Design and Construction of Cut and Cover Road Tunnels

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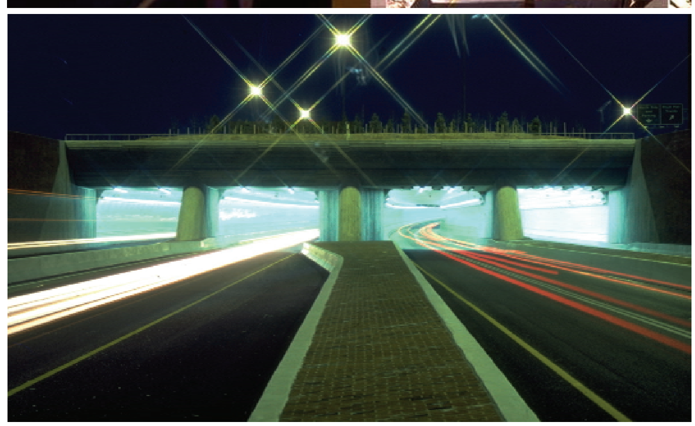
Technical Manual for Design and Construction of Road Tunnels — Civil Elements



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16. Abstract

The increased use of underground space for transportation systems and the increasing complexity and constraints of constructing and maintaining above ground transportation infrastructure have prompted the need to develop this technical manual. This FHWA manual is intended to be a single-source technical manual providing guidelines for planning, design, construction and rehabilitation of road tunnels, and encompasses various types of road tunnels including mined, bored, cut-and-cover, immersed, and jacked box tunnels. The scope of the manual is primarily limited to the civil elements of road tunnels.

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CONVERSION FACTORS

Approximate Conversions to SI Units			Approximate Conversions from SI Units		
When you know	Multiply by	To find	When you know	Multiply by	To find
(a) Length					
inch	25.4	millimeter	millimeter	0.039	inch
foot	0.305	meter	meter	3.28	foot
yard	0.914	meter	meter	1.09	yard
mile	1.61	kilometer	kilometer	0.621	mile
(b) Area					
square inches	645.2	square millimeters	square millimeters	0.0016	square inches
square feet	0.093	square meters	square meters	10.764	square feet
acres	0.405	hectares	hectares	2.47	acres
square miles	2.59	square kilometers	square kilometers	0.386	square miles
(c) Volume					
fluid ounces	29.57	milliliters	milliliters	0.034	fluid ounces
gallons	3.785	liters	liters	0.264	gallons
cubic feet	0.028	cubic meters	cubic meters	35.32	cubic feet
cubic yards	0.765	cubic meters	cubic meters	1.308	cubic yards
(d) Mass					
ounces	28.35	grams	grams	0.035	ounces
pounds	0.454	kilograms	kilograms	2.205	pounds
short tons (2000 lb)	0.907	megagrams (tonne)	megagrams (tonne)	1.102	short tons (2000 lb)
(e) Force					
pound	4.448	Newton	Newton	0.2248	pound
(f) Pressure, Stress, Modulus of Elasticity					
pounds per square foot	47.88	Pascals	Pascals	0.021	pounds per square foot
pounds per square inch	6.895	kiloPascals	kiloPascals	0.145	pounds per square inch
(g) Density					
pounds per cubic foot	16.019	kilograms per cubic meter	kilograms per cubic meter	0.0624	pounds per cubic feet
(h) Temperature					
Fahrenheit temperature(^{o}F)	5/9(^{o}F- 32)	Celsius temperature(^{o}C)	Celsius temperature(^{o}C)	9/5(^{o}C)+ 32	Fahrenheit temperature(^{o}F)

Notes: 1) The primary metric (SI) units used in civil engineering are meter (m), kilogram (kg), second(s), newton (N) and pascal (Pa=N/m^2).
2) In a "soft" conversion, an English measurement is mathematically converted to its exact metric equivalent.
3) In a "hard" conversion, a new rounded metric number is created that is convenient to work with and remember.

FOREWORD

The FHWA Technical Manual for Design and Construction of Road Tunnels – Civil Elements has been published to provide guidelines and recommendations for planning, design, construction and structural rehabilitation and repair of the civil elements of road tunnels, including cut-and-cover tunnels, mined and bored tunnels, immersed tunnels and jacked box tunnels. The latest edition of the AASHTO LRFD Bridge Design and Construction Specifications are used to the greatest extent applicable in the design examples. This manual focuses primarily on the civil elements of design and construction of road tunnels. It is the intent of FHWA to collaborate with AASHTO to further develop manuals for the design and construction of other key tunnel elements, such as, ventilation, lighting, fire life safety, mechanical, electrical and control systems.

FHWA intends to work with road tunnel owners in developing a manual on the maintenance, operation and inspection of road tunnels. This manual is expected to expand on the two currently available FHWA publications: (1) Highway and Rail Transit Tunnel Inspection Manual and (2) Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual.

M. Myint Lwin, Director
Office of Bridge Technology

PREFACE

The increased use of underground space for transportation systems and the increasing complexity and constraints of constructing and maintaining above ground transportation infrastructure have prompted the need to develop this technical manual. This FHWA manual is intended to be a single-source technical manual providing guidelines for planning, design, construction and rehabilitation of road tunnels, and encompasses various types of tunnels including mined and bored tunnels (Chapters 6-10), cut-and-cover tunnels (Chapter 5), immersed tunnels (Chapter 11), and jacked box tunnels (Chapter 12).

The scope of the manual is primarily limited to the civil elements of design and construction of road tunnels. FHWA intended to develop a separate manual to address in details the design and construction issues of the system elements of road tunnels including fire life safety, ventilation, lighting, drainage, finishes, etc. This manual therefore only provides limited guidance on the system elements when appropriate.

Accordingly, the manual is organized as presented below.

Chapter 1 is an introductory chapter and provides general overview of the planning process of a road tunnel project including alternative route study, tunnel type study, operation and financial planning, and risk analysis and management.

Chapter 2 provides the geometrical requirements and recommendations of new road tunnels including horizontal and vertical alignments and tunnel cross section requirements.

Chapter 3 covers the geotechnical investigative techniques and parameters required for planning, design and construction of road tunnels. In addition to subsurface investigations, this chapter also addresses in brief information study; survey; site reconnaissance, geologic mapping, instrumentation, and other investigations made during and after construction.

Chapter 4 discusses the common types of geotechnical reports required for planning, design and construction of road tunnels including: Geotechnical Data Report (GDR) which presents all the factual geotechnical data; Geotechnical Design Memorandum (GDM) which presents interpretations of the geotechnical data and other information used to develop the designs; and Geotechnical Baseline Report (GBR) which defines the baseline conditions on which contractors will base their bids upon.

Chapter 5 presents the construction methodology and excavation support systems for cut-and-cover road tunnels, describes the structural design in accordance with the AASHTO LRFD Bridge Design Specifications, and discusses various other design issues. A design example is included in Appendix C.

Chapters 6 through 10 present design recommendations and requirements for mined and bored road tunnels.

Chapters 6 and 7 present mined/bored tunneling issues in rock and soft ground, respectively. They present various excavation methods and temporary support elements and focus on the selection of temporary support of excavation and input for permanent lining design. Appendix D presents common types of rock and soft ground tunnel boring machines (TBM).

Chapter 8 addresses the investigation, design, construction and instrumentation concerns and issues for mining and boring in difficult ground conditions including: mixed face tunneling; high groundwater pressure and inflow; unstable ground such as running sands, sensitive clays, faults and shear zones, etc.; squeezing ground; swelling ground; and gassy ground.

Chapter 9 introduces the history, principles, and recent development of mined tunneling using Sequential Excavation Method (SEM), as commonly known as the New Austrian Tunneling Method (NATM). This chapter focuses on the analysis, design and construction issues for SEM tunneling.

Chapter 10 discusses permanent lining structural design and detailing for mined and bored tunnels based on LRFD methodology, and presents overall processes for design and construction of permanent tunnel lining. It encompasses various structural systems used for permanent linings including cast-in-place concrete lining, precast concrete segmental lining, steel line plate lining and shotcrete lining. A design example is presented in Appendix G.

Chapter 11 discusses immersed tunnel design and construction. It identifies various immersed tunnel types and their construction techniques. It also addresses the structural design approach and provides insights on the construction methodologies including fabrication, transportation, placement, joining and backfilling. It addresses the tunnel elements water tightness and the trench stability and foundation preparation requirements.

Chapter 12 presents jacked box tunneling, a unique tunneling method for constructing shallow rectangular road tunnels beneath critical facilities such as operating railways, major highways and airport runways without disruption of the services provided by these surface facilities or having to relocate them temporarily to accommodate open excavations for cut and cover construction.

Chapter 13 provides general procedure for seismic design and analysis of tunnel structures, which are based primarily on the ground deformation approach (as opposed to the inertial force approach); i.e., the structures should be designed to accommodate the deformations imposed by the ground.

Chapter 14 discusses tunnel construction engineering issues, i.e., the engineering that must go into a road tunnel project to make it constructible. This chapter examines various issues that need be engineered during the design process including project cost drivers; construction staging and sequencing; health and safety issues; muck transportation and disposal; and risk management and dispute resolution.

Chapter 15 presents the typical geotechnical and structural instrumentation for monitoring: 1), ground movement away from the tunnel; 2), building movement for structures within the zone of influence; 3), tunnel movement of the tunnel being constructed or adjacent tubes; 4), dynamic ground motion from drill & blast operation, and 5), groundwater movement due to changes in the water percolation pattern.

Lastly, **Chapter 16** focuses on the identification, characterization and rehabilitation of structural defects in a tunnel system.

CHAPTER 5
CUT AND COVER TUNNELS

5.1 INTRODUCTION

This chapter presents the construction methodology and excavation support systems for cut-and-cover road tunnels and describes the structural design in accordance with the AASHTO LRFD Bridge Design Specifications (AASHTO, 2008). The intent of this chapter is to provide guidance in the interpretation of the AASHTO LRFD Specifications in order to have a more uniform application of the code and to provide guidance in the design of items not specifically addressed in AASHTO (2008). The designers must follow the latest LRFD Specifications. A design example illustrating the concepts presented in this chapter can be found in Appendix C. Other considerations dealing with support of excavation, maintenance of traffic and utilities, and control of groundwater and how they affect the structural design are discussed.

5.2 CONSTRUCTION METHODOLOGY

5.2.1 General

In a cut and cover tunnel, the structure is built inside an excavation and covered over with backfill material when construction of the structure is complete. Cut and cover construction is used when the tunnel profile is shallow and the excavation from the surface is possible, economical, and acceptable. Cut and cover construction is used for underpasses, the approach sections to mined tunnels and for tunnels in flat terrain or where it is advantageous to construct the tunnel at a shallow depth. Two types of construction are employed to build cut and cover tunnels; bottom-up and top-down. These construction types are described in more detail below. The planning process used to determine the appropriate profile and alignment for tunnels is discussed in Chapter 1 of this manual.

Figure 5-1 is an illustration of cut and cover tunnel bottom-up and top-down construction. Figure 5-1(a) illustrates Bottom-Up Construction where the final structure is independent of the support of excavation walls. Figure 5-1(b) illustrates Top-Down Construction where the tunnel roof and ceiling are structural parts of the support of excavation walls.

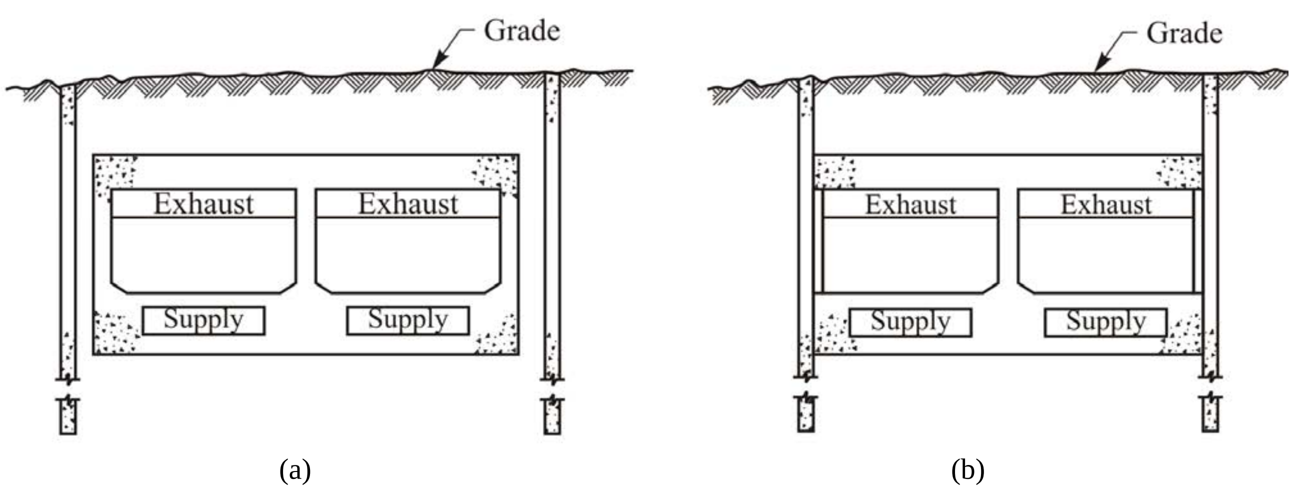


Figure 5-1 Cut and Cover Tunnel Bottom-Up Construction (a); Top-Down Construction (b)

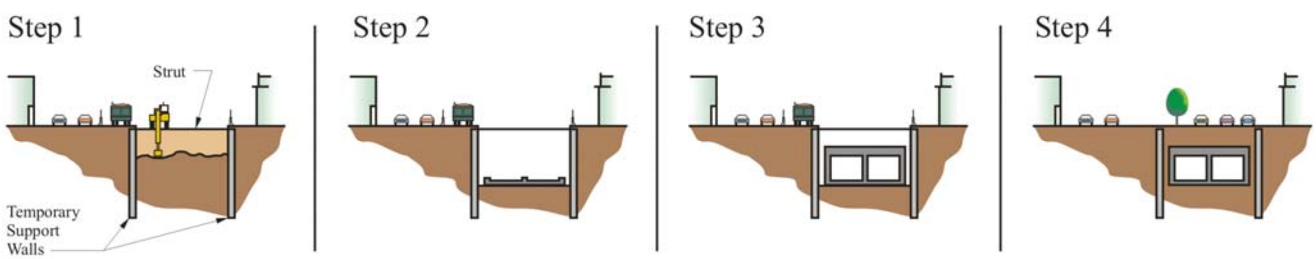
For depths of 30 to 40 feet (about 10 m to 12 m), cut-and-cover is usually more economical and more practical than mined or bored tunneling. The cut-and-cover tunnel is usually designed as a rigid frame box structure. In urban areas, due to the limited available space, the tunnel is usually constructed within a neat excavation line using braced or tied back excavation supporting walls. Wherever construction space permits, in open areas beyond urban development, it may be more economical to employ open cut construction.

Where the tunnel alignment is beneath a city street, the cut-and-cover construction will cause interference with traffic and other urban activities. This disruption can be lessened through the use of decking over the excavation to restore traffic. While most cut-and-cover tunnels have a relatively shallow depth to the invert, depths to 60 feet (18 m) are not uncommon; depths rarely exceed 100 feet (30 m).

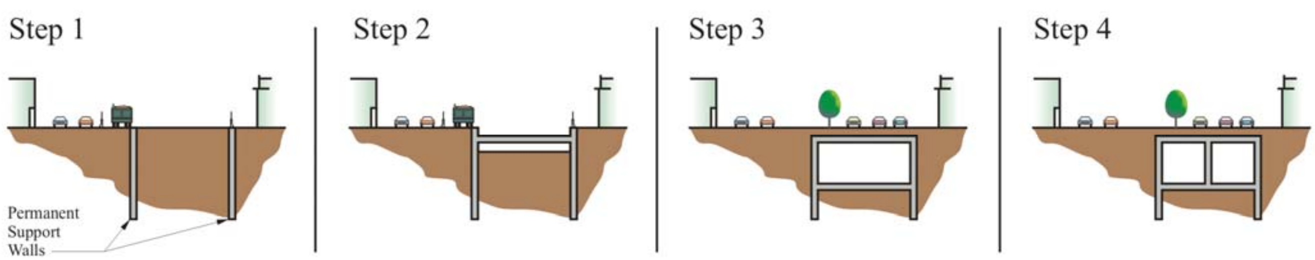
Although the support of excavation is an important aspect of cut and cover construction, the design of support of excavation, unless it is part of the permanent structure, is not covered in this chapter.

5.2.2 Conventional Bottom-Up Construction

As shown in Figure 5-2, in the conventional “bottom-up” construction, a trench is excavated from the surface within which the tunnel is constructed and then the trench is backfilled and the surface restored afterward. The trench can be formed using open cut (sides sloped back and unsupported), or with vertical faces using an excavation support system. In bottom-up construction, the tunnel is completed before it is covered up and the surface reinstated.



(a)



(b)

Figure 5-2 Cut-and-Cover Tunnel Bottom-Up (a) and Top-Down (b) Construction Sequence

Conventional bottom-up sequence of construction in Figure 5-2(a) generally consists of the following steps:

Step 1a: Installation of temporary excavation support walls, such as soldier pile and lagging, sheet piling, slurry walls, tangent or secant pile walls
Step 1b: Dewatering within the trench if required
Step 1c: Excavation and installation of temporary wall support elements such as struts or tie backs
Step 2: Construction of the tunnel structure by constructing the floor;
Step 3: Compete construction of the walls and then the roof, apply waterproofing as required;
Step 4: Backfilling to final grade and restoring the ground surface.

Bottom-up construction offers several advantages:

- It is a conventional construction method well understood by contractors.
- Waterproofing can be applied to the outside surface of the structure.
- The inside of the excavation is easily accessible for the construction equipment and the delivery, storage and placement of materials.
- Drainage systems can be installed outside the structure to channel water or divert it away from the structure.

Disadvantages of bottom-up construction include:

- Somewhat larger footprint required for construction than for top-down construction.
- The ground surface can not be restored to its final condition until construction is complete.
- Requires temporary support or relocation of utilities.
- May require dewatering that could have adverse affects on surrounding infrastructure.

5.2.3 Top-Down Construction

With top-down construction in Figure 5-2 (b), the tunnel walls are constructed first, usually using slurry walls, although secant pile walls are also used. In this method the support of excavation is often the final structural tunnel walls. Secondary finishing walls are provided upon completion of the construction. Next the roof is constructed and tied into the support of excavation walls. The surface is then reinstated before the completion of the construction. The remainder of the excavation is completed under the protection of the top slab. Upon the completion of the excavation, the floor is completed and tied into the walls. The tunnel finishes are installed within the completed structure. For wider tunnels, temporary or permanent piles or wall elements are sometimes installed along the center of the proposed tunnel to reduce the span of the roof and floors of the tunnel.

Top-down sequence of construction generally consists of the following steps:

Step 1a : Installation of excavation support/tunnel structural walls, such as slurry walls or secant pile walls
Step 1b: Dewatering within the excavation limits if required
Step 2a: Excavation to the level of the bottom of the tunnel top slab
Step 2b: Construction and waterproofing of the tunnel top slab tying it to the support of excavation walls
Step 3a: Backfilling the roof and restoring the ground surface
Step 3b: Excavation of tunnel interior, bracing of the support of excavation walls is installed as required during excavation

Step 3c: Construction of the tunnel floor slab and tying it to the support of excavation walls; and
Step 4 Completing the interior finishes including the secondary walls.

Top-down construction offers several advantages in comparison to bottom-up construction:

- It allows early restoration of the ground surface above the tunnel
- The temporary support of excavation walls are used as the permanent structural walls
- The structural slabs will act as internal bracing for the support of excavation thus reducing the amount of tie backs required
- It requires somewhat less width for the construction area
- Easier construction of roof since it can be cast on prepared grade rather than using bottom forms
- It may result in lower cost for the tunnel by the elimination of the separate, cast-in-place concrete walls within the excavation and reducing the need for tie backs and internal bracing
- It may result in shorter construction duration by overlapping construction activities

Disadvantages of top-down construction include:

- Inability to install external waterproofing outside the tunnel walls.
- More complicated connections for the roof, floor and base slabs.
- Potential water leakage at the joints between the slabs and the walls
- Risks that the exterior walls (or center columns) will exceed specified installation tolerances and extend within the neat line of the interior space.
- Access to the excavation is limited to the portals or through shafts through the roof.
- Limited spaces for excavation and construction of the bottom slab

5.2.4 Selection

It is difficult to generalize the use of a particular construction method since each project is unique and has any number of constraints and variables that should be evaluated when selecting a construction method. The following summary presents conditions that may make a one construction method more attractive than the other. This summary should be used in conjunction with a careful evaluation of all factors associated with a project to make a final determination of the construction method to be used.

Conditions Favorable to Bottom-Up Construction:

- No right-of way restrictions
- No requirement to limit sidewall deflections
- No requirement for permanent restoration of surface

Conditions Favorable to Top-Down Construction

- Limited width of right-of-way
- Sidewall deflections must be limited to protect adjacent features
- Surface must be restored to permanent usable condition as soon as possible

5.3 SUPPORT OF EXCAVATION

5.3.1 General

The practical range of depth for cut and cover construction is between 30 and 40 feet (about 10 m to 12 m). Sometimes, it can approach 100 feet. Excavations for building cut and cover tunnels must be designed and constructed to provide a safe working space, provide access for construction activities and protect structures, utilities and other infrastructure adjacent to the excavation. The design of excavation support systems requires consideration of a variety of factors that affect the performance of the support system and that have impacts on the tunnel structure itself. These factors are discussed hereafter.

Excavation support systems fall into three general categories:

- Open cut slope: This is used in areas where sufficient room is available to open cut the area of the tunnel and slope the sides back to meet the adjacent existing ground line (Figure 5-3). The slopes are designed similar to any other cut slope taking into account the natural repose angle of the in-situ material and the global stability.

- Temporary: This is a structure designed to support vertical or near vertical faces of the excavation in areas where room to open cut does not exist. This structure does not contribute to the final load carrying capacity of the tunnel structure and is either abandoned in placed or dismantled as the excavation is being backfilled. Generally it consists of soldier piles and lagging, sheet pile walls, slurry walls, secant piles or tangent piles.

- Permanent: This is a structure designed to support vertical or near vertical faces of the excavation in areas where room to open cut does not exist. This structure forms part of the permanent final tunnel structure. Generally it consists of slurry walls, secant pile walls, or tangent pile walls.

Figure 5-3 Cut and Cover Construction using Side Slopes Excavation- Ft McHenry Tunnel, Baltimore, MD

This section discusses temporary and permanent support of excavation systems and provides issues and concerns that must be considered during the development of a support of excavation scheme. The design of open-cut slopes and support of excavation are not in the scope of this manual. Information on the design of soil and rock slopes can be found in FHWA-NHI-05-123 "Soil Slope and Embankment Design" (FHWA, 2005d), and NHI-99-007 "Rock Slopes" (FHWA, 1999), respectively. Supports of Excavation are referred to FHWA-NHI-05-046 "Earth Retaining Structure" (FHWA, 2005e). Many of the issues described below associated with ground and groundwater behavior are applicable to side slopes also.

5.3.2 Temporary Support of Excavation

Support of excavation structures can be classified as flexible or rigid. Flexible supports of excavation include sheet piling and soldier pile and lagging walls. A careful site investigation that provides a clear understanding of the subsurface conditions is essential to determining the correct support system. Rigid support of excavation such as slurry walls, secant piles or tangent piles are also used as temporary support of excavation. Descriptions of these systems are provided Section 5.3.3 Permanent Support of Excavation.

A sheet piling wall consists of a series of interlocking sheets that form a corrugated pattern in the plan view of the wall. The sheets are either driven or vibrated into the ground. The sheets extend well below the bottom of the excavation for stability. These sheets are fairly flexible and can support only small heights of earth without bracing. As the excavation progresses, bracings or tie backs are installed at specified intervals. Sheet pile walls can be installed quickly and easily in ideal soil conditions. The presence of rock, boulders, debris, utilities, or obstructions will make the use of sheet piling difficult since these features will either damage the sheet pile or in the case of a utility, be damaged by the sheet pile. Figure 5-4 shows a sheet pile wall with complex multi level internal bracing.

Figure 5-4 Sheet Pile Walls with Multi Level-Bracing

A soldier pile wall consists of structural steel shape columns spaced 4 to 8 feet apart and driven into the ground or placed in predrilled holes. The soldier piles extend well below the level of the bottom of excavation for stability. As the excavation progresses, lagging is placed between the soldier piles to retain the earth behind the wall. The lagging could be timber or concrete planks. The soldier piles are relatively flexible and are capable of supporting only modest heights of earth without bracing. As the excavation progresses, bracing or tie backs are installed at specified intervals. Soldier piles can also be installed in more different ground conditions than can a sheet pile wall. The spacing allows the installation of piles around utilities. The finite dimension of the pile allows drilling of holes through obstructions and into rock, making the soldier pile and lagging wall more versatile than the sheet pile wall. Figure 5-5 shows a braced soldier pile and lagging wall.

Figure 5-5 Braced Soldier Pile and Lagging Wall

Support of excavation bracing can consist of struts across the excavation to the opposite wall, knee braces that brace the wall against the ground, and tie backs consisting of rock anchors or soil anchors that tie the wall back into the earth behind the wall. Struts and braces extend into the working area and create obstacles to the construction of the tunnel. Tie backs do not obstruct the excavation space but sometimes they extend outside of the available right-of-way requiring temporary underground easements. They may also encounter obstacles such as boulders, utilities or building foundations. The suitability of tie backs depends on the soil conditions behind the wall. The site conditions must be studied and understood and taken into account when deciding on the appropriate bracing method. Figure 5-6 shows an excavation braced by tie-backs, leaving the inside of the excavation clear for construction activities.

The design and detailing of the support of excavation must consider the sequence of installation and account for the changing loading conditions that will occur as the system is installed. The design of temporary support of excavation is not in the scope of this manual. The information presented herein is intended to make tunnel designers aware of the impact that the selected support of excavation can have on the design, constructability and serviceability of the tunnel structure. Guidance on the design of support of excavation can be found in FHWA-NHI-05-046 "Earth Retaining Structure" (FHWA, 2005e).

Figure 5-6 Tie-back Excavation Support leaves Clear Access

Use of temporary support of excavation does have the advantage of allowing waterproofing to be applied to the outside face of the tunnel structure. This can be accomplished by setting the face of the support of excavation away from the outside face of the tunnel structure. This space provides room for forming and allows the placement of waterproofing directly onto the finished outside face of the structure. As an alternate, the face of the support of excavation can be placed directly adjacent to the outside face of the structure. Under this scenario, the face of the support of excavation is used as the form for the tunnel structure. Waterproofing is installed against the support of excavation and concrete is poured against the waterproofing. In this case, the temporary support of excavation wall is abandoned in place.

5.3.3 Permanent Support of Excavation

Permanent support of excavation typically employs rigid systems. Rigid systems consist of slurry walls, soldier pile tremie concrete (SPTC) walls, tangent pile walls, or secant pile walls. As with temporary support of excavation systems, a careful site investigation that provides a clear understanding of the subsurface conditions is essential to determining the appropriate system.

A slurry wall is constructed by excavating a trench to the thickness required for the external structural wall of the tunnel. Slurry walls are usually 30 to 48 inches thick. The trench is kept open by the placement of bentonite slurry in the trench as it is excavated. The trench will typically extend for some distance below the bottom of the tunnel structure for stability. Reinforcing steel is lowered into the slurry filled trench and concrete is then placed using the tremie method into the trench displacing the slurry. The resulting wall will eventually be incorporated into the final tunnel structure. Excavation proceeds from the original ground surface down to the bottom of the roof of the tunnel structure. The tunnel roof is constructed and tied into the slurry wall. The tunnel roof provides bracing for the slurry wall. Depending on the depth of the tunnel, the roof could be the first level of bracing or an intermediate level. The excavation would then proceed and additional bracing would be provided as needed. At the base of the excavation, the tunnel bottom slab is then constructed and tied into the walls. Figure 5-7 shows a slurry wall supported excavation in an urban area.

Figure 5-7 Braced Slurry Walls

SPTC walls are constructed in the same sequence as a slurry wall. However, once the trench is excavated, steel beams or girders are lowered into the slurry in addition to reinforcing steel to provide added capacity. The construction of the wall then follows the same sequence as that described above for a slurry wall.

Tangent pile (drilled shaft) walls consist of a series of drilled shafts located such that the adjacent shafts touch each other, hence the name tangent wall. The shafts are usually 24 to 48 inches in diameter and extend below the bottom of the tunnel structure for stability. The typical sequence of construction of tangent piles begins with the excavation of every third drilled shaft. The shafts are held open if required by temporary casing. A steel beam or reinforcing bar cage is placed inside the shaft and the shaft is then filled with concrete. If a casing is used, it is pulled as the tremie concrete placement progresses. Once the concrete backfill cures sufficiently, the next set of every third shaft is constructed in the same sequence as the first set. Finally, after curing of the concrete in the second set, the third and final set of shafts is constructed, completing the walls. Excavation within the walls then proceeds with bracing installed as required to the bottom of the excavation. Roof and floor slabs are constructed and tied into the tangent pile. The roof and floor slabs act as bracing levels. Figure 5-8 is a schematic showing the sequence of construction in plan view. Figure 5-9 shows a completed tangent pile wall.

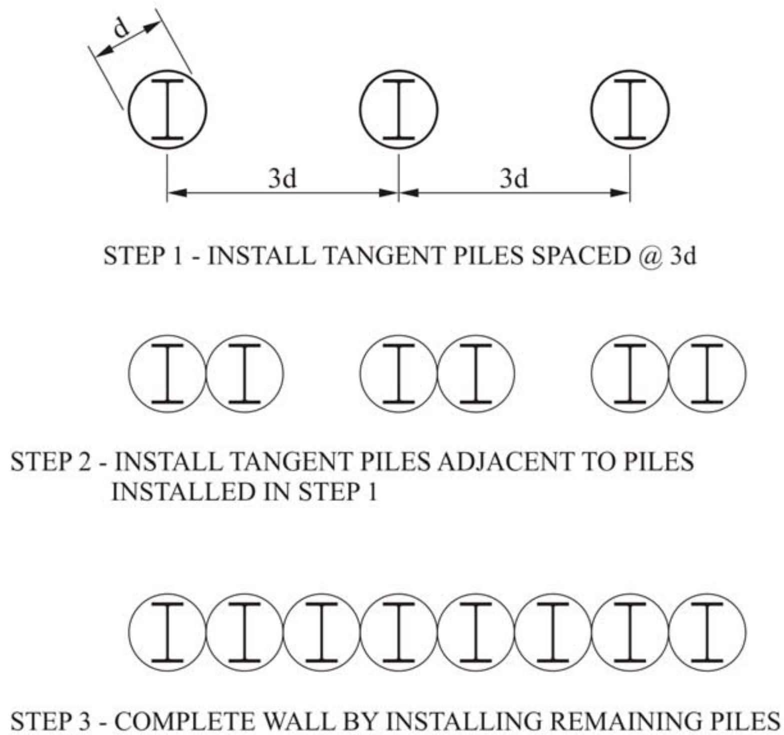


Figure 5-8 Tangent Pile Wall Construction Schematic

Figure 5-9 Tangent Pile Wall Support

Secant pile walls are similar to tangent pile walls except that the drilled shafts overlap each other rather than touch each other. This occurs because the center to center spacing of secant piles is less than the diameter of the piles. Secant pile walls are stiffer than tangent piles walls and are more effective in keeping ground water out of the excavation. They are constructed in the same sequence as tangent pile walls. However, the installation of adjacent secant piles requires the removal of a portion of the previously constructed pile, specifically a portion of the concrete backfill. Figure 5-10 is a schematic showing a plan view of a completed secant pile wall.

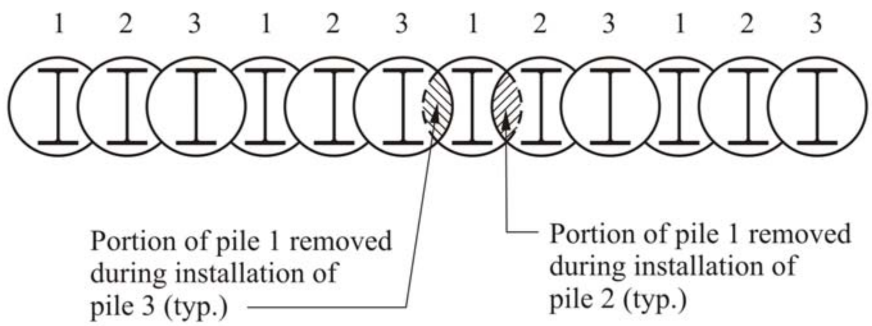


Figure 5-10 Completed Secant Pile Wall Plan View

In general, rigid support systems have more load carrying capacity than flexible systems. This additional load carrying capacity means that they require less bracing. Minimizing the amount of bracing results in fewer obstruction inside the excavation if struts or braces are used, making construction activities easier to execute. Rigid wall systems incorporated into the final structure can also reduce the overall cost of the structure because they combine the support of excavation with the final structure. Waterproofing permanent support walls and detailing the connections between the walls and other structure members are difficult. This difficulty can potentially lead to leakage of groundwater into the tunnel. The design and detailing of the support of excavation must consider the sequence of installation and account for the changing loading conditions that will occur as the excavation proceeds and the system is installed.

5.3.4 Ground Movement and Impact on Adjoining Structures

An important issue for cut-and-cover tunnel analysis and design is the evaluation and mitigation of construction impacts on adjacent structures, facilities, and utilities. By the nature of the methods used, cut-and-cover constructions are much more disruptive than bored tunnels. It is important for engineers to be familiar with analytical aspects of evaluating soil movement as a result of the excavation, and the impacts it can have on existing buildings and utilities at the construction site. Soil movement can be due to deflection of the support of excavation walls and ground consolidation:

- Deflection of support of excavation walls: Walls will deflect into the excavation as it proceeds prior to installation of each level of struts or tiebacks supporting the wall. The deflection is greater for flexible support systems than for rigid systems. The deflections are not recoverable and they are cumulative.
- Consolidation due to dewatering: In excavations where the water table is high, it is often necessary to dewater inside the excavation to avoid instability. Dewatering inside the cut may lead to a drop in the hydrostatic pressure outside the cut. Depending on the soil strata, this can lead to consolidation and settlement of the ground.

Existing buildings and facilities must be evaluated for the soil movement estimated to occur due to the support wall movement during excavation. This evaluation depends on the type of existing structure, its distance and orientation from the excavation, the soil conditions, the type of foundations of the structure, and other parameters. The analysis is site specific, and it can be very complex. Empirical methods and screening tools are available to more generally characterize the potential impacts. The existing buildings and facilities within the zone of influence must be surveyed (Chapter 3) and monitored as discussed in Chapter 15 Geotechnical and Structural Instrumentation.

Measures to deal with this issue include:

- Design of stiffer and more watertight excavation support walls.
- Provide more closely spaced and stiffer excavation support braces and/or tiebacks.
- Use of pre-excavation soil improvement.
- Underpinning of existing structures.
- Provide monitoring and instrumentation program during excavation.
- Establish requirement for mitigation plans if movements approach allowable limits.

5.3.5 Base Stability

Poor soil beneath the excavation bottom may require that the excavation support structure be extended down to a more competent stratum to ensure the base stability of the structure. This may depend upon whether the earth pressures applied to the wall together with its weight can be transferred to the surrounding soil through a combination of adhesion (side friction) and end bearing.

Soft clays below the excavation are particularly susceptible to yielding causing the bottom of the excavation to heave with a potential settlement at the ground surface, or worse to blow up. High groundwater table outside of the excavation can result in base instability as well. Measures to analyze the subsurface condition, and provide sufficient base stability must be addressed by the geotechnical engineer and/or tunnel designer. Readers are referred to FHWA-NHI-05-046 “Earth Retaining Structure” (FHWA, 2005e) for more details.

5.4 STRUCTURAL SYSTEMS

5.4.1 General

A structural system study is often prepared to determine the most suitable structural alternatives for the construction of the cut-and-cover tunnel. This involves a determination of the proposed tunnel section as discussed in Chapter 2, the excavation support system, the tunnel structural system, the construction method (top-down vs. bottom up), and the waterproofing system. Each of these elements is interdependent upon the other. Options for each element are discussed below. The system study should consider all options that are feasible in a holistic approach, taking into account the effect that one option for an element has on another element.

5.4.1.1 Structural Element Sizing

As described in Chapter 1, the shape of the cut and cover tunnels is generally rectangular. The dimensions of the rectangular box must be sufficient to accommodate the clearance requirements (Chapter 2). Dimensional information required for structural sizing includes wall heights and the span lengths of the roof. The width of the tunnel walls added to the clear space width requirements will determine the final width of the excavation required to construct the tunnel. To minimize the horizontal width of the excavation the support of excavation can be incorporated as part of, the final structure.

However, this might have negative impacts on the watertightness of the structure. Some reasons that would require minimization of the out to out width of the excavation are:

- Limited horizontal right-of-way. In urban areas where tunnels are constructed along built up city streets, additional right-of-way may be impractical to obtain. There may be existing buildings foundations adjacent to the tunnel or utilities that are impractical to move.
- There may be natural features that make a wider excavation undesirable or not feasible such as rock or bodies of water.

The depth of the roof and floor combined with the clearance requirements will define the vertical height of the tunnel structure, the depth of excavation required, and the height of the associated support of excavation. It is recommended in cut-and-cover construction that the tunnel depth be minimized to reduce the overall cost which extends beyond the cost of the tunnel structure. A shallower profile grade can also result in shorter approaches and approach grades that are more favorable to the operational characteristics of the vehicles using the tunnel resulting in lower costs for the users of the tunnel.

5.4.2 Structural Framing

The framing model for the tunnel will be different according to whether the support of excavation walls is a temporary (non-integral) or a permanent (integral) part of the final structure. With temporary support of excavation walls, the tunnel section would be considered a frame with fixed joints. When support of excavation walls are to form part of the tunnel structure, fixed connections between the support of excavation walls and the rest of the structure may be difficult to achieve in practice; partial fixity is more probable, but to what degree may be difficult to define. A range of fixities may need to be considered in the design analysis.

Corners of rectangular tunnels often incorporate haunches to increase the member's shear capacity near the support, in effect creating more of an arched shape. A true arch shape provides an efficient solution for the tunnel roof but tends to create other issues. Flat arches result in horizontal loads at the spring line that must be resisted by the walls. Semicircular arches eliminate these forces but result in a section larger than required vertically and drive down the tunnel profile which will add cost. When using temporary support of excavation walls, the tunnel section is constructed totally within them, often with a layer of waterproofing completely enveloping the section. In contrast, when the support of excavation walls become part of the final structure, an enveloping membrane is difficult to achieve. Therefore, provisions for overlapping, enveloping and sealing the joints would be needed. Furthermore, physical keying of the structural top and bottom slabs into the support of excavation walls is essential for any transmission of moments and shear.

Some old tunnels employ a structural system consisting of transverse structural steel frames spaced about 5 feet (1.5 m) apart. Typically, these frames are embedded in un-reinforced cast-in-place floors and walls, while for the roof, these frames are exposed and support a cast-in-place roof slab. This type of construction may still be competitive when applied to shallow tunnels, especially when longer roof spans are required for multiple lane cross sections. More details on these issues are provided in the following paragraphs that described specific materials for construction.

5.4.3 Materials

Cast-in-place concrete is the most common building material used in cut and cover tunnel construction, however other materials such as precast prestressed concrete, post tensioned concrete and structural steel are used. These materials and their application are discussed below.

5.4.3.1 Cast-in-Place Concrete

Cast-in-place concrete is commonly used in tunnel construction due to the ease with which large members can be constructed in restricted work spaces. Formwork can be brought in small manageable pieces and assembled into forms for large thick members. Complex geometry can be readily constructed utilizing concrete, although the formwork may be difficult to construct. Concrete is a durable material that performs well in the conditions that exist in underground structures. The low shear capacity of concrete can be offset by thickening the roof and the floor at the corners as shown in Figure 5-11.

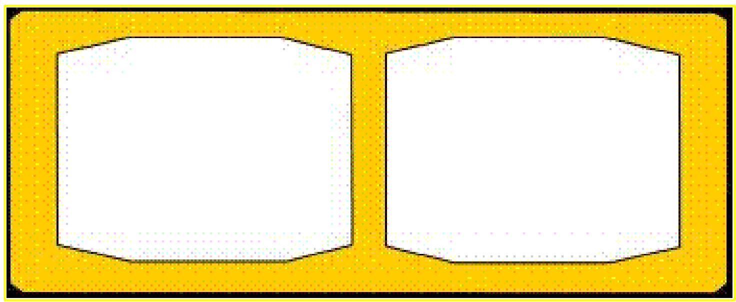


Figure 5-11 Tunnel Structure with Haunches

Connecting the structural concrete members to permanent support of excavation walls can be challenging. A simple end connection can be created quickly by placing the concrete slab in precut seats or pockets in the walls; however this results in a less efficient structure with thicker structural elements. Full moment connections can be created using splicing of reinforcing steel if sufficient wall pockets can be provided. When creating a full moment connection, the walls must be detailed to accept the transferred moment. To minimize the amount of wall pocket required, mechanical splicing or welding can be used. Waterproofing the connection, as well as the remainder of the structure, when using permanent support of excavation walls as part of the structure, is challenging.

Proper detailing of concrete members and application of all AASHTO requirements in terms of reinforcing steel is essential to create a durable concrete structure. The minimum requirements for shrinkage reinforcement should be noted. Using a larger number of smaller bars rather than a small number of large bars helps distribute cracks and consequently reduces their size. Ground water chemistry should be investigated to ensure that proper mix designs compatible with ground water chemistry are used to reduce the potential for chemical attack of the concrete.

5.4.3.2 Structural Steel

Structural steel has excellent weight to strength characteristics. Structural steel beams with a composite slab can be used to reduce the thickness of roof slabs. This can reduce the depth to the profile with the accompanying reductions in overall cost of the tunnel associated with a shallower excavation and shorter retained tunnel approaches. Structural steel is easier to connect to permanent support of excavation walls than are concrete slabs. Local removal of the permanent wall in small isolated pockets is all that is required to provide a seat for the steel beam creating a simple end. If simple ends are used, the movement of the beam due to temperature changes inside the tunnel should be accommodated. If the support of excavation used SPTC, tangent or secant pile walls, the embedded steel cores of these walls can be exposed and a full moment connection can be made. A full moment connection will not allow temperature movements, so the resulting force effects must be evaluated and accommodated by design.

Structural steel beams are best fabricated and delivered in a single piece. However, if the excavation support system has complex internal bracing, it may not be possible to deliver and erect the steel beams inside the excavation which would require splicing of the steel beams. Connections also require careful inspection which adds to the future maintenance cost of the tunnel if the connections are not encased. Waterproofing the connections to the exterior walls can be difficult. Tunnels typically produce a damp environment, if combined with the potential to leak around connections, this results in conditions that can result in aggressive corrosion to steel members. Corrosion protection must be considered as part of the structural steel structural system.

In addition to the roof structure described above, steel frames have also been used in road tunnels and under some circumstances, may still be appropriate. The frame includes columns and the roof beams. In permanent support walls, the columns would be embedded in the walls. The steel columns are erected on a suitable foundation cast on the bottom of the excavation, the beams are then erected and joined with the columns and the entire frames are then encased in concrete, with nominal reinforcement. The roof beams can be completely encased or exposed supporting a thin concrete roof slab. If exposed, inspection and maintenance are required.

5.4.3.3 Prestressed Concrete

Prestressed concrete, including precast prestressed beams such as AASHTO beams or similar, may be suitable for large roof spans when clearances are tight and the overall depth of section must be limited. Precast prestressed beams have been used for the top slab supported on cast in place walls. Precast concrete beams, in the number and lengths required for cut and cover tunnels are impractical to splice. They must be delivered in a single piece and be able to be erected within the space available inside the excavation. The type and configuration of the excavation must therefore be considered when evaluating the use of precast concrete beams. Making connections with permanent support of excavation walls can be accomplished by creating pockets in the walls to support the beams in a simple support arrangement. Simple supports also require a method for allowing movement of the beams during temperature changes inside the tunnel. Waterproofing this connection is difficult. Making a moment connection requires more elaborate details of the junction between the wall and the beam to be able to install the reinforcing required for the moment connection. A moment connection at the beam also requires that the wall itself be capable of accepting the moment transferred by the beam. Therefore the detailing of the wall must be compatible with the structural system selected. A full moment connection will not allow temperature movements, so the resulting force effects must be evaluated and accommodated by the design.

Although seldom, post tensioning is used in cut and cover tunnels; however in developing the post tensioning strategy, it is important to consider the various loading stages and potentially have multiple stages of post tensioning. For example, the introduction of high post-tensioning forces in tunnel slabs before backfilling causes temporary high tensile stresses in the opposite face of the slabs. These stresses may limit the depth to which post-tensioned members can be used, unless some of the tendons are tensioned from inside the box after backfilling. The elastic shortening of the slab will induce resistance to the post-tensioning via the walls, and should be taken into consideration. The additional moments created will also need to be resisted. Isolating the top slab from the walls by means of a movement joint (such as neoprene or Teflon bearings) would eliminate the above shortcomings but also eliminate the advantages of moment connection; waterproofing of the movement joint will need to be addressed. The design should identify space requirements for operation of the stressing jacks from both sides (if required). In many cases, the tendon would be less than 100 ft (30 m) long, needing only one end for stressing. Usually, in such a case, alternate strands would be stressed from alternate ends, requiring suitable space on each side.

5.4.4 Buoyancy

Buoyancy is a major concern in shallow tunnels that are under or partially within the water table. Buoyancy should be checked during the design. The structural system selected should take into account its ability to resist buoyancy forces with its own weight or by providing measures to deal with negative buoyancy. In cases where the structure and backfill are not heavy enough to resist the buoyancy forces, flotation can occur. Measures to resist the forces of flotation must be provided and accounted for in the design.

The resistance against flotation can be achieved by a variety of methods. Typical methods used to increase the effective weight of the structure include:

- Connecting the structure to the excavation support system and thus mobilizing its weight and/or its friction with the ground
- Thickening structural members beyond what is required for strength in order to provide dead load to counter the flotation forces
- Widening the floor slab of the tunnel beyond the required footprint to key it into adjacent soil and thus to include the weight of soil above these protrusions
- Using steel or concrete tension piles to resist the uplift forces associated with flotation
- Using permanent tie-down anchors; in soils, it may be prudent for the anchors only to carry a nominal tension under normal conditions and for the anchors to be fully mobilized only under extreme conditions. Properly protected anchor heads can be located in formed recesses within the base slab
- Permanent pressure relief system beneath the base of the structure. This is a complicated system to remove the buoyant forces by allowing water to be collected from under the bottom slab and removed from the tunnel. This type of system requires maintenance and redundancy in addition to the life cycle costs associated with operating the system. It can also have the effect of lowering the local groundwater table which may have negative consequences.

Considering the long design life of underground structures, the design of tension piles or tie-down anchors to resist flotation forces must include provisions to address the risk of corrosion of these tension elements and consideration of their connection to the tunnel structure. Similarly, the use of an invert pressure relief system and backup system must include provisions to address the risk of the long-term operation and maintenance requirements. For most projects, generally, buoyancy forces are resisted by increased dead load of the structure and/or weight of fill above the structure.

5.4.5 Expansion and Contraction Joints

Many cut and cover tunnels are constructed without permanent expansion or contraction joints. Although expansion joints may not be required except close to the portals, contraction joints are recommended throughout the tunnel. Significant changes in support stiffness or surcharge can cause differential settlement. If the induced moments and shears resulting from this are greater than the section can handle, relieving joints can be used to accommodate localized problems. Expansion joints are usually provided at the interfacing with ventilation building or portals or other rigid structures to allow for differential settlements and movements associated with temperature changes. It is recommended that contraction joints be placed at intervals of approximately 30 feet (about 9 m).

Seismic loading can cause significant bending moments in cut and cover tunnels. Joints may be used to relieve the moments and shears that would have occurred in continuous rigid structures, particularly as the width (and hence the stiffness) of the structure increases. Joints may also be required to handle relative seismic motion at locations where the cross-sectional properties change significantly, such as at ventilation buildings and portals. Such motion can be both longitudinal and transverse (horizontal and vertical) to the tunnel.

Joints are potential areas were leaks can occur. As such, they are potential sources of high maintenance costs over the life of the tunnel. The number of joints should be minimized and special care should be taken in the detailing of joints to ensure water tightness. The type and frequency of joints required will be a function of the structural system required and should be evaluated in the overall decision of the type selected.

5.4.6 Waterproofing

The existence of a high groundwater table or water percolating down from above requires that tunnels be waterproof. Durability is improved when the tunnel is waterproof. Good waterproofing design is also imperative to keep the tunnel dry and reduce future maintenance. Leaking tunnels are unsightly and can give rise to concern by users. In colder climates such as in the North East, leaks can become hazardous ceiling icicles or ice patches on roadways. Tunnel waterproofing is discussed breifly in Chapter 10. The waterproofing system should be selected based on the required performance and its compatibility with the structural system.

5.5 LOADS

5.5.1 General

The relevant loads to be considered in the design of the cut and cover tunnel structures along with how to combine the loads are given in Section 3 of the AASHTO LRFD specifications. Section 3 of the AASHTO LRFD specification divides loads into two categories: Permanent Loads and Transient Loads. Paragraph 3.3.2 "Load and Load Designation" of the AASHTO LRFD specifications defines following permanent loads that are applicable to the design of cut and cover tunnels:

DC = Dead Load: This load comprises the self weight of the structural components as well as the loads associated with nonstructural attachments. Nonstructural attachments can be signs, lighting fixtures, signals, architectural finishes, waterproofing, etc. Typical unit weights for common building materials are given in Table 3.5.1-1 of the AASHTO LRFD specifications. Actual weights for other items should be calculated based on their composition and configuration.

DW = Dead Load: This load comprises the self weight of wearing surfaces and utilities. Utilities in tunnels can include power lines, drainage pipes, communication lines, water supply lines, etc. Wearing surfaces can be asphalt or concrete. Dead loads, wearing surfaces and utilities should calculate based on the actual size and configuration of these items.

EH = Horizontal Earth Pressure Load. The information required to calculate this load is derived by the geotechnical data developed during the subsurface investigation program. In lieu of actual subsurface data, the information contained in paragraph 3.11 of the AASHTO specifications can be used. *At-rest pressures should be used in the design of cut and cover tunnel structure.*

EL = Accumulated locked-in force effects resulting from the construction process including secondary forces from post tensioning if used.

ES = Earth surcharge load. This is the vertical earth load due to fill over the structure that was placed above the original ground line. *It is recommended that a minimum surcharge load of 400 psf be used in the design of cut and cover tunnels.* If there is a potential for future development over the tunnel structure, the surcharge from the actual development should be used in the design of the structure. In lieu of a well defined loading, it is recommended that *a minimum value of 1000 psf be used when future development is anticipated*.

EV = Vertical pressure from the dead load of the earth fill. This is the vertical earth load due to fill over the structure up to the original ground line. The information required to calculate this load are derived by the geotechnical data developed during the subsurface investigation program. In lieu of actual subsurface data, the information contained in paragraph 3.11 of the AASHTO specifications can be used. Note that AASHTO provides modification factors for this load based on soil structure interaction in paragraph 12.11.2.

Paragraph 3.3.2 "Load and Load Designation" of the LRFD specifications defines following transient loads that are applicable to the design of cut and cover structures:

CR = Creep.

CT = Vehicular Collision Force: This load would be applied to individual components of the tunnel structure that could be damaged by vehicular collision. Typically, tunnel walls are very massive or are protected by redirecting barriers so that this load need be considered only under usual circumstances. It is preferable to detail tunnel structural components so that they are not subject to damage from vehicular impact.

EQ = Earthquake. This load should be applied to the tunnel lining as appropriate for the seismic zone for the tunnel. The scope of this manual does not include the calculation of or design for seismic loads. However, some recommendations are provided in Chapter 13 – Seismic Considerations". The designer should be aware that seismic loads should be accounted for in the design of the tunnel lining in accordance with LRFD Specifications.

IM = Vehicle dynamic load allowance: This load can apply to the roadway slabs of tunnels and can also be applied to roof slab of tunnels that are constructed under other roadways, rail lines, runways or other facilities that carry moving vehicles. An equation for the calculation of this load is given in paragraph 3.6.2.2 of the AASHTO LRFD specifications.

LL = Vehicular Live Load: This load can apply to the roadway slabs of tunnels and can also be applied to roof slab of tunnels that are constructed under other roadways, rail lines, runways or other facilities that carry moving vehicles. This load would be distributed through the earth fill prior to being applied to the tunnel roof, unless traffic bears directly on the tunnel roof. Guidance for the distribution of live loads to buried structures can be found in paragraphs 3.6.1 and 12.11.2 of the AASHTO LRFD specifications.

SH = Shrinkage. Cut and cover tunnel structural elements usually are relatively massive. As such, shrinkage can be a problem especially if the exterior surfaces are restrained. This load should be accounted for in the design or the structure should be detailed to minimize or eliminate it.

TG = Temperature Gradient. Cut and cover structural elements are typically constructed of concrete which has a large thermal lag. Combined with being surrounded by an insulating soil backfill that maintains a relatively constant temperature, the temperature gradient across the thickness of the members can be measurable. This load should be examined on case by case basis depending on the local climate and seasonal variations in average temperatures. Paragraph 4.6.6 of the AASHTO LRFD specifications provides guidance on calculating this load. Note that paragraph C3.12.3 allows the use of engineering judgment to determine if this load need be considered in the design of the structure.

TU = Uniform Temperature. This load is used primarily to size expansion joints in the structure. If movement is permitted at the expansion joints, no additional loading need be applied to the structure. Since the structure is rigid in the primary direction of thermal movement, the effects of the friction force resulting from thermal movement can be neglected in the design. Some components may be individually subject to this load. The case where concrete or steel beams support the roof slab is an example. If these beams are framed into the side walls to create a full moment connection, the expansion and contraction of these beams will add force effect to the frames formed by the connection. This effect must be accommodated in the design. This effect is usually not considered in the case of a cast-in-place concrete box structure due to the insulating qualities of the surrounding ground and the large thermal lag of concrete.

WA = Water load. This load represents the hydrostatic pressure expected outside the tunnel structure. Tunnel structures are typically detailed to be watertight without provisions for relieving the hydrostatic pressure. As such, the tunnel is subject to horizontal hydrostatic pressure on the sidewalls, vertical hydrostatic pressure on the roof and a buoyancy force on the floor. Hydrostatic pressure acts normal to the surface of the tunnel. It should be assumed that water will develop full hydrostatic pressure on the tunnel walls, roof and floor. The design should take into account the specific gravity of the groundwater which can be saline near salt water. Both maximum and minimum hydrostatic loads should be used for structural calculations as appropriate to the member being designed. For the purpose of design, the hydrostatic pressures assumed to be applied to underground structures should ignore pore pressure relief obtained by any seepage into the structures unless an appropriately designed pressure relief system is installed and maintained. Two groundwater levels should be considered: normal (observed maximum groundwater level) and extreme, 3 ft (1 m) above the design flood level (100 to 200 year flood).

Some of the loads sown in paragraph 3.3.2 of the LRFD specifications are not shown above because they are not applicable to the design of cut and cover highway tunnels as described below.

DD = Downdrag: This load comprises the vertical force applied to the exterior walls of a top-down structure that can result from the subsidence of the surrounding soil due to the subsidence of the in-situ soil below the bottom of the tunnel. This load would not apply to cut and cover structures since it requires subsidence or settlement of the material below the bottom of the structure to engage the downdrag force of the walls. For the typical highway tunnel, the overall weight of the structure is usually less than the soil it is replacing. As such, unless backfill in excess of the original ground elevation is paced over the tunnel or a structure is constructed over the tunnel, settlement will not be an issue for cut and cover tunnels.

BR = Vehicular Breaking Force: This load would be applied only under special conditions where the detailing of the structure requires consideration of this load. Under typical designs, this force is resisted by the mass of the roadway slab and need not be considered in design.

CE = Vehicular centrifugal force: This load would be applied only under special conditions where the detailing of the structure requires consideration of this load. Under typical designs, this force is resisted by the mass of the roadway slab and need not be considered in design.

CV = Vessel Collision Force is generally not applicable to cut and cover construction unless it is done under a body of water such as in a cofferdam. It is applicable to immersed tube tunnels, which are a specialized form of cut and cover tunnel and are covered separately in Chapter 11 of this manual.

FR = Friction. As stated above, the structure is usually rigid in the direction of thermal movement. Thermal movement is the source of the friction force. In a typical tunnel, the effects of friction can be neglected.

IC = Ice load. Since the tunnel is not subjected to stream flow nor exposed to the weather in a manner that could result in an accumulation of ice, this load is not used in cut and cover tunnel design.

PL = Pedestrian Live load. Pedestrian are typically not allowed in road tunnels, so there is no need to design for a pedestrian loading.

SE = Settlement. For the typical road tunnel, the overall weight of the structure is usually less than the soil it is replacing. As such, unless backfill in excess of the original ground elevation is paced over the tunnel or a structure is constructed over the tunnel, settlement will not be an issue for cut and cover tunnels. If settlement is anticipated due to poor subsurface conditions or due to the addition of load onto the structure or changing ground conditions along the length of the tunnel, it is recommended that ground improvement measures or deep foundation (piles or drilled shafts) be used to support the structure.

WL = Wind on live load. The tunnel structure is not exposed to the environment, so it will not be subjected to wind loads.

WS = Wind load on structure. The tunnel structure is not exposed to the environment, so it will not be subjected to wind loads.

Section 3 of the LRFD specifications provides guidance on the methods to be used in the computations of these loads. The design example in Appendix C shows the calculations involved in computing these loads. The order of construction will impact loading and assumptions. For example, in top down construction, permanent support of excavation walls used as part of the final structure will receive heavier bearing loads, because the roof is placed and loaded before the base slab is constructed. The permanent support of excavation walls are also braced as the excavation progresses by the roof slab resulting a different lateral soil pressure distribution than would be found in the free standing walls of a cast-in-place concrete structure constructed using bottom up construction. The base slab of a top-down construction tunnel acts as a mat for supporting vertical loads, but it is not available until towards the end of construction of the section eliminating its use to resist moments from the walls or to act as bracing for the walls. Typical loading diagrams are illustrated respectively for bottom-up and top-down structures in Figure 5-12, and Figure 5-13, respectively.

5.5.2 Load Combinations

The loads described above should be factored and combined in accordance with the LRFD specification and applied to the structure. Cut and cover structures are considered buried structures and as such the design is governed by Section 12 of the AASHTO LRFD specifications. Paragraph 12.5.1 gives the limit states and load combinations that are applicable for buried structures as Service Limit State Load Combination I and Strength Limit State Load Combinations I and II. These load combinations are given in Table 3.4.1-1 of the AASHTO Specifications. In some cases, the absence of live load can create a governing case. For example, live load can reduce the effects of buoyancy. Therefore, in addition to the

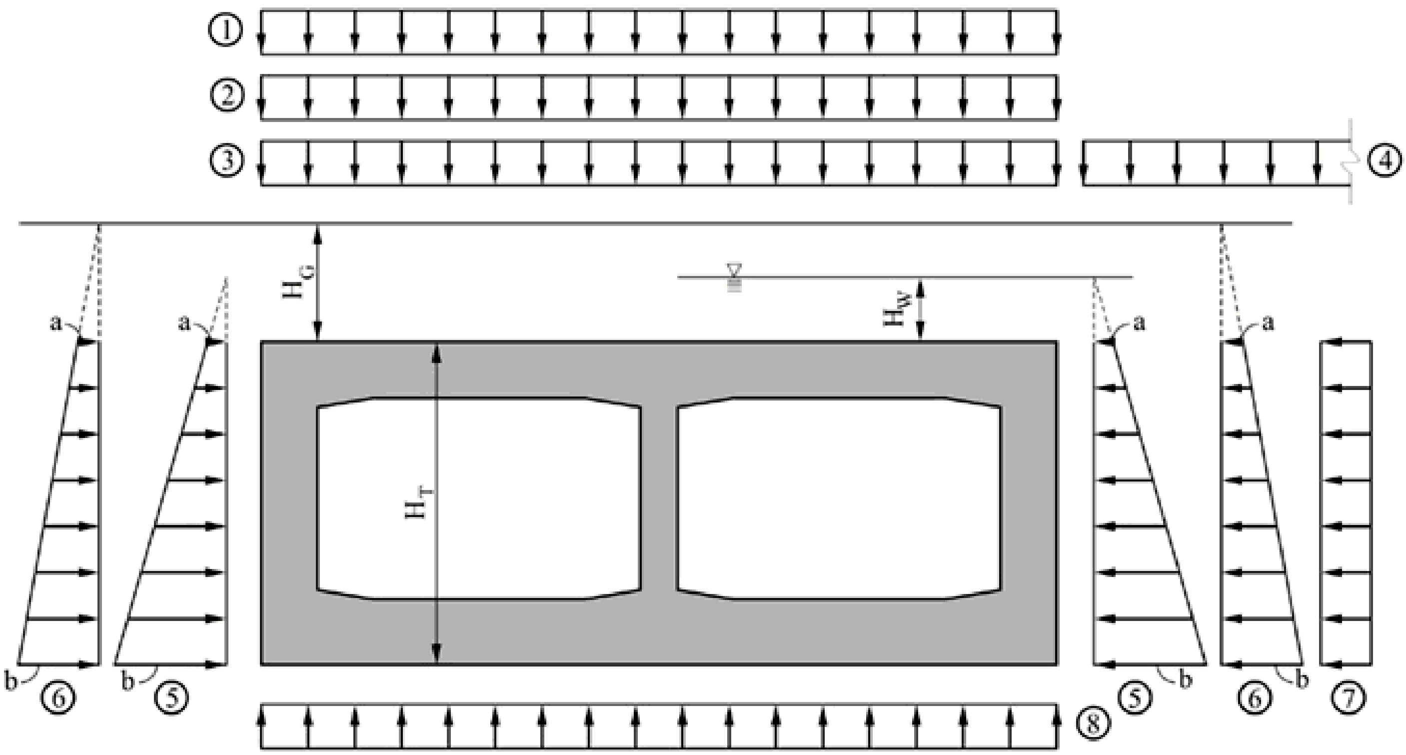


FIGURE 5-12
CUT AND COVER TUNNEL LOADING DIAGRAM - BOTTOM UP CONSTRUCTION IN SOIL

1 - Live load - determined as per site conditions & AASHTO LRFD specifications

2 - Vertical Earth Load = $\gamma_S(H_G - H_W) + \gamma_{S_b}(H_W)$

3 - Vertical Hydrostatic Pressure = $\gamma_W H_W$

4 - Vertical Surcharge Load - determined as per site conditions (F_S)

5 - Horizontal Hydrostatic Load: $a = \gamma_W H_W$ $b = \gamma_W (H_W + H_T)$

6 - Horizontal Earth Load: $a = \gamma_S R_O (H_G - H_W) + \gamma_{S_b} R_O H_W$ $b = a + \gamma_{S_b} R_O H_T$

7 - Horizontal Surcharge Load = $F_S R_O$

8 - Vertical Hydrostatic Load (Buoyancy) = $\gamma_W (H_W + H_T)$

Where:

γ_S = dry unit weight of soil

γ_{S_b} = buoyant unit weight of soil

H_G = height of backfill over the tunnel

H_W = height of water table over the tunnel

H_T = height of the tunnel structure

R_O = at rest lateral earth pressure coeffecient

F_S = magnitude of surcharge in units of Force/Area

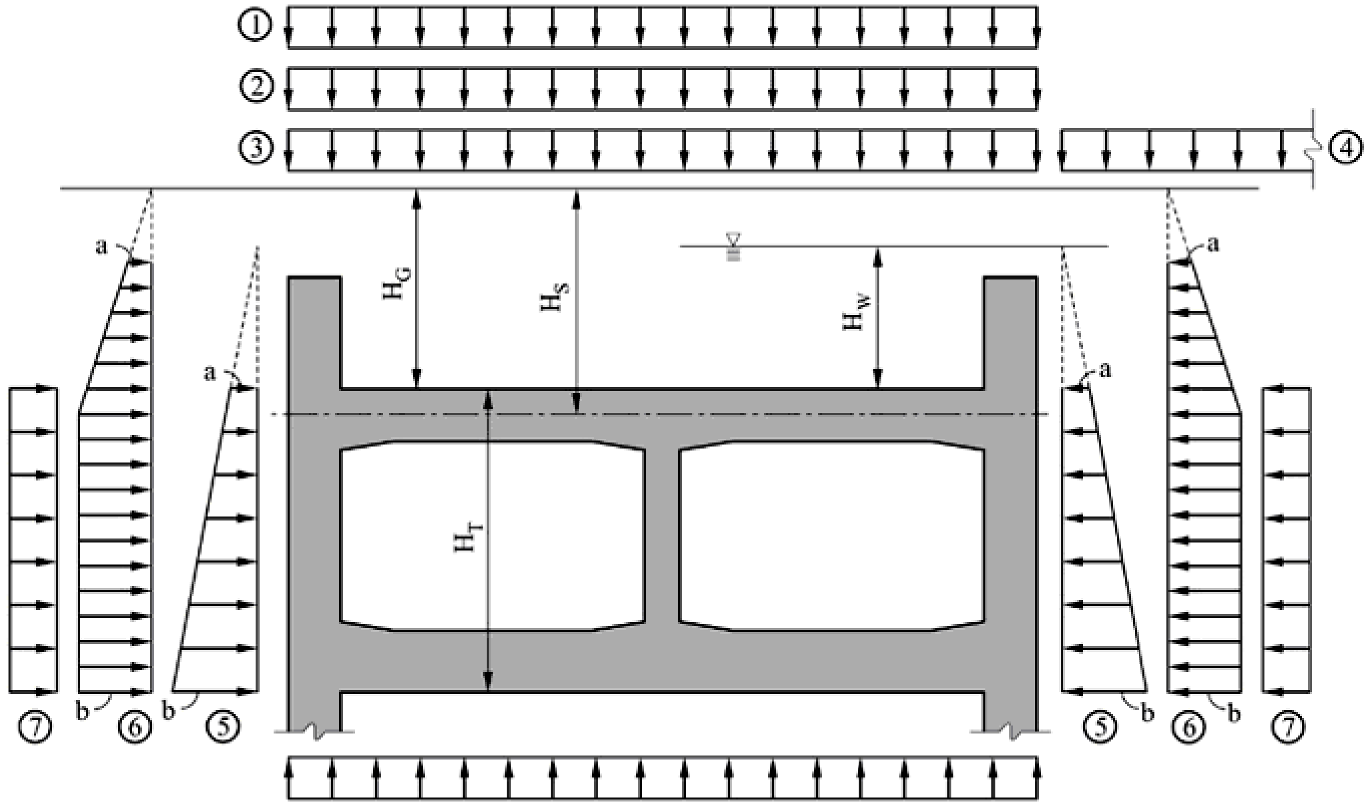


FIGURE 5-13
CUT AND COVER TUNNEL LOADING DIAGRAM TOP-DOWN CONSTRUCTION IN SOIL

1 - Live load - determined as per site conditions & AASHTO LRFD specifications

2 - Vertical Earth Load = $\gamma_S(H_G - H_W) + \gamma_{S_b}(H_W)$

3 - Vertical Hydrostatic Pressure = $\gamma_W H_W$

4 - Vertical Surcharge Load - determined as per site conditions (F_S)

5 - Horizontal Hydrostatic Load: $a = \gamma_W H_W$ $b = \gamma_W(H_W + H_T)$

6 - Horizontal Earth Load: $a = \gamma_S R_O (H_G - H_W) + \gamma_{S_b} R_O H_W$ $b = a + \gamma_{S_b} R_O \mathbf{H_S}$

7 - Horizontal Surcharge Load = $F_S R_O$

8 - Vertical Hydrostatic Load (Buoyancy) = $\gamma_W(H_W + H_T)$

Where:

γ_S = dry unit weight of soil
γ_{S_b} = buoyant unit weight of soil
H_G = height of backfill over the tunnel
H_W = height of water table over the tunnel
H_T = height of the tunnel structure
R_O = at rest lateral earth pressure coeffecient
F_S = magnitude of surcharge in units of Force/Area

load cases specified in Section 12 of the AASHTO LRFD specifications, the strength and service load cases that do not include live load should be used, specifically Strength III and Service IV. Note that load case Strength IV does not include live load. However, when using the loadings applicable to cut and cover tunnels, Strength III and Strength IV are in fact the same load cases. Combining the requirements of Section 12 and Section 3 as described above results in the following possible load combinations for use in the design of cut and cover structures:

Table 5-1 Cut and Cover Tunnel LRFD Load Combination Table

Load Comb. Limit State	DC		DW		EH* EV#		ES		EL	LL, IM	WA	TU, CR, SH		TG
	Max	Min	Max	Min	Max	Min	Max	Min				Max	Min	
Strength I	1.25	0.90	1.50	0.65	1.35	0.90	1.50	0.75	1.00	1.75	1.00	1.20	0.50	0.00
Strength II	1.25	0.90	1.50	0.65	1.35	0.90	1.50	0.75	1.00	1.35	1.00	1.20	0.50	0.00
Strength III	1.25	0.90	1.50	0.65	1.35	0.90	1.50	0.75	1.00	0.00	1.00	1.20	0.50	0.00
Service I	1.00		1.00		1.00		1.00		1.00	1.00	1.00	1.20	1.00	0.50
Service IV	1.00		1.00		1.00		1.00		1.00	0.00	1.00	1.20	1.00	1.00
Service IVA**	0.00		0.90		0.90		0.90		0.00	0.00	1.00	0.00	0.00	0.00
Extreme Event I	1.25	0.90	1.50	0.65	1.35	0.90	1.50	0.75	γEQ^{+}	1.00	N/A	N/A	N/A	N/A

* The load factors shown are for at-rest earth pressure. At-rest earth pressure should be used for all conditions of design of cut and cover tunnel structures. Horizontal earth pressure is not used for Load Combination Service IVA.
# The load factors shown are for rigid frames. All cut and cover tunnel structures are considered rigid frames.
+ This load factor is determined on a project specific basis and is not in the scope of this manual.
** This load case used to check buoyancy for tunnel structures below the permanent groundwater table.

Cut and cover tunnels below the water table should be evaluated for the effect of buoyancy. This check is shown as Load Combination Service IVA in the Table 5-1. The buoyancy force should be assessed to ensure that the applied dead load effect is larger than the applied buoyancy effect. Frequently, structural member sizes will have to be increased to ensure that the buoyancy is completely resisted by the dead load or alternatively, the structure should be tied down. Calculations for buoyancy should be based on minimum characteristic material densities and maximum water density. The net effect of water pressure on the tunnel, i.e., the buoyancy, is the difference between hydrostatic loads on the roof and on the underside. The total uplift force is equal to the weight of water displaced. Friction effects (the theoretical force required to dislodge the wedge of material over the tunnel) of overlying natural materials and backfill should not be taken into account.

When developing the loads to be applied to the structure, each possible combination of load factors should be developed. Engineering judgment can then be used to eliminate the combinations that will not govern.

Extreme event loading is not specifically called for in the ASSHTO LRFD specification. Cut and cover tunnels, however can be subjected to extreme event loadings such as earthquakes, fires and explosions. The analysis and design for these loadings are very specialized and as such are not in the scope of this manual. However, it is recommended that during the planning phase of a tunnel, a risk analysis be performed to identify the probability of these loads occurring, the level at which they may occur and the need for designing the tunnel to resist these loads.

5.6 STRUCTURAL DESIGN

5.6.1 General

Historically there have been three basic methods used in the design of cut and cover tunnel structures:

- Service load or allowable stress design which treats each load on the structure equally in terms of its probability of occurrence at the stated value. The factor of safety for this method is built into the material's ability to withstand the loading.
- Load factor design accounts for the potential variability of loads by applying varying load factors to each load type. The resistance of the maximum capacity of the structural member is reduced by a strength reduction factor and the calculated resistance of the structural member must exceed the applied load.
- Load and resistance factor design takes into account the statistical variation of both the strength of the structural member and of the magnitude of the applied loads.

The fundamental LRFD equation can be found in paragraph 1.3.2.1 of the AASHTO specification (AASHTO Equation 1.3.2.1-1) as follows:

$$\Sigma\eta_i\gamma_i Q_i \leq \phi R_n = R_r \qquad 5\text{-}1$$

In this equation, η_i is a load modifier relating to the ductility, redundancy and operation importance of the feature being designed. The load modifier η is comprised of three components;

η_D = a factor relating to ductility = 1.0 for cut and cover tunnels constructed with conventional details and designed in accordance with the AASHTO LRFD specification.

η_R = a factor relating to redundancy = 1.0 for cut and cover tunnel design. Typical cast in place and prestressed concrete structures are sufficiently redundant to use a value of 1.0 for this factor. Typical detailing using structural steel also provides a high level of redundancy.

η_I = a factor relating to the importance of the structure = 1.05 for cut and cover tunnel design. Tunnels usually are important major links in regional transportation systems. The loss of a tunnel will usually cause major disruption to the flow of traffic, hence the higher importance factor.

γ_i is a load factor applied to the force effects (Q_i) acting on the member being designed. Values for γ can be found in Table 5-1 above.

R_r is the calculated factored resistance of the member or connection.

ϕ is a resistance factor applied to the nominal resistance of the member (R_n) being designed. The resistance factors are given in the AASHTO LRFD specifications for each material in the section that covers the specific material. Specifically, Section 5 covers Concrete Structures and in general, the resistance factors to be used in concrete design can be found in Section 5. However, Section 12 of the AASHTO LRFD specifications gives the following values to be used for ϕ in Table 12.5.5-1:

For Reinforced Concrete Cast-in-Place Box Structures:

ϕ = 0.90 for flexure
ϕ = 0.85 for shear

Since the walls, floors and roofs of cut and cover tunnel sections will experience axial loads, the resistance factor for compression must be defined. The value of ϕ for compression can be found in Section 5.5.4.2.1 of the AASHTO LRFD specifications given as:

ϕ = 0.75 for compression

Values for ϕ for precast construction are also given in Table 12.5.5-1 of the AASHTO LRFD specifications, however due to size of the members involved in road tunnels, it is seldom that precast concrete will be used as a building material.

Structural steel is also used in cut and cover tunnel construction. Structural steel is covered in Section 6 of the AASHTO LRFD specifications. Paragraph 6.5.4.2 gives the following values for steel resistance factors:

For Structural Steel Members:

ϕ_f = 1.00 for flexure
ϕ_v = 1.00 for shear
ϕ_c = 0.90 for axial compression for plain steel and composite members

5.6.2 Structural Analysis

Structural analysis is covered in Section 4 of the AASHTO LRFD specifications. It is recommended that classical force and displacement methods be used in the structural analysis of cut and cover tunnel structures. Other numerical methods may be used, but will rarely yield results that vary significantly from those obtained with the classical methods. The modeling should be based on elastic behavior of the structure as per the AASHTO LRFD specifications paragraph 4.6.2.1.

Since all members of a cut and cover tunnel, with the possible exception of the floor of tunnels built using top-down construction, are subjected to bending and axial load, the secondary affects of deflections on the load affects to the structural members should be accounted for in the analysis. The AASHTO LRFD specifications refer to this type of analysis as “large deflection theory” in paragraph 4.6.3.2. Most general purpose structural analysis software have provisions for including this behavior in the analysis. If this behavior is accounted for in the analysis, no further moment magnification is required.

Paragraph 4.5.1 of the AASHTO LRFD specifications states that the design of the structure should include “…where appropriate, response characteristics of the foundation”. The response of the foundation for a cut and cover tunnel structure can be modeled through the use of a series of non linear springs placed along the length of the bottom slab. These springs are non linear because they should be specified to act in only one direction, the downward vertical direction. This model will provide the proper distribution of loads to the bottom slab of the model and give the designer an indication if buoyancy is a problem. This indication is seen in observing the calculated displacements of the structure. A net upward displacement of the entire structure indicates that there is insufficient resistance to buoyancy.

Structural models for computer analysis are developed using the centroid of the structural members. As such, it is important when calculating the applied loads, that the loads are calculated at the outside surface of the members. The load is then adjusted according to the actual length of the member as input.

Other numerical methods of analysis for cut-and-cover tunnel sections include:

- Frame analysis with a more rigorous soil-structure interaction by modeling the soil properties together with the tunnel. The same frame analysis, but with the addition of a series of unidirectional springs on the underside to model the effect of the soil as a beam on an elastic foundation. Lateral or horizontal springs may be applied in conjunction with assumed soil loads. Care must be taken to ensure that the assumed soil spring acts only when deflection into the soil occurs. This may require multiple iterations of the input parameters for each load combination. Many commercially available programs will automatically adjust the input values and rerun the analysis. This gives a better modeling representation of the structure and takes advantage of more realistic base slab soil support, often resulting in more economical design. Setting up a model is a little more difficult with the springs, and suitable values for the spring modulus are difficult to quantify. It may be appropriate to use a range of values and run the model for each.

- Finite element and finite difference analyses. The material of the tunnel structure and the soil are modeled as a continuum grid of geometric elements. Structural elements are usually treated as linear elastic. A number of different mathematical models for the soil type are available. This method of modeling and analysis can more closely represent actual conditions, especially if better numerical resolution is used where there are conditions of difficult tunnel geometry such as the framing details. The method is usually complex to setup and run, and results require careful interpretation.

As stated above, two-dimensional sectional analysis is sufficient for most tunnel conditions. Three-dimensional modeling may be required where tunnel sections vary along the length of the tunnel or where intersections exist such as at ramps or cross-passages. 3-D modeling is very complex and the accuracy of the loading data, uncertainty about soil behavior, and its inherent lack of homogeneity may not warrant such detailed analysis for highway tunnels except for special locations such as ramps, cross passages, and connections to other structures.

5.7 GROUNDWATER CONTROL

5.7.1 Construction Dewatering

When groundwater levels are higher than the base level of the tunnel, excavations will require a dewatering system. For cut and cover construction, the dewatering systems will depend on the permeability of the various soil layers exposed. Lowering the water table outside the excavation could cause settlement of adjacent structures, impact on vegetations, drying of existing wells, and potential movement of contaminated plumes if present. Precautions should be taken when dewatering the area outside the excavation limits. Within the excavation, dewatering can be accomplished with impermeable excavation support walls that extend down to a firm, reasonably impermeable stratum to reduce or cut-off water flow.

Impervious retaining walls, such as steel interlocking sheeting or concrete slurry walls, could be placed into deeper less pervious layers, such as glacial till or clay, to reduce groundwater inflow during construction and limit draw-down of the existing groundwater table. For most braced excavation sites, dewatering within the excavation is often done. Sometimes the excavation is done in the wet, then the water is pumped out. Subsequent to the excavation, any water intrusion will be pumped from the trench by providing sumps and pumps within the excavation. In some areas, a pumped pressure relief system may be required to prevent the excavation bottom from heaving due to unbalanced hydrostatic pressure.

Pumped wells can be used to temporarily lower the groundwater table outside the excavation support during construction; however this may have environmental impact or adverse effects on adjacent structures. To minimize any lowering of the water table immediately outside the excavation, water pumped from the excavation can be used to recharge the water bearing strata of the groundwater system by using injection wells. Provision would have to be made for disposal of water in excess of that pumped to recharge wells, probably through settlement basins draining to storm drains.

After construction is completed, if there is a concerned that the permanent excavation support walls above the tunnel might be blocking the cross flow of the groundwater or may dam up water between walls above the tunnel, the designer may need to consider to breach the walls above the tunnel at intervals or removed to an elevation to allow movement of groundwater. Granular backfill around tunnels can also help to maintain equal hydrostatic heads across underground structures.

5.7.2 Methods of Dewatering and Their Typical Applications

Groundwater can be controlled during construction either by using impervious retaining walls (such as concrete slurry or tangent pile walls, steel interlocking sheeting, etc.), by well-points drawing down the water table, by chemical or grout injection into the soils, or by pumping from within the excavation. Groundwater may be lowered, as needed, by tiers of well-points. Improper control of groundwater is often a cause for settlement and damage to adjacent structures and utilities; consequently it is important that the method selected is suitable for the proposed excavation.

Where the area of excavations is not too large, an economical method of collecting water is through the use of ditches leading to sump pumps. Provisions to keep fines from escaping into the dewatering system should be made.

In larger excavations in permeable soil, either well points or deep wells are often used to lower the water table in sand or coarse silt deposits, but are not useful in fine silt or clay soils due to their low permeability. It is recommended that test wells be installed to test proposed systems. In certain cases, multiple stages of well points, deep wells with submersible pumps or an eductor system would be needed

5.7.3 Uplift Pressures and Mitigation Measures

After construction is complete and dewatering ceases, hydrostatic uplift (buoyancy) pressures should be considered. Options that have been used to overcome this are included in Section 5.4.42.

5.7.4 Piping and Base Stability

In fine-grained soils, such as silts or clayey silts, differential pressure across the support of excavation may cause sufficient water flow (piping) for it to carry fines. This causes material loss and settlement outside as well as a loss of integrity of soils within, rendering the soils unsuitable as a foundation. In extreme cases, the base of the excavation may become unstable, causing a blow-up and failure of the excavation support. This situation may be mitigated by ensuring that cut-off walls are sufficiently deep, by stabilizing the soil by grouting, or freezing, or by excavating below water without dewatering and making a sufficiently thick tremie slab to overcome uplift before dewatering.

5.7.5 Potential Impact of Area Dewatering

Dewatering an excavation may lower the groundwater outside the excavation and may cause settlements. The lowering of the external groundwater can be reduced by the use of slurry walls, tangent or secant piles, or steel sheet piling. Adjacent structures with a risk of settlement due to groundwater lowering may require underpinning. Furthermore, where lowering of groundwater exposes wooden piles to air, deterioration may occur.

5.7.6 Groundwater Discharge and Environmental Issues

In most cases, the water will require testing and possibly treatment before it can be discharged. Settling basins, oil separators, and chemical treatments may be required prior to disposal. Local regulations and permitting requirements often dictate the method of disposal.

The excavated material itself will require testing before the method of disposal can be determined. Material excavated below water may need to stand in settling ponds to allow excess water to run off before disposal. Contaminated material may need to be placed in confined disposal facilities.

5.8 MAINTENANCE AND PROTECTION OF TRAFFIC

When the excavation crosses existing roads or is being performed under an existing road, decking would be required to maintain the existing road traffic. When decking is required the support of excavation walls must be designed to handle the imposed live loads. The depth of the walls may need to be determined by the necessity of transferring decking loads to a more competent stratum below. This may depend upon whether the load applied to the wall together with its weight can be transferred to the surrounding soil through a combination of adhesion (side friction) and end bearing. Thick types of excavation support walls, such as slurry walls, drilled-in-place soldier piles, and tangent piles, are much more effective than thinner walls, such as sheet piles or driven soldier piles, in carrying the live loads to the bearing stratum.

Decking often consists of deck framing and roadway decking. Figure 5-14 depicts a typical general arrangement for street decking over a cut-and-cover excavation using timber decking. Pre-cast concrete planks have been used also as decking. Structural steel deck beams can be arranged to function also as the uppermost bracing tier of the support of excavation. The deck framing should be designed for AASHTO HL-93 loading, or for loading due to construction equipment that actually will operate on the deck, whichever is greater.

5.9 UTILITY RELOCATION AND SUPPORT

5.9.1 Types of Utilities

Constructing cut and cover tunnels in urban areas often encounters public and private utility lines such as water, sewer, power, communication, etc… Often, utilities are not located where indicated on existing utility information. Therefore, it is important to identify and locate all utilities in the field prior to excavation. Great care must be taken when excavating in the vicinity of utilities, sometimes requiring that the final excavation to expose them be done by hand. Of particular concern are those utilities that are movement-sensitive and those carrying hazardous substances; these include large diameter water pipes, high pressure gas lines, fiber optic lines, petroleum pipes and high voltage cables. Some utilities such as buried high voltage lines are not only extremely expensive to move but have very long lead times. Utilities such as sewers can present a different problem; if gravity flow is used, diversions around a proposed tunnel may pose a serious challenge. Some older water and sewer lines are extremely fragile, particularly if they are of brick or cast iron construction.

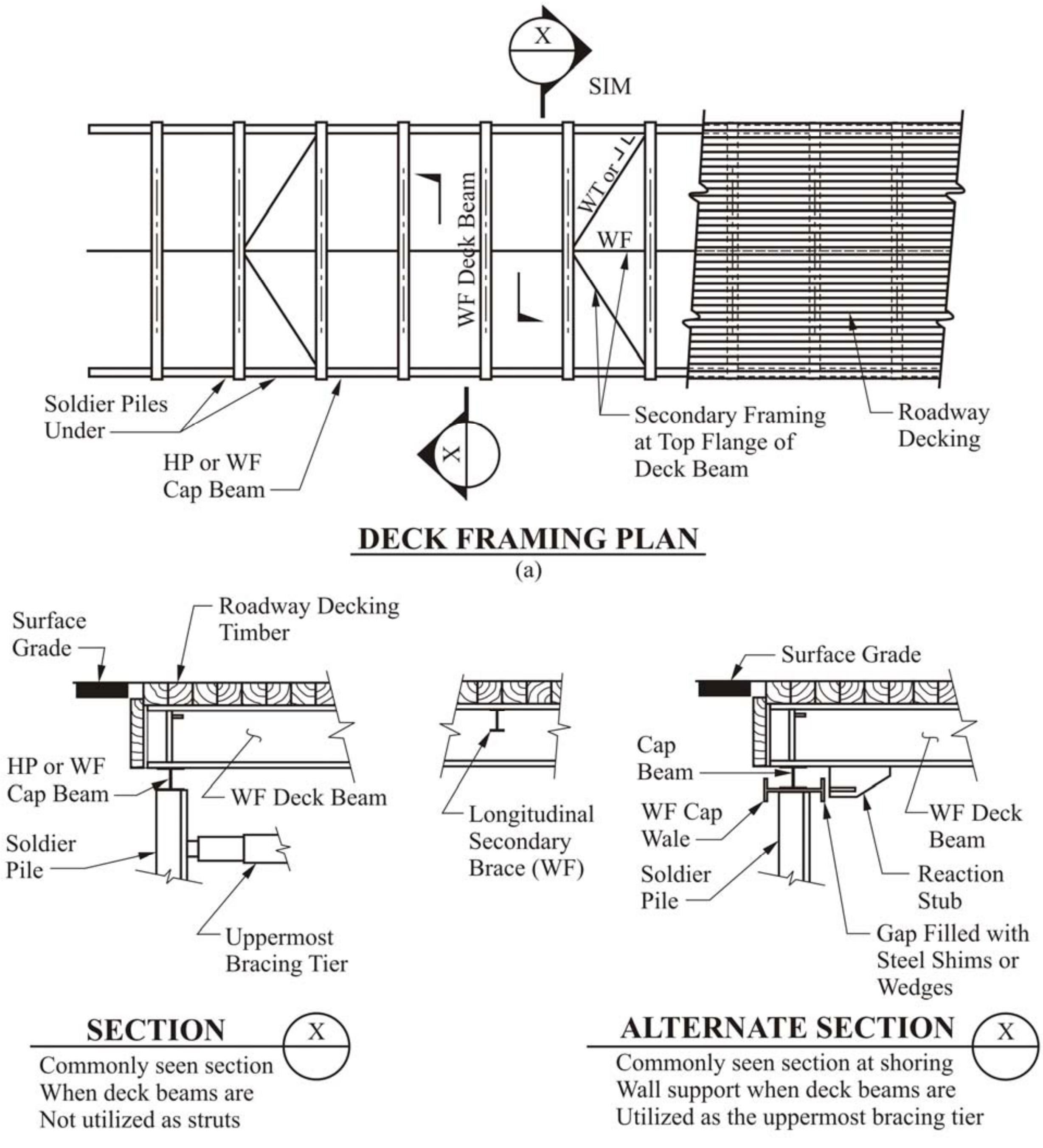


Figure 5-14 Typical Street Decking (After Bickel et al., 1996)

5.9.2 General Approach to Utilities during Construction

It is not uncommon to divert utilities away from the proposed construction corridor. However, diversion is not always possible, it may be too expensive, or a utility crossing may be unavoidable; in such cases, it will be necessary to support the utilities in place. It is essential to have a coordinated effort so that no interferences among the various utilities occurs and that the construction can be done while the utilities are in place. Sometimes, utility relocations are done in stages to accommodate the construction requiring relocating the utility more than once.

Before the start of underground construction, a condition survey should be made of all utilities within the zone of potential influence of construction, making detailed reports for those that may incur movements in excess of those allowable for the utility. The nature of any work required for each utility should be identified, i.e., protection, support or relocation, and the date by which action is required. It is essential that all utilities that need action are identified in sufficient time to allow the construction to progress as programmed.

Supports may either be temporary or permanent. Depending upon the sensitivity of the utility being supported, it may be necessary to provide instrumentation to monitor any movement so that remedial action can be taken before damage occurs. Systems providing vertical support should be designed as bridge structures. Lateral support may be considered as retaining walls.

Most utilities require access for repairs; it is therefore required to have provisions for access to utilities passing beneath a tunnel. In some cases, it has been found appropriate to relocate utilities to a trough or utility tunnel in which all utilities can be easily accessed. In some cases, utilities cannot be raised sufficiently to clear the tunnel roof slab; it may be possible to create a narrow trough across the roof in which the utility may be relocated. In certain situations, utilities were passed through the tunnel by providing a special conduit below the tunnel roof. In all cases, all utility work must be carefully coordinated with the utility owner.