GE-001 Tunnel Planning

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Technical Manual for
Design and Construction of Road Tunnels —
Civil Elements
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).
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, non-
conventional 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](image)

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;

\[
\begin{array}{ll}
\text{Tunnels} & \leq 0.002 \text{ gal/sq. ft/day} \\
\text{Underground public space} & \leq 0.001 \text{ gal/sq. ft/day}
\end{array}
\]

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.

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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 °F (1,000 °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)](image)

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 entirely 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, straightforward 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.