigation data obtained during other phases of the project.

Probing typically consists of drilling horizontally from the tunnel heading by percussion drilling or rotary drilling methods. Coring can be used for probing in rock, but is uncommon due to the greater time needed for coring. Cuttings from the probe holes are visually examined and classified, and assessed for potential impacts to tunnel excavation and support procedures. In rock, borehole cameras can be used to better assess rock quality, orientation of discontinuities, and the presence of shear zones and other important features..

The length of the probe holes can vary considerably, ranging from just 3 or 4 times the length of each excavation stage (round), to hundreds of feet. Shorter holes can be drilled more quickly, allowing them to be performed as part of the normal excavation cycle. However, longer holes, performed less frequently, may result is fewer interruptions to tunneling operations.

3.8.5 Pilot Tunnels

Pilot tunnels (and shorter exploratory adits) are small size tunnels (typically at least 6.5 ft by 6.5 ft in size) that are occasionally used for large size rock tunnels in complex geological conditions. Pilot tunnels, when used, are typically performed in a separate contract in advance of the main tunnel contract to provide prospective bidders a clearer understanding of the ground conditions that will be encountered. Although pilot tunnels are a very costly method of exploration, they may result in considerable financial benefits to the client by a) producing bids for the main tunnel work that have much lower contingency fees, and b) reducing the number and magnitude of differing site condition claims during construction.

In addition to providing bidders the opportunity to directly observe and assess existing rock conditions, pilot tunnels also offer other significant advantages, including a) more complete and reliable information for design of both initial tunnel supports and final lining, if any, b) access for performing in situ testing of the rock along the proposed tunnel, c) information for specifying and selecting appropriate methods of construction and tunneling equipment, d) an effective means of pre-draining groundwater, and more confidently determining short-term and long-term groundwater control measures, e) an effective means for identifying and venting gassy ground conditions, e) a means for testing and evaluating potential tunneling methods and equipment, and f) access for installation of some of the initial supports (typically in the crown area of the tunnel) in advance of the main tunnel excavation. Consideration can also be given to locating the pilot tunnel adjacent to the proposed tunnel, using the pilot tunnel for emergency egress, tunnel drainage, tunnel ventilation, or other purposes for the completed project.

3.9 GEOSPATIAL DATA MANAGEMENT SYSTEM

Geographic Information System (GIS) is designed for managing a large quantity of data in a complex environment, and is a capable tool used for decision making, planning, design, construction and program management. It can accept all types of data, such as digital, text, graphic, tabular, imagery, etc., and organize these data in a series of interrelated layers for ready recovery. Information stored in the system can be selectively retrieved, compared, overlain on other data, composite with several other data layers, updated, removed, revised, plotted, transmitted, etc.

GIS can provide a means to enter and quickly retrieve a wide range of utility information, including their location, elevation, type, size, date of construction and repair, ownership, right-of-way, etc. This information is stored in dedicated data layers, and can be readily accessed to display or plot both technical and demographic information.

Typical information that could be input to a GIS database for a tunnel project may include street grids; topographic data; property lines; right-of-way limits; existing building locations, type of construction, heights, basement elevations, building condition, etc.; proposed tunnel alignment and profile information; buried abandoned foundations and other underground obstructions; alignment and elevations for existing tunnels; proposed structures, including portals, shafts, ramps, buildings, etc.; utility line layout and elevations, vault locations and depths; boring logs and other subsurface investigation information; geophysical data; inferred surfaces for various soil and rock layers; estimated groundwater surface; areas of identified soil and groundwater contamination; and any other physical elements of jurisdictional boundaries within the vicinity of the project.

CHAPTER 4
GEOTECHNICAL REPORTS

4.1 INTRODUCTION

Conventionally, for typical roadway and bridge projects, the geotechnical engineer prepares "geotechnical reports" that serve to summarize the subsurface investigations performed, interpret the existing geological conditions, establish the geotechnical design parameters for the various soil and rock strata encountered, provide geotechnical recommendations for design of the proposed foundations and/or geotechnical features, and identify existing conditions that may influence construction. The term geotechnical report is often used generically to include all types of geotechnical reports, e.g. geotechnical investigation report, geotechnical design report, landslide study report, soil report, foundation report, etc. (FHWA, 1988). The concept is the geotechnical report is only used to communicate the site conditions and design and construction recommendations to the roadway design, bridge design and construction personnel. It may or may not be made available to prospective contractors; and when provided, they are generally only included as a reference document and may typically include disclaimers stating that the report is not intended to be used for construction, and that there is no warranty regarding the accuracy of the data or the conclusions and recommendations of the report; contractors must make their own interpretation of the data to determine the means and associated costs for construction.

Although this approach is commonly used, and may still be applicable for cut-and-cover and immersed tunnel projects, it is not appropriate for mined and bored tunnel and other underground construction projects. Underground projects entail great uncertainty and risk in defining typically complex geological and groundwater conditions, and in predicting ground behavior during tunneling operations. Even with extensive subsurface investigations, considerable judgment is required in the interpretation of the subsurface investigation data to establish geotechnical design parameters and to identify the issues of significance for tunnel construction. This situation is further complicated for tunneling projects since the behavior of the ground during construction is typically influenced by the contractor's selected means and methods for tunnel excavation and type and installation of tunnel supports.

Using conventional geotechnical reports for tunnel projects would essentially assign the full risk of construction to the contractor since the contractor is responsible for interpreting the available subsurface information. Although this approach appears to protect the owner from the uncertainties and risks of construction, experience on underground projects has demonstrated that it results in high contingency costs being included in the contractors' bids, and does not avoid costly contractor claims for additional compensation when subsurface conditions vary from those that could reasonably be anticipated.

Current practice for tunnel and underground projects in the U.S. seeks to obtain a more equitable sharing of risks between the contractor and the owner. This approach recognizes that owners largely define the location, components and requirements of a project and the extent of the site investigations performed, and therefore should accept some of the financial risk should ground conditions encountered during construction differ significantly from those anticipated during design and preparation of the contract documents, and should they negatively impact the contractor. The overall objectives of this risk sharing approach are to:

- Reduce the contractors' uncertainty regarding the financial risks of tunneling projects to obtain lower bid prices
- Foster greater cooperation between the contractor and the owner

- Quickly and equitably resolve disputes between the contractor and the owner that may arise when ground conditions encountered during construction differ substantially from those reflected in the contract documents at the time of bidding
- Obtain the lowest final cost for the project.

Contracting practices for underground projects in the U.S. have evolved and currently include a number of measures to help achieve the above objectives. These measures vary somewhat between projects, depending on specific project conditions and owner preferences, but typically consist of the following fundamental elements:

- Thorough geotechnical site investigations
- Full disclosure of available geotechnical information to bidding contractors
- Preparation of a **Geotechnical Data Report (GDR)** to present all the factual data for a project
- Preparation of **Geotechnical Design Memorandum (GDM)** to present an interpretation of the available geotechnical information, document the assumptions and procedures used to develop the design, and facilitate communication within the design team during development of the design. GDMs are not intended to be incorporated into the Contract Documents and are subsequently superseded by the Geotechnical Baseline Report (GBR).
- Preparation of a **Geotechnical Baseline Report (GBR)** to define the baseline conditions on which contractors will base their bids and select their means, methods and equipment, and that will be used as a basis for determining the merits of contractor claims of differing site conditions during construction
- Making the GDR and GBR contractually binding documents by incorporating them within the contract documents for the project; the GBR takes precedence;
- Carefully coordinating the provisions of the contract specifications and drawings with the information presented in the GBR
- Including a Differing Site Condition clause in the specification that allows the contractor to seek compensation when ground conditions vary from those defined in the GBR, and that result in a corresponding increase in construction cost and/or delay in the construction schedule; Establishing a dispute resolution process to quickly and equitably resolve disagreements that may arise during construction without reverting to costly litigation procedures
- Providing escrow of bid documents

This chapter focuses on the three types of geotechnical reports (GDR, GDM, and GBR) noted above for bore/mined tunnel projects, will discuss the specific purposes and typical contents of these reports, and provide guidelines for their preparation. Related topics, including subsurface investigations for tunnel projects and provisions for dispute resolution, are addressed in other chapters of this manual. Additional information on geotechnical reports for underground projects is provided by ASCE (1989, 1991, 1997, and 2007), Brierley (1998), Essex (2002), and Edgerton (2008).

4.2 GEOTECHNICAL DATA REPORT

The Geotechnical Data Report (GDR) is a document that presents the factual subsurface data for the project without including an interpretation of these data. The purpose of the GDR is to compile all factual geological, geotechnical, groundwater, and other data obtained from the geotechnical investigations (Chapter 3) for use by the various participants in the project, including the owner, designers, contractors and third parties that may be impacted by the project. It serves as a single and comprehensive source of geotechnical information obtained for the project.

The GDR should avoid making any interpretation of the data since these interpretations may conflict with the data assessment subsequently presented in the Geotechnical Design Memorandum or other geotechnical interpretive or design reports, and the baseline conditions defined in the Geotechnical Baseline Report. Any such discrepancies could be a source of confusion to the contractors and open opportunities for claims of differing site conditions. In practice, it may not be possible to eliminate all data interpretation from the GDR. In such case, the data reduction should be limited to a determination of the properties obtained from that individual test sample, while avoiding any recommendations for the geotechnical properties for the stratum from which the sample was obtained.

The GDR should contain the following information (ASCE, 2007):

- Descriptions of the geologic setting
- Descriptions of the site exploration program(s)
- Logs of all borings, trenches, and other site investigations
- Descriptions/discussions of all field and laboratory test programs
- Results of all field and laboratory testing

Table 4-1 presents a typical outline for a GDR, modified from Brierley (1998).

The GDR would include the logs of all borings performed for the project, but should not present a subsurface profile constructed from the borings since such a profile requires considerable judgment and interpolation of the borehole records to show inferred strata boundaries. As illustrated in the outline, the text of the GDR provides background information and a discussion of the subsurface investigations performed, while the specific data are presented in appendices to the report. The introduction provides a general project description and notes the purpose and scope of the report. The section on background information should identify other sources of geotechnical information that may have been obtained by others at or near the project site, and may include subsurface investigation data and records from previous construction activities. If such additional information is limited in volume, consideration should be given to including these data in an appendix to the report.

Background information should also include a discussion of the regional and local geologic setting, since such information will be invaluable in the assessment of the limited amount of factual data obtained from site investigations. It is recognized that a description of geological conditions requires interpretation of information in the literature and an understanding of the geological processes controlling the formation and properties of soil and rock deposits; however, since an understanding of the geological setting is fundamental to a successful tunneling project, such information is considered an essential component of the GDR.

The report section on field investigations should include a brief description of the type of investigations performed, references to applicable standards for performing the investigations, the method of obtaining and handling samples, and discussion of any special procedures used for the investigations. If specialty work, such as geophysical investigations, is performed by others, the report prepared by the specialty firm can be included as an appendix to the GDR and simply referenced within the text of the GDR.

The section on laboratory testing should document the number of each type of test performed, the name and location of the testing laboratory, the specific standards used to perform each test, and other information pertinent to the testing program.

The attachments and appendices would present the field and laboratory test records, and may also include helpful summary tables and plots that summarize the factual data obtained from the investigations.

Table 4-1 Sample Outline for Geotechnical Data Reports (After Brierley, 1998)

Introduction
- General
- Purpose and Scope
- Survey Control
- Report Organization
- Report Limitations

Background Information
- General
- Other Investigations
- Regional Geologic Setting
- Local Geology

Field Investigations
- General
- Test Borings
- Test Pits
- Observation Wells
- Geophysical Investigations
- In-Situ Testing
- Geologic Mapping

Laboratory Testing Program
- General
- Soil Testing
- Rock Testing

References

Tables
- Summary of Subsurface Explorations
- Summary of Observation Wells
- Summary of Laboratory Test Results

Figures
- Project Location Map
- Subsurface Exploration Plan

Appendices
- Glossary of Technical Terminology
- Logs of Test Borings
- Logs of Observation Wells
- Geophysical Investigation Data
- In-Situ Test Results
- Laboratory Soil Test Results
- Laboratory Rock Test Results
- Geologic Mapping Data
- Existing Information (optional)

4.3 GEOTECHNICAL DESIGN MEMORANDUM

For tunnel projects, one or more interpretive reports may be prepared to evaluate the available data as presented in the GDR, address a broad range of design issues, and communicate design recommendations for the design team's internal consideration. These interpretive reports are also used to evaluate design alternatives, assess the impact of construction on adjacent structures and facilities, focus on individual elements of the project, and discuss construction issues. The current guidelines recommend referring to such design reports as Geotechnical Design Memoranda (GDM), instead of Geotechnical Interpretive Report (GIR) (ASCE, 2007).

GDM, or GIR may be prepared at different stages of a project, and therefore may not accurately reflect the final design or final contract documents. Hence, preparation of such interpretive reports in the course of the final design is superfluous, and is strongly discouraged to avoid a potential source of confusion and conflict.

Since GDMs are used internally within the design team and with the owner as part of the project development effort, it is not appropriate to include GDMs as part of the contract documents. Thus, GDMs should be clearly differentiated from the Geotechnical Baseline Report (GBR) (Section 4.4). The GBR should be the only interpretive report prepared for use in bidding and constructing the project. The GBR must supersede – take precedence over any other Geotechnical Report(s). However, in the interest of "full disclosure" to prospective bidders, GDMs are often made available "for information only." In such instances, the GDM must include a disclaimer clearly noting the specific purposes of the report and stating that the information provided in the report is not intended for construction. The GDM must also clearly state that the contract documents, including the GDR and GBR, are the only documents to be considered by contractors when assessing project requirements and determining their bid price for the work. A sample outline for a GDM, similar to the previously recommended outline for GIR, is presented in Table 4-2.

The GDM should include other disclaimers to highlight the interpretive nature of the report. Following are several issues that are commonly addressed by disclaimers:

- The boring logs only represent the conditions at the specific borehole location at the time it was drilled; ground conditions may be different beyond the borehole location, and may change with time as a result of nearby activities as well as natural processes
- Water levels in the boreholes and observation wells are seasonal and may also change as a result of other factors
- The findings and recommendations presented in the report are applicable only to the proposed facilities and should not be used for other purposes

In evaluating the engineering properties of the soil and rock materials, it is appropriate for the GDM to note the likely ranges for these properties and to recommend a value, or range of values, for use in design. The report should document the basis for selecting these parameters and discuss their significance to the design and construction of the proposed facilities. As an interpretive report, it is appropriate and useful to discuss the reasoning and judgment associated with these and other design recommendations presented in the report.

Table 4-2 Sample Outline for Geotechnical Design Memorandum (After Brierley, 1998)

EXECUTIVE SUMMARY

Introduction
- General
- Purpose and Scope
- Report Organization
- Report Limitations

Project Requirements
- Project Status
- Proposed Facilities
- Third-Party Facilities

Site Conditions
- General
- Geologic Setting
- Subsurface Profile
- Geotechnical Properties for Soil and Rock
- Groundwater Conditions

Design Recommendations
- Tunnel Design Considerations
- Initial Support
- Final Tunnel Lining
- Shafts and Portals
- Tunnel Approaches
- Groundwater Control
- Third-Party Impacts
- Construction Monitoring

Construction Considerations
- Tunnel Excavation and Initial Support
- Construction Dewatering
- Support of Excavations
- Third-Party Impacts

References

Tables
- Summary of Field Investigations
- Summary of Laboratory Investigations

Figures
- Project Location Map
- Subsurface Exploration Plan
- Subsurface Profiles
- Project Layout Drawings
- Design Details

Appendices
- Glossary of Technical Terminology
- Design Investigations by Others
- Recommended Technical Specifications

Presenting a range of parameters, along with a discussion of their consequences on the design, helps the owner and the design team understand and quantify the inherent uncertainty and risk associated with the proposed underground project. Such information allows the owner to determine the level of risk to be accepted, and the share of the risk to be borne by the contractor. An example of this decision process would be a case where a tunnel must be constructed through relatively low strength rock that contains intrusive dikes of very hard igneous rock of unknown frequency and thickness. Based on limited geotechnical investigations, the geotechnical engineer determines that the amount of hard rock may range from 10 to 30 percent of the total length of the tunnel. This range, and possibly a best estimate percentage, would be reported in the GDM. During subsequent preparation of the GBR and other contract documents, a specific baseline value would be determined and referenced for contractual purposes and reflected in the design. If the owner, in an effort to get lower bid prices, is willing to accept the greater risk of cost increases during construction, a value closer to the lower end of the range would be selected as the baseline. However, if the owner wishes to reduce the risk of cost extras during construction, a value closer to the conservative end of the range would be selected. However, in choosing this second option, the owner needs to recognize that it will result in higher bid prices.

In preparing a GDM it is acceptable to use ambiguous terms, such as "may," should," likely," etc. in discussing the various technical issues. Such terms reflect the reality of our uncertainty in defining subsurface stratigraphy and the engineering properties of natural materials, and in predicting the behavior of these materials during construction.

The GDM should reference the Geotechnical Data Report (GDR) as the source of information used to develop the conclusions and recommendations of the GDM. The GDM should also identify any other sources of information that may have influenced the findings of the GDM, including technical references, reports, and site reconnaissance observations, among others.

The GDM should include generalized subsurface profiles developed from an assessment of the available geotechnical and geological information. These subsurface profiles greatly facilitate a visualization and understanding of the existing subsurface conditions for design purposes. However, it must be recognized that such definition of subsurface conditions is highly dependent on the quantity and quality of the available geotechnical investigation data, and the judgment of the geotechnical engineer in interpreting these data and the relevant geological information. Accordingly, the report must emphasize that the profiles are based on an interpolation between widely spaced borings, and that actual subsurface conditions between the borings may vary considerably from those indicated on the profiles.

In addition to providing recommendations for design, the GDM should also address construction issues, including the general methods of construction considered appropriate for the existing site conditions and proposed facilities. However, the engineers preparing the report must recognize that the contractor is responsible for selecting the specific equipment, means and methods for performing the work, thus must avoid any detailed recommendations on these issues accordingly. For example, for a proposed subaqueous tunnel through highly permeable sand deposits, it is appropriate to state that a closed face Tunnel Boring Machine (TBM) consisting of either an Earth Pressure Balance (EPB) Shield or Slurry Shield TBM should be used, but it is inappropriate to recommend a specific TBM model, horsepower, etc.

It is also particularly important for the GDM to identify and discuss all potential hazards that may be encountered during construction, and discuss possible measures to mitigate these hazards. A thorough discussion of such issues should help both the design team and the contractor to anticipate and avoid problems that could cause major cost and schedule impacts. For example, for a tunnel to be excavated in mixed face conditions, the GDM should note that typical problems may include: a), large water inflow at the contact between the soil and rock that will be difficult to fully dewater, b), steering problems for the

TBM, and c), ground loss, and corresponding surface settlement due to excavation of the soil in the upper part of the tunnel heading at a faster rate than the rock in the lower part of the heading. For this example, the report should also note mitigating measures, such as grouting the soil to reduce seepage and ground loss, and facilitate steering of the TBM; drilling drainage holes horizontally from the tunnel heading; providing an articulated TBM to facilitate steerage corrections; etc.

In summary, the GDM is written by the engineers solely for use by the design team in developing the design for the proposed facilities. It provides an interpretation of the available subsurface information to determine likely subsurface conditions for design purposes. Depending on its specific purpose and the time of its preparation, the GDM may not reflect the final design shown on the contract drawings. An important element of the GDM is a general discussion of the appropriate methods of construction and the potential hazards that may be encountered during construction, as well as the possible measures that can be considered to mitigate these hazards. The GDM is not intended to be a definitive representation of the actual ground conditions, and is not to be used as a baseline for contractual purposes.

4.4 GEOTECHNICAL BASELINE REPORT

4.4.1 Purpose and Objective

As discussed in Section 4.1, a fundamental principal in current U.S. contracting practices for tunnel projects is the equitable sharing of risk between the owner and contractor, with the objectives of reducing contingency fees in contractor bids, achieving lower total cost for the project, and streamlining resolution of contractor claims for changed conditions during construction. Over the years, various forms and names have been given to the interpretive geotechnical report to be incorporated into the Contract Documents for underground projects in order to achieve the aforementioned objectives. Originally, this was called the Geotechnical Design Summary Report (GDSR). However, since 1997 and continuing with the current (2007) “Geotechnical Baseline Reports-Suggested Guidelines” the industry has determined that the incorporated report be called GBR (Geotechnical Baseline Report).

The primary purposes of the GBR are:

- Establish a contractual document that defines the specific subsurface conditions to be considered by contractors as baseline conditions in preparing their bids,
- Establish a contractual procedure for cost adjustments when ground conditions exposed during construction are poorer than the baseline conditions defined in the contract documents.

Although it reflects the findings of the geotechnical investigations and design studies, a GBR is not intended to predict the actual geotechnical and geological conditions at a project site, or to accurately predict the ground behavior during construction. Rather, it establishes the bases for delineating the financial risks between the owner and the contractor.

ASCE (1997) also noted the secondary purposes of the GBR as listed below:

- It presents the geotechnical and construction considerations that formed the basis of design
- It enhances contractor understanding of the key project issues and constraints, and the requirements of the contract plans and specifications
- It identifies important considerations that need to be addressed during bid preparation and construction
- It assists the contractor in evaluating the requirements for tunnel excavation and support; and

- It guides the construction manager in administering the contract and monitoring contractor performance

A common misconception of the GBR is that it represents a warranty of the existing site conditions by the geotechnical engineer and designer. Based on this understanding, the owner of the project may believe they are entitled to compensation by the designer should actual conditions be found less favorable than the conditions defined in the GBR. However, since it principally serves as a contractual instrument for allocating risks, the GBR is not intended to predict or warranty actual site conditions. If the GBR were to become a warranty, it is reasonable to expect that the geotechnical engineer and designer would more conservatively define subsurface conditions and ground behavior, resulting in a higher cost for the project, a consequence clearly contrary to the primary motivation for adopting a risk-sharing approach to tunnel construction contracts.

It is also important to clearly differentiate the GBR from other interpretive reports may be prepared by the design team to addressing a broad range of design issues for the team's internal consideration. As discussed in Section 4.3, such reports should be referred to as Geotechnical Design Memoranda (GDM). The GBR should be the only final report prepared for use in bidding and constructing the project. The GBR should be limited to interpretive discussion and baseline statements, and should make reference to, rather than repeat or paraphrase, information contained in the GDR, drawings, or specifications (ASCE, 2007).

4.4.2 General Considerations

The various elements of the construction contract documents each serve a different purpose. The GDR provides the factual information used by the designer for designing the various components of the project, and by the contractor for developing appropriate means and methods of construction. The contract plans and specifications detail the specific requirements for the work to be performed, without providing an explanation or background information. The GBR is based on the factual information presented in the GDR as well as input from the owner regarding risk allocation, and provides an explanation for the project requirements as presented in the contract plans and specifications. The baseline information presented in the GBR must be coordinated with the GDR, contract plans and specifications, and contract payment provisions to assure consistency throughout the contract. However, the GBR should not repeat or paraphrase statements made in these other contract documents since even minor rewording of a statement may cause confusion or an unintended interpretation of the statement. Any inconsistency or confusion in the contract documents could lead to a successful contractor claim for additional compensation during construction since these are usually judged against the owner as the originator of the contract.

The contract General Provisions or Special Provisions should clearly define the hierarchy between the various parts of the contract documents to help resolve any conflicts that may inadvertently remain after issuing the documents. The GBR takes precedence over the GDR and any and all other geotechnical report prepared for any reason.

Most often, there is a possible baseline range that can be established for a given set of geologic and construction conditions. As a consequence, where the baseline is set determines the risk allocation for the project. When an adverse baseline is adopted; 1), more risk is assigned to the Contractor who will bid higher, 2), less risk and reduced potential for change orders accrue to the owner, and, 3), higher costs accrue to the owner due to paying for the contingency of encountering the adverse condition(s). Conversely, when a less adverse baseline is adopted: 1) Contractor bids less due to less risk and contingency, 2) higher risk and potential for change orders accrue to the owner, 3) owner pays more if adverse conditions are encountered but less if they are not encountered. In either case, the cost of site conditions remains with the Owner.

4.4.3 Guidelines for Preparing a GBR

The GBR translates facts, interpretations and opinions regarding subsurface conditions into clear, unambiguous statements for contractual purposes. Items typically addressed in a GBR include:

- The amounts and distribution of different materials along the selected alignment;
- Description, strength, compressibility, grain size, and permeability of the existing materials;
- Description, strength and permeability of the ground mass as a whole;
- Groundwater levels and expected groundwater conditions, including baseline estimates of inflows and pumping rates;
- Anticipated ground behavior, and the influence of groundwater, with regard to methods of excavation and installation of ground support;
- Construction impacts on adjacent facilities; and
- Potential geotechnical and man-made sources of potential difficulty or hazard that could impact construction, including the presence of faults, gas, boulders, solution cavities, existing foundation piles, and the like.

A general checklist for a GBR is presented in Table 4-3. This checklist assumes that the Geotechnical Data Report contains the information noted in Section 4.2

Following are general guidelines that should be followed for preparation of a Geotechnical Baseline Report:

- The GBR should be brief. The length of a GBR should be limited to not more than 30 pages of text for typical projects, and not more than 50 pages for more complex projects. The length should allow reading the GBR in a single sitting.
- Select baseline parameters following discussions with the owner regarding the levels of risk to be allotted to the owner and contractor
- Use and reference the information presented in the GDR as the basis for selecting baseline parameters
- Avoid using ambiguous terminology, such as “may,” “should,” “can,” etc; rather, use definitive terms, such as “is,” ”are,” “will,” etc.
- Whenever possible, refer baselines to properties and parameters that can be objectively observed and measured in the field
- Avoid the use of general adjectives, such as “large,” “significant,” “minor,” etc. unless these terms are defined and quantified
- Carefully select the specific wording used in the GBR to avoid unintended interpretation of the report
- For parameters that are anticipated to vary considerably, the GBR should note the potential range of values, but clearly state a specific baseline value for contractual purposes
- Since ground behavior is largely influenced by construction means and methods, statements of ground behavior in the GBR should also note the corresponding construction equipment, procedures and sequencing on which these statements were based
- Include an independent review of the GBR at different stages of completion to identify possible ambiguity and inconsistencies, and to verify that all relevant issues are appropriately addressed.

Individuals who prepare the GBR must be highly knowledgeable of both the design and construction of underground facilities, with construction experience particularly important for the necessary understanding of construction methods, equipment capabilities, ground behavior during tunnel excavation, and the potential hazards associated with the different ground conditions and methods of construction. In addition, these individuals must be experienced in the preparation of a GBR and clearly understand its role as a contract document establishing reference baseline conditions. In general, to achieve greater consistency in the contract documents, the individuals preparing the GBR should belong to the same organization that prepares the contract plans and specifications.

Table 4-3 Checklist for Geotechnical Baseline Reports (After ASCE, 2007)

Introduction

- Project name
- Project owner
- Design team (and Design Review Board)
- Purpose of reports; organization of report
- Contractual precedence relative to the GDR and other contract documents (refer to general conditions)
- Project constraints and latitude

Project Description

- Project location
- Project type and purpose
- Summary of key project features (dimensions, lengths, cross sections, shapes, orientations, support types, lining types, required construction sequences)
- Reference to specific specification sections and drawings to avoid repeating information from other Contract Documents in GBR

Sources of Geologic and Geotechnical Information

- Reference to GDR
- Designated other available geologic geotechnical reports
- Include the historical precedence for earlier sources of information

Project Geologic Setting

- Brief overview of geologic and groundwater setting, origin of deposits, with cross reference to GDR text, maps, and figures
- Brief overview of site exploration and testing programs – avoid unnecessary repetition of GDR text
- Surface development and topographic and environmental conditions affecting project layout
- Typical surficial exposures and outcrops
- Geologic profile along tunnel alignment(s) showing generalized stratigraphy and rock/soil units, and with stick logs to indicate drill hole locations, depths, and orientations

Previous Construction Experience (key points only in GBR if detailed in GDR)

- Nearby relevant projects
- Relevant features of past projects, with focus on excavation methods, ground behavior, groundwater conditions, and ground support methods
- Summary of problems during construction and how they were overcome (with qualifiers as appropriate)

Table 4-3 Continued

Ground Characterization

- Physical characteristic and occurrences of each distinguishable rock or soil unit, including fill, natural soils, and bedrock; describe degree of weathering / alteration; including near-surface units for foundations/pipelines
- Groundwater conditions; depth to water table; perched water; confined aquifers and hydrostatic pressures; pH; and other key groundwater chemistry details
- Soil/rock and groundwater contamination and disposal requirements
- Laboratory and field test results presented in histogram (or some other suitable) format, grouped according to each pertinent distinguishable rock or soil unit; reference to tabular summaries contained in the GDR
- Ranges and values for baseline purposes; explanations for why the histogram distributions (or other presentations) should be considered representative of the range of properties to be encountered, and if not, why not; rationale for selecting the baseline values and ranges
- Blow count data, including correlation factors used to adjust blow counts to Standard Penetration Test (SPT) values, if applicable
- Presence of boulders and other obstructions; baselines for number, frequency (i.e., random or concentrated along geologic contacts), size and strength
- Bulking/swell factors and soil compaction factors
- Baseline descriptions of the depths/thicknesses or various lengths or percentages of each pertinent distinguishable ground type or stratum to be encountered during excavation; properties of each ground type; cross-references to information contained in the drawings or specifications
- Values of ground mass permeability, including direct and indirect measurements of permeability values, with reference to tabular summaries contained in the GDR; basis for any potential occurrence of large localized inflows not indicated by ground mass permeability values
- For TBM projects, interpretations of rock mass properties that will be relevant to boreability and cutter wear estimates for each of the distinguishable rock types, including test results that might affect their performance (avoid explicit penetration rate estimated or advance rate estimates)

Design Considerations – Tunnels and Shafts

- Description of ground classification system(s) utilized for design purposes, including ground behavior nomenclature
- Criteria and methodologies used for the design of ground support and ground stabilization systems, including ground loadings (or reference the drawings/specifications)
- Criteria and bases for design of final linings (or reference to drawings/specifications)
- Environmental performance considerations such as limitations on settlement and lowering of groundwater levels (or in specifications)
- The manner in which different support requirements have been developed for different ground types, and, if required, the protocol to be followed in the field for determination of ground support types for payment; reference to specifications for detailed descriptions of ground support methods/sequences
- The rationale for ground performance instrumentation included in the drawings and specifications

Table 4-3 Continued

Design Considerations – Other Excavations and Foundations

- Criteria and methodologies used for the design of excavation support systems, including lateral earth pressure diagrams (or in drawings/specifications) and need to control deflections/deformations
- Feasible excavation support systems
- Minimum pile tip elevations for deep foundations
- Refusal criteria for driven piles
- Allowable skin friction for tiebacks
- Environmental considerations such as limitations on settlement and lowering of groundwater levels (or in specifications)
- Rationale for instrumentation/monitoring shown in the drawings and specifications

Construction Considerations – Tunnels and Shafts

- Anticipated ground behavior in response to construction operations within each soil and rock unit
- Required sequences of constructions (or in drawings/specifications)
- Specific anticipated construction difficulties
- Rationale for requirements contained in the specifications that either constrain means and methods considered by the contractor or prescribe specific means and methods, e.g., the required use of an EPB or slurry shield.
- The rationale for baseline estimates of groundwater inflows to be encountered during construction, with baselines for sustained inflows at the heading, flush inflows at the heading, and cumulative sustained groundwater inflows to be pumped at the portal or shaft
- The rationale behind ground improvement techniques and groundwater control methods included in the contract
- Potential sources of delay, such as groundwater inflows, shears and faults, boulders, logs, tiebacks, buried utilities, other manmade obstruction, gases, contaminated soils and groundwater, hot water, and hot rock, etc.

Construction Considerations – Other Excavations and Foundations

- Anticipated ground behavior in response to required construction operations within each soil and rock unit
- Rippability of rock, till, caliche, or other hard materials, and other excavation considerations including blasting requirements/limitations
- Need for groundwater control and feasible groundwater control methods
- Casing requirements for drilled shafts
- Specific anticipated construction difficulties
- Rationale for requirements contained in the specifications that either constrain means and methods considered by the Contractor or prescribe specific means and methods
- The rationale for baseline estimates of groundwater inflows to be encountered during construction, with baselines for sustained inflows to be pumped from the excavation
- The rationale behind ground improvement techniques and groundwater control methods included in the Contract
- Potential sources of delay, such as groundwater inflows, shears and faults, boulders, buried utilities, manmade obstruction, gases, or contaminated soils or groundwater

Appendix A

Executive Summary
2005 Scan Study for the Underground Transportation Systems in Europe

Appendix A – Executive Summary – The International Scan Study for Underground Transportation Systems in Europe: Safety, Operation, and Emergency Responses Entire Report available on the FHWA web site at

http://International.fhwa.dot.gov/uts/uts.pdf

A.1 Introduction

Increasing traffic congestion in urban areas and growing land values in the United States make underground structures increasingly attractive for highways and transit compared to other options. A tunnel can preserve the land above for parks, buildings, homes, and other uses while providing an efficient, cost-effective underground corridor to move people and goods. Unfortunately, only limited national guidelines, standards, or specifications are available for tunnel design, construction, safety inspection, traffic and incident management, maintenance, security, and protection against natural or manmade disasters.

An 11-member team was formed to study European practices on the aforementioned topics. This team consisted of three representatives from the Federal Highway Administration (FHWA), four representatives from State departments of transportation (DOTs), one representative from the Bay Area Rapid Transit District (BART), one representative from the Massachusetts Turnpike Authority who also represented the International Bridge, Tunnel, and Turnpike Association (IBTTA), one tunnel engineering design consultant, and the report facilitator. The scan was sponsored by FHWA, the American Association of State Highway and Transportation Officials (AASHTO), and the National Cooperative Highway Research Program (NCHRP). During late September and early October 2005, the team visited Denmark, France, Norway, Sweden, and Switzerland. In addition, the team had meetings with representatives from Austria, Germany, Italy, and the Netherlands. These countries were selected on the basis of desk scan findings that showed they are innovators in underground transportation systems.

The objectives of the scan were to learn what is being done internationally for underground transportation systems in the areas of safety, operations, and emergency response. The focus of the scan was on equipment, systems, and procedures incorporated into modern underground and underwater tunnels by leading international engineers and designers. The study considered the following:

- Tunnel systems and designs that provide fire protection, blast protection, and areas of refuge or evacuation passages for users.
- Arrangements of the various components to maximize their effectiveness, assure inspectability and maintainability, and promote cost savings.
- Tunnel operations, including incident detection and deterrent technology, and incident response and recovery planning.
- Specialized technologies and standards used in monitoring or inspecting structural elements and operating equipment to ensure optimal performance and minimize downtime during maintenance or rehabilitation.

Regarding the safety and security aspects, the team was interested in learning about planning approaches, standards, manpower roles and responsibilities, communication techniques, and state-of-the-art products and equipment used to deter, detect, deny, defend, respond to, and recover from both natural and manmade disasters and other incidents.

Team members were interested in not only tunnel practices and innovations for highways, but also those for passenger and freight rail.

A.2 Findings and Recommendations

Team members identified a number of underground transportation system initiatives and practices that varied from those in the United States in some respect. The team recommended that nine of these initiatives or practices, briefly described below, be further considered for possible implementation in the United States. Little was discovered related to the threat from terrorism to underground structures, perhaps because of the confidential nature of this information or the lack of perceived need for such measures. The scan team learned that the Europeans consider response and safety measures already in place for crashes and other incidents to also be applicable for many terrorist actions.

The Europeans are doing extensive research resulting in innovative design and emergency management plans that consider how people react in tunnel emergencies. Because motorist behavior is unpredictable in tunnel incidents, Europeans make instructions for drivers, passengers, and tunnel operators as straightforward as possible to reduce required decision making during an incident such as a tunnel fire. The nine initiatives and practices listed below relate to human factors, planning, design, and incident and asset management.

1. Develop Universal, Consistent, and More Effective Visual, Audible, and Tactile Signs for Escape Routes

The scan team noted that the signs Europeans use to indicate emergency escape routes are consistent and uniform from country to country. Emergency escape routes are indicated by a sign showing a white-colored running figure on a green background. Other signs that indicate the direction (and in tunnels, the distance in meters) to the nearest emergency exit also have the white figure on a green background, as used in European buildings and airports. All SOS stations in the tunnels were identified by the color orange. This widespread uniformity promotes understanding by all people, and helps assure that in the event of an emergency, any confusion related to the location of the emergency exit will be minimized. In addition, the team learned that combining the use of sound that emanates from the sign, such as a sound alternating with a simple verbal message (e.g., “Exit Here”) with visual (and, where possible, tactile) cues makes the sign much more effective.

The U.S tunnel engineering community relies on National Fire Protection Association (NFPA) 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, and NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, for fire protection and fire life safety design standards. These standards should be reviewed and revised as necessary to incorporate the most current technology and results of recent human response studies on identification and design of escape portals, escape routes, and cross passages.

2. Develop AASHTO Guidelines for Existing and New Tunnels

Single-source guidelines for planning, design, construction, maintenance, and inspection of roads and bridges have been in place for many years. NFPA has developed standards for safety in highway tunnels and passenger rail tunnels. The American Public Transportation Association (APTA) has general safety standards and guidelines for passenger rail operations and maintenance that incorporate some of the NFPA standards by reference. However, AASHTO does not have standards or guidelines specifically for highway or passenger and freight rail tunnels. Recently, the AASHTO Subcommittee on Bridges and Structures created a new committee, the Technical Committee on Tunnels (T–20), to help address this problem. T–20 should take the lead in developing AASHTO standards and guidelines for existing and new tunnels, working with NFPA, APTA, FHWA, and the appropriate TRB committees on standards and guidelines for highway and passenger and freight rail tunnels. T–20 should consider tunnel safety measures such as the Mont Blanc Tunnel emergency pullout area and variable message sign showing maximum speed limit and required vehicle spacing, as well as refuge room requirements.

3. Conduct Research and Develop Guidelines on Tunnel Emergency Management that Includes Human Factors

Tunnel design solutions may not anticipate human behavior, and consistently predicting the way people will behave in an incident is not easy. During emergency situations, human behavior is even harder to predict as the stress of the situation replaces intellect with curiosity, fear, or even panic. During a tunnel emergency, people often must be their own first rescuers and must react correctly within a few minutes to survive. Tunnel emergency management scenarios and procedures must take human behavior into account to be fully effective in saving lives. The European experience in human factor design provides a good basis for the United States to discover and include more effective measures for tunnel planning, design, and emergency response.

4. Develop Education for Motorist Response to Tunnel Incidents

During an emergency situation, most people do not immediately know what to do to save themselves and others. Motorists are their own first rescuers, and European studies indicate that self-rescue may be the best first response for a tunnel incident. For this to be an effective strategy, it is important to educate the public about the importance of reacting quickly and correctly to a tunnel incident, such as a fire.

5. Evaluate Effectiveness of Automatic Incident Detection Systems and Intelligent Video for Tunnels

The scan team learned of sophisticated software that—using a computer system interfacing with ordinary video surveillance cameras—automatically detects, tracks, and records incidents. As it does so, it signals the operator to observe the event in question and allows the operator the opportunity to take the appropriate action. This concept can also be applied to detect other activities and incidents in areas besides tunnels, including terrorist activities, crashes, vandalism and other crimes, fires, and vehicle breakdowns.

6. Develop Tunnel Facility Design Criteria to Promote Optimal Driver Performance and Response to Incidents

The Europeans found that innovative tunnel design that includes improved geometry or more pleasing visual appearance will enhance driver safety, performance, and traffic operation. For example, the full-size model of one section of the twin roadway tube for the A–86 motorway in Paris demonstrates the effectiveness of good lighting and painting to improve motorist safety. It is a particularly important consideration for a tunnel roadway section designed with limited headroom. Tunnel designers should evaluate the materials and design details that are incorporated to reduce risks to ensure that they do not pose other unacceptable hazards. For example, paint used to enhance the visual experience should not produce toxic fumes or accelerate fire.

7. Investigate One-Button Systems to Initiate Emergency Response and Automated Sensor Systems to Determine Response

The European scan revealed that one of the most important considerations in responding to an incident is to take action immediately. For this to be effective, the operator must initiate several actions simultaneously. An example of how this immediate action is accomplished is the “press one button” solution that initiates several critical actions without giving the operator the chance to omit an important step or perform an action out of order. On the Mont Blanc Tunnel operations center control panel, operators can initiate several actions by moving a yellow line over the area where a fire incident is indicated on a computer screen. This “one-button” action reduces the need for time-consuming emergency decisions about ventilation control and operational procedures.

The Europeans observed that tunnel operations personnel have difficulty keeping up with events like tunnel fires, and they believe that an automatic system using devices like opacity sensors can help determine the correct response. A closed-loop data collection and analysis system that takes atmospheric conditions, tunnel air speed, and smoke density into account may best control fans and vents.

8. Use Risk-Management Approach to Tunnel Safety Inspection and Maintenance

The scan team learned that some organizations use a risk-based schedule for safety inspection and maintenance. Through knowledge of the systems and the structure gained from intelligent monitoring and analysis of the collected data, the owner can use a risk-based approach to schedule the time and frequency of inspections and establish priorities. It makes more sense to inspect less critical or more durable portions of the system on a less frequent basis, and concentrate inspection efforts on the more critical or more fragile components. A risk-based assessment of the condition of facilities also can be used to make optimal decisions on the scope and timing of facility maintenance or rehabilitation. This method offers a statistical process to manage the tunnel assets.

9. Implement Light-Emitting Diode Lighting for Safe Vehicle Distance and Edge Delineation in Tunnels

The scan team noted that in several European tunnels, light-emitting diode (LED) lights were installed along the edge of the tunnel at regular intervals of approximately 10 to 20 meters (m) (33 to 66 feet (ft)) to clearly identify the edge of the roadway. These lights were either white or a highly visible yellow color. In some tunnels, spaced among these edge-delineation lights were blue lights at 150-m (490-ft) intervals. Motorists are instructed through formal (for truck and bus drivers) and informal driver education to keep a safe distance between them and the vehicle in front, and that distance is indicated by the spacing of the blue lights. This visual cue is more reliable than asking motorists to establish distance between vehicles using speed-based guidelines, such as maintaining one car length spacing for every 16 kilometers per hour (10 miles per hour) of speed. The LED markers are also less susceptible to loss of visibility because of road grime and smoke during a tunnel fire.

A.3 IMPLEMENTATION ACTIVITIES

The scan team has developed a detailed implementation plan for the nine recommended initiatives and practices. Included in the plan are a number of technical presentations and written papers at national meetings and conferences sponsored by FHWA, AASHTO, and other organizations to disseminate information from the scan. Also included in the plan is coordination with AASHTO, FHWA, NFPA, and

APTA to advance these initiatives and practices, including assisting with the development of AASHTO standards and guidelines for highway tunnels and passenger and freight rail tunnels. Considerations for outreach to the public include the development of brochures and radio and television announcements. These and other planned activities are discussed in Chapter 3 of the Scan Report a. available on the FHWA web site at http://International.fhwa.dot.gov/uts/uts.pdf.

Appendix B

Descriptions for Rock Core Samples

Appendix B –Glossary of Terms Used in Rock Core Boring Logs

Arenaceous: A sedimentary rock descriptive term that signifies the rock consists in part of sand-size particles.

Argillaceous: A sedimentary rock descriptive term that signifies the rock is comprised of a large percentage (but less than 50%) of clay.

Bedding: A surface, generally planar or nearly planar, that visibly separates each successive layer of stratified rock from the preceding or following layer.

Swirly bedding: Tightly curved, wavy pattern throughout texture of rock.

Color-banding: Shades of alternating color in very thin bands parallel to the bedding. Differing lithology or grain size in the various bands is possible.

Discontinuity: A collective term for most types of joints, bedding planes, schistosity planes, shear and fault zones.

Fault: A fracture or fracture zone along which there has been recognizable displacement.

Fissile: Exhibiting the property of easily splitting into very thin layers parallel to the bedding.

Friable: Easily crumbled, as would be the case with rock that is poorly cemented.

Grain size:

Fine-grained (rock): Grain size not visible to just barely visible with naked eye.

Medium-grained (rock): Grain size barely to easily visible with the naked eye; up to 1/8 in. (3 mm).

Coarse-grained (rock): Grain size 1/8 in. (3 mm) or greater.

Joints: A break of geological origin in the continuity of a rock mass along which there has been no visible displacement.

Horizontal: Natural breaks inclined to a horizontal plane from 0^o to 5^o.

Low angle: Natural breaks inclined to a horizontal plane from 5^o to 35^o.

Moderately dipping: Natural breaks inclined to a horizontal plane from 35^o to 55^o.

High angle: Natural breaks inclined to a horizontal plane from 55^o to 85^o.

Vertical: Natural breaks inclined to a horizontal plane from 85^o to 90^o.

Mottling: Irregular color patches of limited extent.

Oolitic: Composed of smooth, rounded granules.

Parting: Natural break in the rock caused by change in lithology or grain size, parallel to the bedding. Unlike joints, which can be limited in extent or trend by the thickness of the formation, partings are usually persistent in every direction parallel to the bedding. Often marked by a very thin bed or seam of soft rock or mineral. Stylolitic partings are rough, irregular, and faced with argillaceous materials (see Stylolite).

Pit: Cavity up to 1/4 in. (6mm) size.

Shear: A localized expression of strain resulting from stresses that cause or tend to cause slippage along a plane at the contact of two contiguous parts of a body.

Slickensides: Smooth, highly polished argillaceous facing on a shear. Trace slickensides are not highly polished, but marked by some sign of small movement, such as very small polished areas and/or parallel grooves and striations on a joint face.

Stylolite: A surface, usually in homogeneous carbonate rocks, marked by an irregular and interlocking penetration of the two sides; in cross section it resembles a suture; the seam is characterized by a concentration of clay, carbon, or iron oxides.

Surface Planarity:

Planar - A flat surface.

Stepped - A surface with asperities or steps. The height of the asperity should be estimated or measured.

Wavy - A moderate undulating surface; curved, smoothly uneven.

Surface Roughness:

Very Rough - Near vertical steps and ridges occur on the discontinuity surface.

Rough - Some ridges and side-angle steps are evident; asperities are clearly visible; and discontinuity surface feels very abrasive.

Slightly Rough - Asperities on the discontinuity surface are distinguishable and can be felt.

Smooth - Surface appears smooth and feels so to the touch.

Slickensided - Visual evidence of polishing exists.

Trace: Amount less than 10%; not common.

Vug: Cavity larger than a pit; from 1/4 (6 mm) to 2 in. (50 mm) in size.

Many of the terms above were defined in the following two references:

1. Bates, R.L. and Jackson, J.A., EDS., Glossary of Geology, American Geological Institute, Falls Church, Va, 1980.
2. I.S.R.M., Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses.

Summary of Terms for Describing Rock Cores

GRAIN SIZE

TERM	GRAIN SIZE
Fine-grained	Not visible to barely visible with naked eye
Medium-grained	Barely to easily visible with naked eye; up to 1/8" (3 mm)
Coarse-grained	> 1/8" (3 mm)

CONTINUITY

TERM	LENGTH OF DRILL CORE STEM PIECES
Sound	>8" (200 mm)
Slightly Fractured	4"-8" (100-200 mm)
Moderately Fractured	1"-4" (25-100 mm)
Extremely Fractured	<1" (25 mm)

DISCONTINUITY DESCRIPTION

FRACTURE SPACING (JOINTS, FAULTS, OTHER FRACTURES)			BEDDING SPACING (MAY INCLUDE FOLIATION OR BANDING)		
DESCRIPTION	**SPACING**		**DESCRIPTION**	**SPACING**	
Extremely close	< 3/4 in	(<19 mm)	Laminated	< 1/2 in	(12 mm)
Very close	3/4 in - 2-1/2 in	(19 - 60 mm)	Very thin	1/2 in - 2 in	(12 - 50 mm)
Close	2-1/2 in - 8 in	(60 - 200 mm)	Thin	2 in - 1 ft	(50 - 300 mm)
Moderate	8 in - 2 ft	(200 - 600 mm)	Medium	1 ft - 3 ft	300 - 900 mm)
Wide	2 ft - 6 ft	(600 mm - 2.0 m)	Thick	3 ft - 10 ft	(900 mm - 3 m)
Very wide	6 ft - 20 ft	(2.0 - 6 m)	Massive	> 10 ft	(3 m)

Discontinuity Orientation (Angle): Measure the angle of discontinuity relative to a plane perpendicular to the longitudinal axis of the core. (For most cases, the core axis is vertical; therefore, the plane perpendicular to the core axis is horizontal.) Record orientation (angle) on log. For example, a horizontal bedding plane would have a 0 degree angle.

WEATHERING

TERM	DESCRIPTION	Grade
Unweathered	No visible sign of rock material weathering, perhaps slight discoloration on major discontinuity surfaces	I
Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discolored by weathering and may be somewhat weaker externally than in its fresh condition.	II
Moderately weathered	Less than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as corestones.	III
Highly weathered	More than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a discontinuous framework or as corestones.	IV
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.	V
Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported	VI

The terms and description below help to define some of the descriptions used in the above table.

Fresh	No visible sign of weathering of the rock material.
Discolored	The color of the original fresh rock material is changed. The degree of change from the original color should be indicated. If the color change is confined to particular mineral constituents, this should be mentioned
Decomposed	The rock is weathered to the condition of a soil in which the original material fabric is still intact, but some or all of the mineral grains are decomposed.
Disintegrated	The rock is weathered to the condition of a soil in which the original fabric is still intact. The rock is friable, but the mineral grains are not decomposed.

Summary of Terms for Describing Rock Cores (Continued)

STRENGTH OR HARDNESS

GRADE	DESCRIPTION	FIELD IDENTIFICATION	UNIAXIAL COMPRESSIVE STRENGTH , PSI (MPa)
R0	Extremely weak	Indented by thumbnail	40-150 (0.3-1)
R1	Very weak	Crumbles under firm blows with point of geological hammer, can be peeled by a pocket knife	150-700 (1-5)
R2	Weak rock	Can be peeled by a pocket knife with difficulty, shallow indentations made by firm blow with point of geological hammer	700-4000 (5-30)
R3	Medium strong	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with single firm blow of geological hammer	4000-7000 (30-50)
R4	Strong rock	Specimen requires more than one blow of geological hammer to fracture it	7000-15,000 (50-100)
R5	Very strong	Specimen requires many blows of geological hammer to fracture it	15,000-36,000 (100-250)
R6	Extremely strong	Specimen can only be chipped with geological hammer	>36,000 (>250)

Assess the strength of any filling materials along discontinuity surfaces in accordance with the following descriptions and grades.

GRADE	DESCRIPTION	FIELD IDENTIFICATION	UNIAXIAL COMPRESSIVE STRENGTH, KSF (KPa)
S1	Very soft clay	Easily penetrated several inches (cm) by fist	0.5 (25)
S2	Soft clay	Easily penetrated several inches (cm) by thumb	0.5-1.0 (25-50)
S3	Firm clay	Can be penetrated several inches (cm) by thumb with moderate effort	1.0-2.0 (50-100)
S4	Stiff clay	Readily indented by thumb but penetrated only with great effort	2.0-5.0 (100-250)
S5	Very stiff clay	Readily indented by thumbnail	5.0-10.0 (250-500)
S6	Hard clay	Indented with difficulty by thumbnail	>10.0 (>500)

- Grades S1 to S6 apply to cohesive soils for example clays, silty clays, and combinations of silts and clays with sand, generally slow draining. If non-cohesive fillings are identified, qualitatively identify, e.g., fine sand.
- Discontinuity wall strength will generally be characterized by grades R0-R6 (rock) while S1-S6 (clay) will generally apply to filled discontinuities.

JOINT ROUGHNESS (J_r) NUMBER

		J_r
ROCK WALL CONTACT ALONG DISCONTINUITY SURFACE		
A.	Discontinuous joints	4
B.	Rough or irregular, undulating	3
C.	Smooth, undulating	2
D.	Slickensided, undulating	1.5
E.	Rough or irregular, planar	1.5
F.	Smooth, planar	1.0
G.	Slickensided, planar	0.5
NO ROCK WALL CONTACT ALONG DISCONTINUITY SURFACE		
H.	Zone containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)
I.	Sandy, gravelly, or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)

JOINT ALTERNATION (J_a) NUMBER

		J_a
ROCK WALL CONTACT, OR COATING <1/8 IN. (3 MM) THICK		
A.	Tightly healed, hard, non-softening, impermeable filling. i.e., quartz or epidote	0.75
B.	Unaltered joint walls, surface staining only	1.0
C.	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock etc.	2.0
D.	Silty- or sandy-clay coatings, small clay-fraction (non-softening)	3.0
E.	Softening or low friction clay mineral coatings, i.e., kaolinite, mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	4.0
NO ROCK WALL CONTACT, CONTINUOUS COATINGS <1/4 IN (5 MM) THICK		
F.	Sandy particles, clay-free disintegrated rock etc.	4.0
G.	Strongly over-consolidation, softening, clay mineral fillings. (Continuous, <5 mm in thickness)	6.0
H.	Medium or low over-consolidation, softening, clay mineral fillings. (Continuous, <5 mm in thickness)	8.0
J.	Swelling clay fillings, i.e., montmorillonite (Continuous, <5 mm in thickness). Value of J_a depends on percent of swelling clay-size particles and access to water, etc.	8.0-12.0
NO ROCK WALL CONTACT, CONTINUOUS COATINGS >1/4 IN (5 MM) THICK		
K.,L.,M.	Crushed rock and clay (see G., H., J., for description of clay condition)	6.0, 8.0 or 8.0-12.0
N.	Zones or bands of silty- or sandy clay, small clay fraction (nonsoftening)	5.0
O.,P.,R.	Thick continuous zones or bands or clay (see G., H., J. for description of clay condition)	10.0, 13.0 or 13.0-20.0

Project: **Project Location:** **Project Number:**	**Log of Core Boring ___** Sheet 1 of ___

Date(s) Drilled		Logged By		Checked By	
Drilling Method		Drill Bit Size/Type		Total Depth Drilled (meters)	
Drill Rig Type		Drilled By		Inclination from Vertical/Bearing	
Apparent Groundwater Depth	___ m ATD ___ m after ___ hrs		___ m after ___ hrs	Approx. Surface Elevation (meters)	
Comments				Borehole Backfill	

Depth, meters	Elevation, meters	ROCK CORE							MATERIAL DESCRIPTION	Packer Tests	Laboratory Tests	Drill Rate, meters/hour	FIELD NOTES
		Run No.	Box No.	Recovery, %	Frac. Freq.	R Q D, %	Fracture Drawing/Number	Lithology					
0													
1													

Project: Project Location: Project Number:	**Key to Rock Core Log** Sheet 1 of 2

Depth, meters	Elevation, meters	ROCK CORE Run No.	Box No.	Recovery, %	Frac. Freq.	R Q D, %	Fracture Drawing/	Number	Lithology	MATERIAL DESCRIPTION	Packer Tests	Laboratory Tests	Drill Rate, meters/hour	FIELD NOTES
0														
1	2	3	4	5	6	7	8	9	10	11 META-ARKOSE, light gray, moderately weathered, moderately strong.	13	14	15	16
2		1	1	100	1	80				12 a b c d e f g h 1: 75, J, VN, Fe, Su, Pl, S, VC M: Mechanical Breakage				Slow drilling
4					0			1 M						

1 **Depth:** Distance (in meters) from the collar of the borehole.

2 **Elevation:** Elevation (in meters) from the collar of the borehole.

3 **Run No.:** Number of the individual coring interval, starting at the top of bedrock.

4 **Box No.:** Number of the core box which contains core from the corresponding run.

5 **Recovery:** Amount (in percent) of core recovered from the coring interval; calculated as the length of core recovered divided by the length of the run.

6 **Frac. Freq.:** (Fracture Frequency) The number of naturally occurring fractures in each foot of core; does not include mechanical breaks, which are considered to be induced by drilling.

7 **R Q D:** (Rock Quality Designation) Amount (in percent) of intact core (pieces of sound core greater than 100 mm in length) in each coring interval; calculated as the sum of the lengths of intact core divided by the length of the core run.

8 **Fracture Drawing:** Sketch of the naturally occurring fractures and mechanical breaks, showing the angle of the fractures relative to the cross-sectional axis of the core. "NR" indicates no recovery.

9 **Fracture Number:** Location of each naturally occurring fracture (numbered) and mechanical break (labeled "M"). Naturally occurring fractures are described in Column 11 (keyed by number) using descriptive terms defined on the following page (Items a - h).

10 **Lithology:** A graphic log presentation using symbols to represent differing rock types.

11 **Description:** Lithologic description in this order: rock type, color, texture, grain size, foliation, weathering, strength, and other features; descriptive terms are defined on the following page. A detailed descriptive log of overburden materials is not necessarily provided.

12 **Discontinuity Description:** Abbreviated description of fracture corresponding to number of naturally occurring fracture in Column 9 using terms defined on the following page (Items a - h).

13 **Packer Tests:** A vertical line depicts the interval over which a packer test is performed.

14 **Laboratory Tests:** A vertical line depicts the interval over which core has been removed for laboratory testing. Laboratory tests performed are indicated in Column 16.

15 **Drill Rate:** Rate (in meters per hour) of penetration of drilling. "N/O" indicates rate not observed.

16 **Field Notes:** Comments on drilling, including water loss, reasons for core loss, and use of drilling mud; also, laboratory tests performed on core.

Project: **Project Location:** **Project Number:**	**Key to Rock Core Log** Sheet 2 of 2

Depth, meters	Elevation, meters	ROCK CORE: Run No.	Box No.	Recovery, %	Frac. Freq.	R Q D, %	Fracture Drawing/ Number	Lithology	MATERIAL DESCRIPTION	Packer Tests	Laboratory Tests	Drill Rate, meters/hour	FIELD NOTES

KEY TO DESCRIPTIVE TERMS USED ON CORE LOGS

DISCONTINUITY DESCRIPTORS

a Dip of fracture surface measured relative to horizontal

b **Discontinuity Type:**
- F - Fault
- J - Joint
- Sh - Shear
- Fo - Foliation
- V - Vein
- B - Bedding

c **Discontinuity Width (millimeters):**
- W - Wide (12.5-50)
- MW - Moderately Wide (2.5-12.5)
- N - Narrow (1.25-2.5)
- VN - Very Narrow (<1.25)
- T - Tight (0)

d **Type of Infilling:**
- Cl - Clay
- Ca - Calcite
- Ch - Chlorite
- Fe - Iron Oxide
- Gy - Gypsum/Talc
- H - Healed
- No - None
- Py - Pyrite
- Qz - Quartz
- Sd - Sand

e **Amount of Infilling:**
- Su - Surface Stain
- Sp - Spotty
- Pa - Partially Filled
- Fi - Filled
- No - None

f **Surface Shape of Joint:**
- Wa - Wavy
- Pl - Planar
- St - Stepped
- Ir - Irregular

g **Roughness of Surface:**
- Slk - Slickensided [surface has smooth, glassy finish with visual evidence of striations]
- S - Smooth [surface appears smooth and feels so to the touch]
- SR - Slightly Rough [asperities on the discontinuity surfaces are distinguishable and can be felt]
- R - Rough [some ridges and side-angle steps are evident; asperities are clearly visible, and discontinuity surface feels very abrasive]
- VR - Very Rough [near-vertical steps and ridges occur on the discontinuity surface]

h **Discontinuity Spacing (meters):**
- EW - Extremely Wide (>20)
- W - Wide (7-20)
- M - Moderate (2.5-7)
- C - Close (0.7-2.5)
- VC - Very Close (<0.7)

ROCK WEATHERING / ALTERATION

Description	Recognition
Residual Soil	Original minerals of rock have been entirely decomposed to secondary minerals, and original rock fabric is not apparent; material can be easily broken by hand
Completely Weathered/Altered	Original minerals of rock have been almost entirely decomposed to secondary minerals, minerals, although original fabric may be intact; material can be granulated by hand
Highly Weathered/Altered	More than half of the rock is decomposed; rock is weakened so that a minimum 50-mm-diameter sample can be broken readily by hand across rock fabric
Moderately Weathered/Altered	Rock is discolored and noticeably weakened, but less than half is decomposed; a minimum 50-mm-diameter sample cannot be broken readily by hand across rock fabric
Slightly Weathered/Altered	Rock is slightly discolored, but not noticeably lower in strength than fresh rock
Fresh	Rock shows no discoloration, loss of strength, or other effect of weathering/alteration

ROCK STRENGTH

Description	Recognition	Approximate Uniaxial Compressive Strength (kPa)
Extremely Weak Rock	Can be indented by thumbnail	250 - 1,000
Very Weak Rock	Can be peeled by pocket knife	1,000 - 5,000
Weak Rock	Can be peeled with difficulty by pocket knife	5,000 - 25,000
Medium Strong Rock	Can be indented 5 mm with sharp end of pick	25,000 - 50,000
Strong Rock	Requires one hammer blow to fracture	50,000 - 100,000
Very Strong Rock	Requires many hammer blows to fracture	100,000 - 250,000
Extremely Strong Rock	Can only be chipped with hammer blows	> 250,000

Design & Construction of Road Tunnels: Part 1 Panning Quiz

1. **Road tunnels are defined as:**
   - Enclosed roadways with vehicle access that is restricted to portals
   - An enclosed roadway created by bridges
   - Open air highways
   - A black hole to another dimension
2. **The life expectancy of a tunnel is __________ those of bridges or roads.**
   - Significantly longer than
   - Significantly shorter than
   - Equal to
   - None measurable
3. **Road tunnels should have ______ traffic capacity as that of surface roads.**
   - The same
   - Less
   - More
   - Congestion
4. **What is the typical life expectancy of a tunnel?**
   - 90 Years
   - 125 Years
   - 100 Years
   - 3 billion years

Design & Construction of Road Tunnels: Part 1 Panning Quiz

5. **Which is not part of the basic process used in the design of a road tunnel?**

   - Perform tunnel type studies to determine the most appropriate method of tunneling
   - Perform risk analysis and identify mitigation measures and implement those measures
   - Establish tunnel alignment, profile and cross-section
   - None of the above

6. **Emergency exits should be spaced throughout the tunnel, not to exceed ______ feet**

   - 100
   - 2000
   - 1000
   - 500

7. **The tunnel drainage system should be designed to deal with:**

   - Surface drainage
   - Groundwater infiltration
   - None of the above
   - Both A & B

8. **In addition to general roadway requirements, road tunnels also require special considerations, such as:**

   - Fire protection systems
   - Emergency egress capacity
   - Lighting and ventilation
   - All of the above

Design & Construction of Road Tunnels: Part 1 Panning Quiz

9. **When planning and designing a tunnel, which conditions must be considered?**

   - Groundwater
   - Geotechnical
   - Geological
   - All of the above

10. **Maximum effective grades in tunnels, preferably, should not exceed:**

    - 15%
    - 10%
    - 5%
    - 4%

11. **Which type of curve may be required at the tunnel exit to allow drivers to gradually adjust to the brightness outside of the tunnel?**

    - Vertical
    - Horizontal
    - Diagonal
    - Parallel

12. **Which is not a typical shape of a tunnel?**

    - Rectangular
    - Square
    - Circular
    - Horseshoe

Design & Construction of Road Tunnels: Part 1 Panning Quiz

13. **What are the two primary criteria when determining the ventilation requirements of a tunnel?**

- The handling of noxious emissions from vehicles and handling the noxious emissions from environment
- The handling of noxious emissions from vehicles and the handling of smoke during a fire
- The handling of noxious emissions from the environment and the handling of smoke during a fire
- The handling of noise pollution and traffic congestion

14. **What is the "Black Hole Effect"?**

- The feeling of going from one end to the other end faster than the actual travel speed
- The tunnel structure shadowing the roadway
- The feeling of going from one end to the other end slower than the actual travel speed
- The tunnel structure leading to another dimension in time and space

15. **True or False: Orientation of the portals should avoid, if possible, direct East and West, to avoid blinding sunlight.**

- True
- False

16. **Which is a type of ventilation system used in tunnels?**

- Full transverse
- Semi-full transverse
- Longitudinal
- All of the above

Design & Construction of Road Tunnels: Part 1 Panning Quiz

17. **Which type of ventilations system has air supply ducts located above, below or to the side of the traffic tube?**

   - Full-transverse
   - Semi-full transverse
   - Longitudinal
   - Semi-Horizontal

18. **Which type of light is suggested to improve safety during a fire?**

   - LED light
   - Low-light
   - Hi-Light
   - Strobe light

19. **Which is not an investigation program for planning and designing a road tunnel?**

   - Surveys and site reconnaissance
   - Bridge safety investigations
   - Seismicity
   - Subsurface Investigations

20. **True or False: It is not necessary to obtain new aerial photography after examining older topographic maps and aerial photos, once a project corridor has been defined.**

   - True
   - False

21. **Which of the following techniques may be used for topographic surveys?**

   - Laser Scanning
   - Global Positioning System
   - Conventional Survey
   - All of the above

Design & Construction of Road Tunnels: Part 1 Panning Quiz

22. **When is a hydrographic survey required?**
    - For agriculture zones
    - When there is a large body of water near the project corridor
    - When there is a river near the project corridor
    - For subaqueous tunnels
23. **Which is not one of the three geotechnical reports for tunnel projects?**
    - Geotechnical Data Report
    - Geotechnical Design Memorandum
    - Geotechnical Contractual Agreement
    - Geotechnical Baseline Report
24. **True or False: For underground projects, vertical and slightly in lined test borings and soil/ rock samplings are key elements of any subsurface investigations.**
    - True
    - False
25. **Why is it important to properly seal all borings?**
    - To prevent cross contamination of sail strata and groundwater
    - To control inflow of water
    - To prevent the escape of slurry from a slurry shield
    - All of the above
26. **Which is not a typical item included in describing general rock lithology?**
    - Strength
    - Hardness
    - Rarity
    - Color

Design & Construction of Road Tunnels: Part 1 Panning Quiz

27. **Which is not a specialized test required for assessing a tunnel boring machine (TBM) performance rates?**
    - Drilling Rate Index
    - Bit Life Index
    - Bit Wear Index
    - Cutter Life Index
28. **What is the purpose of a pilot tunnel?**
    - A cheaper alternative to a tunnel project
    - To provide prospective bidders a clearer understanding of the ground conditions
    - The first mile of a tunnel
    - The last mile of a tunnel
29. **Which is not an element of a typical tunnel construction phase investigation program?**
    - Test pits
    - Geological mapping
    - Pilot tunnels
    - None of the above
30. **Why is it important to have continuous pumping tests?**
    - They are used to determine the permeability of subsurface materials
    - They are used to determine the water yield of individual wells
    - Both A and B
    - None of the above