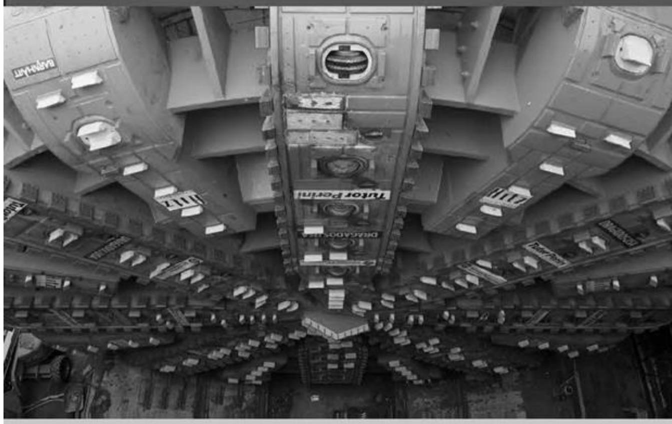
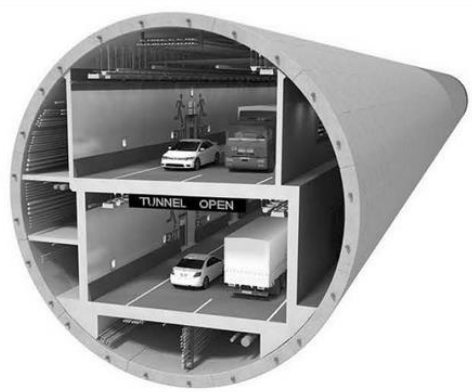
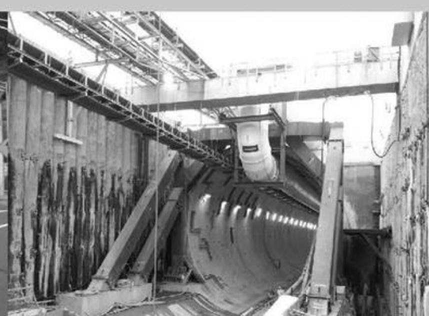




LRFD Road Tunnel Design and Construction Guide Specifications

First Edition, 2017



Publ. Code: LRFDTUN-1
ISBN: 978-1-56051-643-9

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS
AASHTO

AASHTO LRFD Road Tunnel Design and Construction Guide Specifications

ABBREVIATED TABLE OF CONTENTS

Section 1	Introduction
Section 2	General Features and Requirements
Section 3	Loads and Load Combinations
Section 4	Structural Materials and Design Considerations
Section 5	Geotechnical Considerations
Section 6	Cut-and-cover Tunnel Structures
Section 7	Mined and Bored Tunnel Structures
Section 8	Immersed Tunnel Structures
Section 9	Initial Ground Support Elements and Ground Improvement
Section 10	Seismic Considerations
Appendix A	Planning and Route Considerations
Appendix B	Recommended Construction Specification Sections

SECTION 1 – INTRODUCTION

TABLE OF CONTENTS

1.1—PURPOSE AND SCOPE 1-1
1.2—DEFINITIONS 1-2
1.3—DESIGN PHILOSOPHY 1-3
1.3.1—General 1-3
1.3.2—Limit States 1-4
1.3.2.1—General 1-4
1.3.2.2—Service Limit State 1-5
1.3.2.3—Fatigue and Fracture Limit State 1-5
1.3.2.4—Strength Limit State 1-5
1.3.2.5—Extreme Event Limit State 1-5
1.3.3—Ductility 1-5
1.3.4—Redundancy 1-6
1.3.5—Operational Importance 1-6
1.4—REFERENCES 1-7

1.1—PURPOSE AND SCOPE

The provisions of these Specifications are intended for the design, evaluation, and rehabilitation of highway tunnels. These Specifications are intended for the design of tunnels constructed using cut-and-cover, bored, mined, and immersed tunnel construction methodologies.

Provisions are not included in these Specifications for water conveyance, utility, transit, or rail tunnels or for shafts. For tunnel elements not explicitly covered herein, the provisions of these Specifications may be applied, as augmented by the Engineer with additional design criteria where required.

Construction specifications consistent with these design Specifications are not included. There is a listing of suggested construction specification sections included in Appendix B.

Structures internal to tunnels that support roadways over ventilation plenums, roadways, or other openings in the tunnel shall be designed in accordance with the *AASHTO LRFD Bridge Design Specifications* (hereafter referred to as the *LRFD Specifications*) including all applicable interim changes and as modified or supplemented herein. The load effects of these internal structures shall be applied to the tunnel lining, walls, or other supporting members in accordance with these Specifications.

Retaining walls for retained cut approaches to tunnels shall be designed in accordance with the *LRFD Specifications*.

Support and ancillary structures such as ventilation, control, and administrative buildings are not covered by these Specifications. These structures shall be designed in accordance with local building codes.

These Specifications are not intended to supplant proper training and experience or the exercise of judgment by the Engineer, and provide only the minimum requirements necessary for public safety. The Owner or the Engineer may require the sophistication of design or the quality of materials and construction to be higher than the minimum requirements. The design of tunnels is strongly dependent upon the geologic setting, site conditions, and construction methodology, and this fact is considered in the Specifications. The concept of ground/structure interaction is emphasized for mined and bored tunnels; however, it is also applicable to cut-and-cover and immersed tunnels.

The concept of safety through redundancy and ductility is emphasized for tunnel elements subject to repeated loads and load reversals.

The design provisions of these Specifications employ the Load and Resistance Factor Design (LRFD) methodology. The load factors have been calibrated using structural analysis modeling for a limited number of loading conditions that take into account ground/structure interaction.

C1.1

These Specifications are modeled after the *LRFD Specifications* and the AASHTO *Guide Specifications for LRFD Seismic Bridge Design*. The philosophy and guidance provided in those documents are carried forward and implemented in this document.

Whenever the *LRFD Specifications* are referenced in this document, the reference is to the latest edition including all applicable interim changes.

The term "notional" is often used in these Specifications to indicate an idealization of a physical phenomenon, as in "notional load" or "notional resistance." Use of this term strengthens the separation of an engineer's "notion" or perception of the physical world in the context of design from physical reality itself.

The term "shall" denotes a requirement for compliance with these Specifications.

The term "should" indicates a strong preference for a given criterion.

The term "may" indicates a criterion that is usable, but other local and suitably documented, verified, and approved criteria may also be used in a manner consistent with the LRFD approach to tunnel design.

The load factors specified in Section 3 have been calibrated to provide designs with member proportions consistent with the current practice in tunnel design.

The calibration is based upon analyses performed for a circular bored tunnel. Additional calibration for different tunnel cross-sectional geometry and loadings from a variety of ground conditions would be useful in further validating and refining the load factors.

The primary loads on structural components of tunnels are groundwater and earth loads. For immersed tunnels, loads imposed by transporting immersed elements from the fabrication site to the tunnel location can also govern the design of these tunnels. For pre-fabricated linings used in bored tunnels, construction-imposed loading can govern the design. The determination of groundwater, earth, transportation, and other construction loads varies based on the in-situ conditions, level of testing during subsurface investigations, and ground conditions may have great variation. There are little data available to establish a statistically significant sampling in order to calibrate these Specifications based upon structural reliability theory. As such, judgment and past experience were also used to select the load factors.

These Specifications are an initial attempt to codify and standardize highway tunnel design. As such, as future data that are produced in a systematic fashion in accordance with these Specifications become available, recalibration may be implemented based on statistical evaluation of these data.

The commentary is not intended to provide a complete historical background concerning the development of these Specifications, nor is it intended to provide a detailed summary of the studies and research data reviewed in formulating the provisions of the Specifications. However, references to some of the research data are provided for those who wish to study the background material in more depth.

The commentary directs attention to other documents that provide suggestions for carrying out the requirements and intent of these Specifications. However, those documents and this commentary are not intended to be a part of these Specifications.

The Specifications direct the Engineer to utilize other documents in the development of designs. When this occurs, the most current edition of those documents should be utilized. Those documents referenced in the Specifications are intended to be part of these Specifications by reference.

Unless otherwise specified, the Materials Specifications referenced herein are the *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing*.

1.2—DEFINITIONS

For definitions not shown, see the *LRFD Specifications.*

Bored Tunnel—A tunnel constructed utilizing a tunnel boring machine.

Calibration—The selection of load and resistance factors to achieve a specified goal such as uniform reliability, as is the case with the bridge design specifications, or member proportions consistent with past practice, as is the case with these Specifications.

Collapse—A major change in the geometry of the tunnel lining or other structural component rendering it unfit for use.

Component—Either a discrete element of the tunnel or a combination of elements requiring individual design consideration.

Contract Documents—Drawings, specifications, reports, and memoranda that provide direction and/or guidance for the construction of a tunnel and that form a contractual basis for the work to be performed.

Contractor—Entity responsible for the construction of the tunnel and associated construction engineering.

Cut-and-cover—Sequence of construction in which a trench is excavated and the tunnel or conduit section is constructed and then covered with backfill. (AASHTO, 2010)

Design—Proportioning and detailing the components and connections of a tunnel.

Design Life—Period of time on which the statistical derivation of transient loads is based: 150 years for these Specifications.

Engineer—Agency, design firm, or person responsible for the design of the tunnel and/or review of design related to field submittals.

Evaluation—Determination of the load carrying capacity of one or more components of an existing tunnel.

Extreme Event Limit States—Limit states relating to events such as earthquakes, flooding, vehicle fire, or vehicle and vessel collision, with return periods in excess of the design life of the tunnel.

Force Effect—A deformation, stress, or stress resultant (i.e., axial force, shear force, torsional or flexural moment) caused by applied loads, imposed deformations, temperature changes, or volumetric changes.

Immersed Tunnel—A tunnel constructed from prefabricated elements constructed off the tunnel alignment, floated into place over the tunnel alignment, and placed into a prepared trench. Placement is facilitated by the addition of ballast to the elements to cause them to be immersed to the pre-determined depth and then joined to the adjacent element(s) already in place.

Limit State—A condition beyond which the tunnel or component ceases to satisfy the provisions for which it was designed.

Load Modifier—A factor accounting for ductility, redundancy, and the operational classification of the tunnel.

Mined—Any tunnel construction methodology that involves excavation of the tunnel without opening the excavation to the surface and without the use of a tunnel boring machine, including mechanical excavation, blasting, and hand excavation.

Model—An idealization of a structure or structure–ground system for the purpose of analysis.

Owner—Person or agency having jurisdiction over the tunnel.

Regular Service—Condition excluding the presence of special permit vehicles and extreme events.

Rehabilitation—A process in which the resistance or functionality of a tunnel component or connection is either restored or increased.

Resistance Factor—A statistically or experience-based multiplier applied to nominal resistance accounting primarily for variability of material properties, structural dimensions, and workmanship, an uncertainty in the prediction of resistance, but also related to the statistics of the loads through the calibration process.

Service Life—The period of time that the tunnel is expected to be in operation.

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

Tunnel Boring Machine (TBM)—Machine that excavates a tunnel by drilling out the heading to full size in one operation. Sometimes called a mole, the TBM is typically propelled forward by jacking off the excavation supports emplaced behind it or by gripping the side of the excavation (AASHTO, 2010).

1.3—DESIGN PHILOSOPHY

1.3.1—General

Tunnels shall be designed for specified limit states to achieve the objectives of constructability, safety, and serviceability, with due regard to issues of inspectability, maintenance and economy. Additional information regarding tunnel systems, planning, ancillary facilities, and appurtenances can be found in Section 2. Regardless of the type of analysis used, Equation 1.3.2.1-1 shall be satisfied for all specified force effects and combinations thereof.

C1.3.1

The limit states specified herein are intended to provide for a buildable, serviceable tunnel capable of safely operating for a specified design life. As defined in Article 1.2, the design life relates to the return period of the transient loads of the strength limit states and hence their nominal magnitude. The design life should not be confused with the service life. As defined in Article 1.2, the service life relates to the eventual demonstrated durability of the tunnel. The service life of

The specified 150-year design life is appropriate for the design of tunnel geotechnical features and soil–structure-interaction-systems given the high capital costs of rehabilitation and replacement and the likely importance to the transportation network. Internal structures such as roadway slabs and suspended ceilings as well as system components, such as signs, piping, and their supports; communication and signal devices; and ventilation equipment that are more easily replaced, may have design lives assigned to them by the Owner.

a tunnel is not specified in these Specifications, just as the service life of a bridge is not specified in the *LRFD Specifications*, as the durability of tunnels or bridges is not well quantified.

The resistance of components and connections is determined, in many cases, on the basis of inelastic behavior. In other words, the capacity of tunnel components used to define their nominal resistance at the strength limit states is based upon behavior past first yield of the material. On the other hand, the force effects on the load side of the LRFD equation, Equation 1.3.2.1-1, are determined using elastic analysis but amplified by the specified load factors. This apparent inconsistency is consistent with most modern structural-design codes including the *LRFD Specifications*. The application of this comparison of loads and resistances for design is a result of incomplete knowledge of inelastic structural action combined with the behavior of the earth surrounding the tunnel that acts in concert with the tunnel structure.

1.3.2—Limit States

1.3.2.1—General

Each component and connection shall satisfy Equation 1.3.2.1-1, for each limit state unless otherwise specified. For service and extreme limit states, resistance factors shall be taken as 1.0 except for bolts. For bolts, the provisions of Article 6.5.5 of the *LRFD Specifications* shall apply.

$$\Sigma \eta_i \gamma_i Q_i \leq \phi R_n = R_r \qquad (1.3.2.1\text{-}1)$$

in which:

For loads for which a maximum value of γ_i is appropriate:

$$\eta_i = \eta_D \eta_R \eta_I \geq 1.0 \qquad (1.3.2.1\text{-}2)$$

For loads for which a minimum value of γ_i is appropriate:

$$\eta_i = \frac{1}{\eta_D \eta_R \eta_I} \leq 1.0 \qquad (1.3.2.1\text{-}3)$$

where:

γ_I = load factor: a multiplier applied to force effects

ϕ = resistance factor: a multiplier applied to nominal resistance, as specified herein

η_i = load modifier: a factor relating to ductility, redundancy, and operational classification

C1.3.2.1

Equation 1.3.2.1-1 is the basis of the LRFD methodology.

Ductility, redundancy, and operational classification are considered in the load modifier η. Whereas the ductility and redundancy directly relate to physical strength, operational classification concerns the consequences of the tunnel being out of service. The grouping of these aspects of the load side of Equation 1.3.2.1-1 is therefore, arbitrary. However, it constitutes a first effort at codification. In the absence of more precise information, each effect is estimated as ±5 percent, accumulated geometrically, a clearly subjective approach.

Groundwater is an example of a loading that would be appropriate to apply as a maximum and a minimum. Variation in groundwater elevations are common due to seasonal changes and tidal influences. Tunnel linings are designed as compression members; therefore, maximum groundwater pressures would produce maximum axial loads and vice versa. As such, both maximum and minimum groundwater loads should be checked.

η_D = a factor relating to ductility as specified in Article 1.3.3

η_R = a factor relating to redundancy as specified in Article 1.3.4

η_I = a factor relating to operational classification as specified in Article 1.3.5

Q_i = force effect

R_n = nominal resistance

R_r = factored resistance: ϕR_n

1.3.2.2—Service Limit State

The service limit state shall be taken as restrictions on stress, deformation and crack width under regular service conditions.

C1.3.2.2

The service limit state provides certain experience-related provisions that cannot always be derived solely from strength or statistical consideration.

For tunnels, this limit state controls tunnel lining deformation, cracking, and leaking.

1.3.2.3—Fatigue and Fracture Limit State

The fatigue and fracture limit state shall be taken as restrictions on stress range as a result of repetitive machinery or ventilation loads at the number of expected stress range cycles.

C1.3.2.3

The fatigue and fracture limit state is intended to limit crack growth under repetitive loads to prevent fracture during the design life of the component. Additionally, the fatigue limit state is intended to prevent premature failure of anchoring and supporting components subject to machinery or ventilation loads.

1.3.2.4—Strength Limit State

Strength limit state shall be taken to ensure that strength and stability, both local and global, are provided to resist the specified statistically significant load combinations that a tunnel and its component parts are expected to experience in its design life.

C1.3.2.4

The strength limit state considers stability or yielding of each structural element. If the resistance of any element, including splices and connections, is exceeded, it is assumed that the tunnel resistance has been exceeded. The redistribution of loads that can occur due to structure–ground interaction typically allows the tunnel ground supporting structure to support loads in excess of the capacity calculated utilizing linear elastic static analysis. Extensive distress and structural damage may occur under the strength limit state, but overall structural integrity is expected to be maintained.

1.3.2.5—Extreme Event Limit State

The extreme event limit state shall be taken to ensure the structural survival of a tunnel during a major earthquake, flood, tsunami, collision, blast, or fire, or when an immersed tunnel is subject to sinking vessel or anchor drag loads possibly during, or in conjunction with, a scour event.

C1.3.2.5

Extreme event limit states are considered to be unique occurrences whose return period may be significantly greater than the design life of the tunnel.

1.3.3—Ductility

The structural system of a tunnel shall be proportioned and detailed to ensure the development of

C1.3.3

The response of structural components or connections beyond the elastic limit can be significant and visible inelastic deformations at the strength and extreme limit states before failure.

For the strength limit state:

$\eta_D \geq 1.05$ for nonductile components and connections

$= 1.00$ for conventional designs and details complying with these Specifications

For all other limit states:

$\eta_D \geq 1.00$

Internal components of tunnels including structural elements, equipment supports, and their connections shall be designed to exhibit ductile behavior, especially when subject to extreme events such as earthquakes.

Attention shall be given to the ductility of transitions between structural systems of tunnels, specifically at the interfaces between retained cut and cut-and-cover structures; between cut-and-cover structures and mined, bored, or immersed tunnels; and at the joints between immersed tunnel elements.

characterized by either brittle or ductile behavior. Brittle behavior is undesirable because it implies a sudden loss of load-carrying capacity immediately when the elastic limit is reached. Ductile behavior is characterized by significant inelastic deformations before any loss of load carrying capacity occurs. The redistribution of load effects provided by ground–structure interaction results in ductile behavior of concrete tunnel linings when proper detailing of the reinforcing is used. Internal components, however, should be designed to exhibit ductile behavior. The provisions of the *LRFD Specifications* provide guidance and direction for the ductile design of these internal components.

While the *LRFD Specifications* have a value of η_D less than one in implementation, the value is unused. Traditionally, structural engineers characterize structures as ductile, $\eta_D = 1.00$, or non-ductile, $\eta_D = 1.05$.

1.3.4—Redundancy

The provisions of the *LRFD Specifications* shall be used to ensure that the internal components of tunnels and all aspects of cut-and-cover and immersed tunnels incorporate redundancy in their design.

For the strength limit state:

$\eta_R \geq$ 1.05 for nonredundant members

$= 1.00$ for conventional levels of redundancy

For all other limit states:

$\eta_R \geq 1.00$

C1.3.4

Tunnel linings for bored and mined tunnels are considered redundant due to ground–structure interaction and the ability to share load along the length of tunnel.

While the *LRFD Specifications* include a value of η_R less than one, in implementation the value is unused. Traditionally, structural engineers characterize structures as redundant, $\eta_R = 1.00$, or non-redundant, $\eta_R = 1.05$.

1.3.5—Operational Importance

This Article shall apply to the strength and extreme limit states only.

The Owner may declare a tunnel or any structural component, or connection thereof, to be of operational priority.

For the strength limit state:

$\eta_I \geq$ 1.05 for critical or essential tunnels

$= 1.00$ for typical and relatively less important tunnels

For all other limit states:

$\eta_I \geq 1.00$

C1.3.5

Such classification should be done by personnel responsible for the affected transportation network and knowledgeable of its operational needs. The definition of operational priority may differ from Owner to Owner. Guidelines for classifying critical or essential tunnels are as follows:

- Tunnels that are required to be open to all traffic once inspected after the design event and are usable by emergency vehicles and for security, defense, economic, or secondary life safety purposes immediately after the design event.

- Tunnels that should, as a minimum, be open to emergency vehicles and for security, defense, or economic purposes after the design event, and open to all traffic within days after that event.

Owner classified tunnels may use a value of $\eta < 1.0$ based on ADTT, available detour length, or other rationale to use less stringent criteria.

1.4—REFERENCES

1. AASHTO. *LRFD Bridge Design Specifications*. 7th ed. American Association of State Highway and Transportation Officials, Washington, DC, 2014.

2. AASHTO. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing.* American Association of State Highway and Transportation Officials, Washington, DC, 2016.

3. AASHTO. *Technical Manual for Design of Road Tunnels—Civil Elements*. American Association of State Highway and Transportation Officials, Washington, DC, 2010.

SECTION 2 – GENERAL FEATURES AND REQUIREMENTS

TABLE OF CONTENTS

2.1—SCOPE 2-1
2.2—DEFINITIONS 2-1
2.3—NOTATION 2-2
2.3.1—General 2-2
2.3.2—Abbreviations 2-3
2.4—TYPES OF ROAD TUNNEL STRUCTURES 2-3
2.4.1—Cut-and-Cover Tunnels 2-4
2.4.2—Mined Tunnels 2-4
2.4.3—Bored Tunnels 2-4
2.4.4—Immersed Tunnels 2-4
2.4.5—Shafts 2-5
2.5—PLANNING AND ROUTE CONSIDERATIONS 2-5
2.5.1—General 2-5
2.6—DESIGN CONSIDERATIONS FOR INSPECTION AND MAINTENANCE 2-6
2.7—CLEARANCE AND GEOMETRIC REQUIREMENTS 2-7
2.7.1—Vertical Clearances 2-8
2.7.2—Horizontal Clearances 2-8
2.7.3—Shoulders and Walkways 2-8
2.7.4—Vertical Alignment 2-8
2.7.5—Horizontal Alignment 2-8
2.7.6—Tunnel Approaches 2-9
2.8—SYSTEMS 2-10
2.8.1—Codes and Standards 2-10
2.8.2—Supervisory Control and Data Acquisition (SCADA) System 2-11
2.8.3—Tunnel Ventilation System (TVS) 2-12
2.8.3.1—Tunnel Ventilation Operational Modes 2-13
2.8.3.2—TVS General Performance Requirements 2-14
2.8.3.3—TVS Design Analysis Calculations 2-15
2.8.3.3.1—Emissions Ventilation Flow Rate 2-15
2.8.3.3.2— Emergency Ventilation Capacity 2-16
2.8.3.3.3—Egress Calculations 2-16
2.8.3.3.4—Fan Sound Attenuation 2-16
2.8.3.4—Engineering Design Software 2-17
2.8.3.4.1—CFD Flow Monitoring Software 2-17
2.8.3.4.2—Egress Modeling Software 2-17
2.8.4—Drainage System 2-17
2.8.5—Lighting 2-18
2.8.5.1—Tunnel Lighting System 2-19
2.8.5.1.1—Design Approach 2-19
2.8.5.1.2—Design Parameters 2-20
2.8.5.1.3—Lighting Control System 2-20
2.8.5.1.4—Tunnel Lighting Fixture Circuitry 2-21
2.8.5.1.5—Tunnel Lighting Fixtures 2-21
2.8.5.2—Tunnel Cross Passages, Egress Stairwells, and Ancillary Spaces 2-21
2.8.5.3—Tunnel Fixed Message Sign Lighting 2-22
2.8.6—Electrical Systems 2-23
2.8.6.1—General 2-23
2.8.6.2—Primary Distribution 2-23

2.8.6.3—Primary Switchgear 2-23
2.8.6.4—Secondary Distribution Systems....2-24
2.8.6.4.1—Low Voltage Switchgear/Switchboard....2-24
2.8.6.4.2—Panelboards....2-25
2.8.6.4.3—Motor Controllers and Control Devices....2-25
2.8.6.4.4—Dry-Type Distribution Transformers (600 Volts and Below)....2-25
2.8.6.4.5—Power and Convenience Outlets....2-25
2.8.6.4.6—Conductors and Cables....2-25
2.8.6.4.7—Standby Power Systems....2-26
2.8.6.4.7.1—Generator Units....2-26
2.8.6.4.7.2—Generator Switchboard....2-26
2.8.6.4.8—Uninterruptible Power Supply (UPS)....2-26
2.8.6.5—Grounding, Bonding, and Lighting Protection....2-27
2.8.6.5.1—Systems Grounding....2-27
2.8.6.5.2—Equipment Grounding....2-28
2.8.6.5.3—Grounding for Personal Safety....2-28
2.8.6.5.4—Grounding Materials....2-29
2.8.6.5.5—Lighting Protection....2-29
2.8.7—Tunnel Architectural Systems....2-29
2.8.7.1—General....2-29
2.8.7.2—Egress Design....2-30
2.8.7.3—Tunnel Occupant Load Design....2-30
2.8.8—Fire Protection....2-30
2.8.8.1—Fire Alarm and Detection Systems....2-31
2.8.8.2—Tunnel Fire Suppression Systems....2-31
2.8.8.3—Structural Fire Protection....2-31
2.8.9—Tunnel Security Systems....2-32
2.8.10—Corrosion Control Systems....2-33
2.8.10.1—Soil and Water Corrosion Control....2-33
2.8.10.2—Stray Current Corrosion Control....2-33
2.8.10.3—Atmospheric Corrosion Control....2-33
2.8.11—Communication and Traffic Control Intelligent Transportation Systems (ITS)....2-33
2.8.11.1—Communication Systems....2-34
2.8.11.2—Traffic Control and Monitoring ITS....2-35
2.8.12—Structural Systems....2-38
2.9—REFERENCES....2-39

SECTION 3 – LOADS AND LOAD COMBINATIONS

TABLE OF CONTENTS

3.1—SCOPE....3-1
3.2—DEFINITIONS....3-1
3.3—NOTATION....3-3
3.3.1—General....3-3
3.3.2—Loads and Load Designation....3-3
3.3.3—Abbreviations....3-4
3.4—LOAD FACTORS AND COMBINATIONS....3-4
3.5—PERMANENT LOADS....3-8
3.5.1—Dead Loads *(DC, DW)*....3-8
3.5.2—Earth Pressures *(EV, EH)*....3-8
3.5.2.1—Cut-and-Cover and Immersed Tunnels in Soft Ground....3-9
3.5.2.2—Apparent Earth Pressure (AEP) Diagrams for Design of Braced Support of Excavation (SOE) Walls Used as Part of the Permanent Structure....3-9
3.5.2.2.1—AEP Diagrams for Cohesionless Soil....3-11
3.5.2.2.2—AEP Diagrams for Cohesive Soil....3-12
3.5.2.2.2.1—Stiff to Hard Cohesive Soil....3-12
3.5.2.2.2.2—Medium Stiff to Stiff Cohesive Soil....3-13
3.5.2.2.2.3—Soft to Medium Stiff Cohesive Soil....3-13
3.5.2.3—Cut-and-Cover and Immersed Tunnels in Rock....3-13
3.5.2.4—Mined Soft Ground Tunnels....3-14
3.5.2.5—Mined Rock Tunnels....3-14
3.5.3—Surcharge Loads *(ES)*....3-18
3.5.4—Piping Loads *(PI)*....3-18
3.6—LIVE LOADS....3-18
3.6.1—Gravity Loads *(LL* and *PL)*....3-18
3.6.1.1—Vehicular Live Load (LL)....3-18
3.6.1.2—Pedestrian Loads (PL)....3-19
3.6.1.3—Vehicular Dynamic Load Allowance (IM)....3-19
3.6.1.4—Attachment Dynamic Load Allowance (IA)....3-19
3.6.1.5—Centrifugal Forces (CE) and Braking Forces (BR)....3-19
3.6.1.6—Live Load Surcharge (LS)....3-20
3.7—WATER LOADS $(WA, WA_f, WA_t, WAt_{tsu})$....3-20
3.8—AIR PRESSURE LOADS *(AP)*....3-20
3.9—EARTHQUAKE EFFECT *(EQ)*....3-21
3.10—FORCE EFFECTS DUE TO SUPERIMPOSED DEFORMATIONS *(TU, TG, SH, CR, SE, PS)*....3-22
3.10.1—Uniform Temperature *(TU)*....3-22
3.10.2—Temperature Gradient *(TG)*....3-22
3.10.3—Differential Shrinkage *(SH)*....3-22
3.10.4—Creep *(CR)*....3-22
3.10.5—Settlement *(SE)*....3-22
3.10.6—Secondary Forces from Post-Tensioning *(PS)*....3-23
3.11—BLAST LOADING *(BL)*....3-23
3.12—FIRE LOAD *(FI)*....3-24
3.13—SHIP SINKING *(SS)*....3-24
3.14—ANCHOR DROP *(AD)*....3-25
3.15—CONSTRUCTION LOADS *(CS)*....3-26
3.16—REFERENCES....3-26

SECTION 4 – STRUCTURAL MATERIALS AND DESIGN CONSIDERATIONS

TABLE OF CONTENTS

4.1—SCOPE 4-1
4.1.1—Material Properties 4-1
4.2—DEFINITIONS 4-1
4.3—NOTATION 4-1
4.3.1—Abbreviations 4-2
4.4—DESIGN REQUIREMENTS 4-2
4.4.1—General 4-2
4.4.2—Limit States 4-2
4.4.3—Load Combinations 4-3
4.5—CONCRETE STRUCTURES 4-3
4.5.1—Limit States 4-3
4.5.1.1—Service Limit State 4-3
4.5.1.2—Fatigue Limit State 4-3
4.5.1.3—Strength Limit State 4-3
4.5.1.4—Extreme Event Limit State 4-4
4.5.2—Reinforced and Prestressed Concrete 4-4
4.5.2.1—Material Properties 4-4
4.5.2.2—Design Considerations 4-4
4.5.2.3—Details of Reinforcement 4-6
4.5.3—Structural Plain Concrete 4-6
4.5.3.1—Material Properties 4-6
4.5.4—Fiber-Reinforced Concrete (FRC) 4-7
4.5.4.1—Material Properties 4-7
4.5.4.1.1—Steel Fibers 4-7
4.5.4.1.2—Fiber-Reinforced Concrete 4-8
4.5.4.2—Resistance Factors 4-8
4.5.4.3—Design for Flexural and Axial Force Effects 4-9
4.5.4.3.1—Assumptions for Service Limit State 4-9
4.5.4.3.2—Assumptions for Strength and Extreme Limit States 4-9
4.5.4.3.3—Flexural Members 4-10
4.5.4.3.3.1—General 4-10
4.5.4.3.3.2—Factored Flexural Resistance 4-10
4.5.4.3.3.3—Factored Early Age Flexural Resistance 4-10
4.5.4.3.3.4—Factored Axial Resistance 4-11
4.5.4.3.3.5—Factored Axial/Moment Resistance 4-11
4.5.4.3.4—Bearing 4-11
4.5.4.3.4.1—General 4-11
4.5.4.3.4.2—Factored Bearing Resistance 4-11
4.5.4.3.4.3—Factored Splitting Resistance 4-11
4.5.4.3.5—Shear 4-12
4.5.4.3.5.1—General 4-12
4.5.4.3.5.2—Factored Shear Resistance 4-12
4.5.4.3.6—Details of Reinforcement 4-12
4.5.4.3.6.1—Minimum Dosage Requirements 4-12
4.5.5—Shotcrete 4-12
4.5.5.1—Service Limit State 4-13
4.6—STEEL STRUCTURES 4-14
4.6.1—Material Properties 4-14

4.7—WOOD STRUCTURES 4-14
4.8—LATTICE GIRDERS....................4-14
4.8.1—General 4-14
4.8.1.1—Definitions 4-15
4.8.1.2—Notation 4-15
4.8.2—Material Properties 4-15
4.8.3—Limit States 4-15
4.8.3.1—General 4-15
4.8.3.2—Service Limit State 4-16
4.8.3.3—Fatigue Limit State 4-16
4.8.3.4—Strength Limit State 4-16
4.8.3.5—Extreme Event Limit State 4-16
4.8.4—Design Considerations....................4-16
4.8.5—Design for Flexural and Axial Load Effects....................4-16
4.8.6—Shear....................4-17
4.9—REFERENCES 4-17

SECTION 5 – GEOTECHNICAL CONSIDERATIONS

TABLE OF CONTENTS

5.1—SCOPE 5-1
5.2—DEFINITIONS 5-2
5.3—NOTATION 5-3
  5.3.1—General 5-3
  5.3.2—Abbreviations 5-4
5.4—GEOTECHNICAL INVESTIGATION 5-4
  5.4.1—General 5-4
  5.4.2—Office Studies 5-5
    5.4.2.1—Review of Existing Reports 5-5
    5.4.2.2—Review of Historical Maps 5-6
    5.4.2.3—Imagery Evaluation 5-6
  5.4.3—Field Reconnaissance and Geologic Mapping 5-10
  5.4.4—Geotechnical Borings 5-11
  5.4.5—In-Situ Tests and Sampling of Soil and Rock 5-12
    5.4.5.1—Soil Sampling 5-12
    5.4.5.2—Rock Coring 5-13
    5.4.5.3—Bore Hole Sealing 5-13
  5.4.6—Geophysical Tests 5-17
  5.4.7—Laboratory Tests 5-20
    5.4.7.1—Soil Tests 5-20
    5.4.7.2—Rock Tests 5-20
  5.4.8—Groundwater and Surface Water Investigation 5-20
5.5—SELECTION OF SOIL AND ROCK PARAMETERS FOR DESIGN 5-21
  5.5.1—General 5-21
  5.5.2—Soil Strength 5-22
    5.5.2.1—Undrained Shear Strength of Cohesive Soils 5-22
    5.5.2.2—Drained Strength of Cohesive Soils 5-22
    5.5.2.3—Drained Strength of Granular Soils 5-23
  5.5.3—Soil Deformation 5-23
  5.5.4—Rock Shear Strength 5-23
  5.5.5—Rock Deformation Modulus 5-26
  5.5.6—Poisson's Ratio 5-29
5.6—ENVIRONMENTAL ISSUES 5-29
5.7—INSTRUMENTATION AND MONITORING 5-29
5.8—GEOTECHNICAL REPORTS 5-30
  5.8.1—Geotechnical Data Report 5-30
  5.8.2—Geotechnical Baseline Report 5-30
5.9—GEOTECHNICAL DESIGN MEMORANDA 5-31
5.10—REFERENCES 5-32

SECTION 6 – CUT-AND-COVER TUNNEL STRUCTURES

TABLE OF CONTENTS

6.1—SCOPE ... 6-1
6.2—DEFINITIONS ... 6-1
6.3—NOTATION ... 6-2
6.3.1—General ... 6-2
6.3.2—Abbreviations ... 6-2
6.4—GROUND AND MATERIAL PROPERTIES ... 6-2
6.4.1—Determination of Ground Properties ... 6-2
6.4.1.1—General ... 6-2
6.4.1.2—Invert Condition ... 6-2
6.4.1.3—Envelope Ground ... 6-3
6.4.1.4—Groundwater ... 6-3
6.4.2—Materials ... 6-4
6.4.2.1—Concrete ... 6-4
6.4.2.2—Structural Steel ... 6-4
6.4.2.3—Reinforcing Steel ... 6-4
6.4.2.4—Prestressing Steel ... 6-4
6.4.2.5—Shotcrete ... 6-5
6.5—CONSTRUCTION OF CUT-AND-COVER TUNNEL STRUCTURES ... 6-5
6.5.1—General ... 6-5
6.5.2—Reinforced Concrete Diaphragm Walls (RCDW) ... 6-6
6.5.3—Soldier Pile and Tremie Concrete (SPTC) Walls ... 6-7
6.5.4—Secant Pile and Tangent Pile Walls ... 6-8
6.5.5—Precast, Prestressed Panel Walls ... 6-9
6.5.6—Cast-in-Place Concrete Box Structures ... 6-9
6.5.7—Structural Steel Frames ... 6-9
6.6—LIMIT STATES AND RESISTANCE FACTORS ... 6-10
6.6.1—General ... 6-10
6.6.2—Service Limit State ... 6-10
6.6.3—Strength Limit State ... 6-10
6.6.4—Extreme Event Limit State ... 6-10
6.6.5—Load Factors and Load Combinations ... 6-11
6.6.6—Resistance Factors ... 6-12
6.7—GENERAL DESIGN FEATURES ... 6-12
6.7.1—Ground Movement ... 6-12
6.7.2—Buoyancy ... 6-12
6.7.2.1—Partially Completed Structure ... 6-13
6.7.2.2—Complete Structure ... 6-13
6.7.3—Loading ... 6-13
6.7.3.1—Symmetrical Loading ... 6-14
6.7.3.2—Asymmetrical Loading ... 6-14
6.7.3.3—Construction Condition ... 6-14
6.7.3.4—Distribution of Loads ... 6-15
6.7.3.5—Superimposed Loads ... 6-15
6.8—JOINTS ... 6-15
6.8.1—General ... 6-15
6.8.2—Construction Joints ... 6-15
6.8.3—Contraction Joints ... 6-16
6.8.4—Expansion Joints ... 6-16

6.9—STRUCTURAL ANALYSES 6-16
6.9.1—Load Distribution and Sharing 6-16
6.9.2—Ground–Structure Interaction 6-16
6.9.3—Empirical Methods 6-17
6.9.4—Frame Analyses 6-17
6.10—WATERPROOFING 6-17
6.10.1—Treatment of Penetrations 6-18
6.10.2—Gaskets 6-18
6.10.3—Permissible Leakage 6-18
6.11—PRESSURE RELIEF SYSTEMS 6-18
6.12—REFERENCES 6-19

SECTION 7 – MINED AND BORED TUNNEL STRUCTURES

TABLE OF CONTENTS

7.1—SCOPE 7-1
7.2—DEFINITIONS 7-1
7.3—NOTATION 7-2
7.3.1—General 7-2
7.3.2—Abbreviations 7-2
7.4—GROUND AND MATERIAL PROPERTIES 7-3
7.4.1—Determination of Ground Properties 7-3
7.4.1.1—General 7-3
7.4.1.2—Ground Classification 7-3
7.4.1.3—Groundwater 7-4
7.4.1.4—In-Situ Ground Stresses 7-4
7.4.2—Materials 7-5
7.4.2.1—Concrete 7-5
7.4.2.2—Structural Steel 7-5
7.4.2.3—Steel Reinforcing 7-5
7.4.2.4—Prestressing Steel 7-6
7.4.2.5—Shotcrete 7-6
7.5—CONSTRUCTION OF MINED AND BORED TUNNEL STRUCTURES 7-6
7.5.1—General 7-6
7.5.2—Construction of Mined Tunnel Structures 7-7
7.5.3—Construction of Bored Tunnel Structures 7-8
7.6—LIMIT STATE AND RESISTANCE FACTORS 7-8
7.6.1—General 7-8
7.6.2—Service Limit State 7-9
7.6.3—Strength Limit State 7-9
7.6.4—Extreme Limit State 7-9
7.6.5—Load Factors and Load Combinations 7-10
7.6.6—Resistance Factors 7-10
7.7—GENERAL DESIGN FEATURES 7-10
7.7.1—General 7-10
7.7.1.1—Initial Ground Support 7-10
7.7.1.2—Final Lining 7-11
7.7.1.3—Cross Passages, Sumps, and Ancillary Spaces 7-11
7.7.2—Ground Movements 7-12
7.7.2.1—General 7-12
7.7.2.2—Empirical Method 7-13
7.7.3—Buoyancy 7-16
7.7.4—Loading 7-16
7.7.4.1—Symmetrical Loading 7-17
7.7.4.2—Asymmetrical Loading 7-17
7.7.4.3—Construction Condition 7-17
7.7.4.4—Distribution of Loads 7-18
7.7.4.5—Superimposed Loads 7-18
7.7.5—Analysis and Design 7-18
7.7.5.1—General 7-18
7.7.5.2—Design 7-18
7.7.5.3—Moment of Inertia 7-19
7.7.5.4—Ground/Structure Interaction 7-19
7.8—JOINTS 7-20
7.8.1—General 7-20
7.8.2—Construction Joints 7-20
7.8.3—Contraction Joints 7-20
7.8.4—Expansion Joints 7-20

7.8.5—Segment Joints 7-21
7.9—WATERPROOFING 7-21
7.9.1—Treatment of Penetrations 7-21
7.9.2—Gaskets 7-22
7.9.3—Permissible Leakage 7-22
7.10—REFERENCES 7-22

SECTION 8 – IMMERSED TUNNEL STRUCTURES

TABLE OF CONTENTS

8.1—SCOPE 8-1
8.2—DEFINITIONS 8-1
8.3—NOTATION 8-2
8.3.1—Loads and Load Designations 8-2
8.3.2—Abbreviations 8-2
8.4—DESIGN CONSIDERATIONS 8-2
8.4.1—Determination of Ground Properties 8-2
8.4.1.1—General 8-2
8.4.1.2—Foundation 8-3
8.4.1.3—Fill Material 8-4
8.4.1.4—Sideslopes 8-5
8.4.2—Materials 8-5
8.4.3—Support Loss 8-6
8.5—CONSTRUCTION 8-6
8.5.1—Shipping Channel Traffic 8-6
8.5.2—Trench Excavation 8-6
8.5.3—Element Length 8-7
8.5.4—Fabrication Facility 8-7
8.5.5—Transportation 8-7
8.5.6—Outfitting 8-8
8.5.7—Immersion 8-9
8.5.8—Joining and Backfilling 8-9
8.6—Limit States and Resistance Factors 8-10
8.6.1—General 8-10
8.6.2—Service Limit States 8-10
8.6.3—Strength Limit States 8-10
8.6.4—Extreme Limit States 8-10
8.6.5—Load Factors and Load Combinations 8-11
8.6.6—Resistance Factors 8-11
8.7—GENERAL FEATURES OF DESIGN 8-11
8.7.1—Loading 8-11
8.7.1.1—Permanent Loads 8-11
8.7.1.1.1—Settlement (SE) 8-12
8.7.1.2—Transient Loads 8-12
8.7.1.2.1—Transient Water Loads (WA_p) 8-12
8.7.1.3—Construction Loads 8-13
8.7.1.3.1—Launching (LA) 8-13
8.7.1.3.2—Transportation (TR) 8-13
8.7.1.3.3—Immersion (IN) 8-13
8.7.1.3.4—Joining (JO) 8-14
8.7.2—Joints 8-14
8.7.3—Scour Protection 8-15
8.8—STRUCTURAL ANALYSIS 8-15
8.9—WATERPROOFING 8-16
8.9.1—Waterproofing Systems 8-16
8.9.2—Water Infiltration 8-16
8.10—REFERENCES 8-16

SECTION 9 – INITIAL GROUND SUPPORT ELEMENTS AND GROUND IMPROVEMENT

TABLE OF CONTENTS

9.1—SCOPE 9-1
9.2—DEFINITIONS 9-1
9.3—NOTATION 9-2
9.3.1—General 9-2
9.3.2—Abbreviations 9-2
9.4—GENERAL 9-3
9.4.1—Criteria for Initial Ground Support Design 9-3
9.4.1.1—Soft Ground and Mixed Face Conditions *9-3*
9.4.1.2—Rock Conditions *9-3*
9.4.2—Initial Support Types Appropriate for Different Ground Conditions 9-6
9.4.2.1—Soft Ground and Mixed Face Conditions *9-6*
9.4.2.2—Rock Conditions *9-6*
9.5—INITIAL GROUND SUPPORT ELEMENTS 9-6
9.5.1—Soil and Rock Reinforcement Elements 9-7
9.5.1.1—Steel Reinforcement Elements 9-7
9.5.1.2—Glass Reinforced Plastic (GRP) Elements 9-7
9.5.1.3—Friction Rock Stabilizers 9-7
9.5.2—Lattice Girders 9-8
9.5.3—Shotcrete 9-8
9.5.4—Steel Ribs and Lagging 9-8
9.6—LIMIT STATES AND RESISTANCE FACTORS 9-9
9.6.1—General 9-9
9.6.2—Service Limit State 9-9
9.6.3—Strength Limit State 9-9
9.6.4—Extreme Limit State 9-9
9.6.5—Resistance Factors 9-9
9.7—INITIAL SUPPORT DESIGN 9-10
9.7.1—Rock Reinforcement 9-10
9.7.1.1—Pattern Rock Reinforcement 9-10
9.7.1.1.1—Selection of Element Length and Spacing 9-10
9.7.1.1.2—Pattern Design 9-11
9.7.1.2—Spot Rock Reinforcement 9-13
9.7.1.3—Deformation and Excavation Sequence Analysis 9-14
9.7.2—Shotcrete 9-14
9.7.2.1—Shotcrete Membranes 9-14
9.7.2.2—Structural Shotcrete 9-14
9.7.3—Steel Ribs and Lagging 9-14
9.7.4—Precast Concrete Segments 9-14
9.7.5—Spiles 9-15
9.8—GROUND IMPROVEMENT 9-15
9.9—PORTALS, CROSS PASSAGES, AND ANCILLARY STRUCTURES 9-15
9.10—REFERENCES 9-16
APPENDIX 9-A—Recommendations for Software Use for Design and Performance Evaluation of Rock Reinforcement, Shotcrete, and Direct Rock Support for Underground Openings in Rock 9-17
A9.1—Introduction 9-17
A9.2—General Description of Software Packages 9-17
A9.2.1—Rigid Block Software 9-17
A9.2.2—Two-Dimensional Distinct Element Method (DEM) Software 9-17
A9.2.3—Three-Dimensional Distinct Element Method (3-D DEM) Software 9-18
A9.3—Recommendations 9-18
A9.3.1—Use of Rigid Block Software 9-18
A9.3.2—Use of Two-Dimensional Distinct Element Method (DEM) Software 9-19
A9.3.3—Use of Three-Dimensional Distinct Element Method (3-D DEM) Software 9-20

SECTION 10 – SEISMIC CONSIDERATIONS

TABLE OF CONTENTS

10.1—SCOPE………… 10-1
10.2—DEFINITIONS………… 10-1
10.3—NOTATION…………10-2
10.3.1—Abbreviations…………10-2
10.4—SEISMIC PERFORMANCE AND SCREENING REQUIREMENTS…………10-3
10.4.1—Seismic Performance Criteria and Design Earthquake Levels…………10-3
10.4.2—Structural Design Check…………10-3
10.4.3—Screening Criteria…………10-4
10.5—DESIGN GROUND MOTION PARAMETERS…………10-4
10.5.1—Design Earthquakes…………10-4
10.5.2—Ground Motion Hazard Analysis…………10-5
10.5.2.1—Earthquake Magnitude and Distance…………10-5
10.5.2.2—Peak Ground Motion Parameters…………10-5
10.5.2.3—Attenuation of Peak Ground Motion Parameters…………10-6
10.5.2.4—Design Response Spectra…………10-6
10.5.2.5—Ground Motion Time Histories…………10-6
10.5.2.6—Spatially Varying Ground Motion Effects…………10-7
10.6—SEISMIC LOADS AND LIMIT STATES…………10-7
10.6.1—Load Combinations and Load Factors…………10-7
10.6.2—Resistance Factors…………10-8
10.7—SEISMIC SITE CHARACTERIZATION AND DYNAMIC SOIL/ROCK PROPERTIES…………10-8
10.7.1—General…………10-8
10.7.2—Seismic Site Classes…………10-8
10.7.3—Dynamic Soil/Rock Properties…………10-8
10.8—SEISMIC DESIGN…………10-9
10.8.1—General…………10-9
10.8.2—Seismic Loading Effects…………10-9
10.8.3—Method of Analysis and Assessment—Ground Shaking Effects…………10-11
10.8.3.1—Transverse Ovaling/Racking Deformation Effects…………10-11
10.8.3.1.1—Simplified Method for Ovaling Response of Circular Tunnels…………10-12
10.8.3.1.2—Simplified Method for Racking Response of Rectangular Tunnels…………10-12
10.8.3.1.3—Numerical Modeling Approach…………10-13
10.8.3.2—Longitudinal Axial and Curvature Deformation Effects…………10-16
10.8.4—Method of Analysis and Assessment—Ground Failure Effects…………10-18
10.8.4.1—Liquefaction and Liquefaction-Induced Ground Deformations…………10-18
10.8.4.1.1—Evaluation of Liquefaction Potential…………10-18
10.8.4.1.2—Post-Liquefaction Settlements…………10-19
10.8.4.1.3—Liquefaction-Induced Lateral Spreading…………10-19
10.8.4.2—Seismic Slope Instability and Landslides…………10-19
10.8.4.3—Active Fault Crossing Displacement Effects…………10-20
10.9—SEISMIC DESIGN OF TEMPORARY STRUCTURES…………10-20
10.10—RETAINING STRUCTURES AND PORTALS…………10-20
10.11—INTERFACES WITH CROSS-PASSAGES AND OTHER STRUCTURES…………10-21
10.12—SEISMIC JOINTS…………10-21
10.13—NON-STRUCTURAL COMPONENTS AND EQUIPMENT…………10-21
10.14—REFERENCES…………10-21

APPENDIX A

PLANNING AND ROUTE CONSIDERATIONS

TABLE OF CONTENTS

A.1—SCOPE A-1
A.2—ABBREVIATIONS A-1
A.3—ENVIRONMENTAL A-1
A.3.1—General A-1
A.3.2—Environmental Permits A-2
A.3.3—Avoidance/Minimization of Environmental Resources A-2
A.3.4—Floodplains A-3
A.3.5—Wetlands/Waterways A-4
A.3.6—Navigable Waterways A-5
A.3.7—Groundwater A-5
A.3.8—Cultural Resources A-6
A.3.9—Environmental Justice A-6
A.3.10—Section 4(f) Resources A-7
A.3.11—Environmental Compliance A-7
A.3.12—Public and Agency Involvement A-8
A.3.13—Economics A-9
A.3.14—Aesthetics A-9
A.4—GEOLOGIC FEATURES AND SUBSURFACE CONDITIONS A-10
A.4.1—Subsurface Investigation A-10
A.4.2—Ground Conditions A-10
A.5—EXISTING INFRASTRUCTURE A-11
A.6—CONSTRUCTABILITY CONSIDERATIONS A-12
A.6.1—Construction Methodology A-13
A.6.2—Noise and Vibration A-14
A.6.2.1—Noise Controls A-14
A.6.2.2—Vibration Controls A-15
A.6.3—Muck Removal and Disposal A-16
A.6.4—Staging Areas A-17
A.6.5—Traffic and Public Transportation A-18
A.6.6—Safety and Security A-19