JUNE 2010
EDITION

Technical Manual *for* Design *and* Construction *of* Road Tunnels—CIVIL ELEMENTS

American Association of State Highway and Transportation Officials

JUNE 2010
EDITION

Technical Manual *for* Design *and* Construction *of* Road Tunnels—CIVIL ELEMENTS

American Association of State Highway and Transportation Officials

American Association of State Highway and Transportation Officials
444 North Capitol Street, NW Suite 249
Washington, DC 20001
202-624-5800 phone/202-624-5806 fax
www.transportation.org

ISBN: 978-1-56051-457-2
Pub Code: DCRT-1

© 2010 by the American Association of State Highway and Transportation Officials.
All rights reserved. Duplication is a violation of applicable law.

EXECUTIVE COMMITTEE
2009–2010

Voting Members

Officers:

President: Larry L. "Butch" Brown, Mississippi

Vice President: Susan Martinovich, Nevada

Secretary-Treasurer: Carlos Braceras, Utah

Regional Representatives:

REGION I:	Joseph Marie, Connecticut, One-Year Term Gabe Klein, District of Columbia, Two-Year Term
REGION II:	Dan Flowers, Arkansas, One-Year Term Mike Hancock, Kentucky, Two-Year Term
REGION III:	Nancy J. Richardson, Iowa, One-Year Term Thomas K. Sorel, Minnesota, Two-Year Term
REGION IV:	Paula Hammond, Washington, One-Year Term Amadeo Saenz, Jr., Texas, Two-Year Term

Nonvoting Members

Immediate Past President: Allen Biehler, Pennsylvania
AASHTO Executive Director: John Horsley, Washington, DC

HIGHWAY SUBCOMMITTEE ON BRIDGES AND STRUCTURES
2009

MALCOLM T. KERLEY, *Chair*
JAMES A. MOORE, *Vice Chair*
M. MYINT LWIN, Federal Highway Administration, *Secretary*
RAJ AILANEY, Federal Highway Administration, *Assistant Secretary*
KEN KOBETSKY, *AASHTO Liaison*
KELLEY REHM, *AASHTO Liaison*

ALABAMA, John F. "Buddy" Black, William "Tim" Colquett, George H. Conner
ALASKA, Richard A. Pratt
ARIZONA, Jean A. Nehme
ARKANSAS, Phil Brand
CALIFORNIA, Kevin Thompson, Susan Hida, Barton J. Newton
COLORADO, Mark A. Leonard, Michael G. Salamon
CONNECTICUT, Julie F. Georges
DELAWARE, Jiten K. Soneji, Barry A. Benton
DISTRICT OF COLUMBIA, Nicolas Galdos, L. Donald Cooney, Konjit "Connie" Eskender
FLORIDA, Marcus Ansley, Sam Fallaha, Jeff Pouliotte
GEORGIA, Paul V. Liles, Jr.
HAWAII, Paul T. Santo
IDAHO, Matthew M. Farrar
ILLINOIS, Ralph E. Anderson, Thomas J. Domagalski
INDIANA, Anne M. Rearick
IOWA, Norman L. McDonald
KANSAS, Kenneth F. Hurst, James J. Brennan, Loren R. Risch
KENTUCKY, Mark Hite
LOUISIANA, Hossein Ghara, Arthur D'Andrea, Paul Fossier
MAINE, David B. Sherlock, Jeffrey S. Folsom
MARYLAND, Earle S. Freedman, Robert J. Healy
MASSACHUSETTS, Alexander K. Bardow, Shirley Eslinger
MICHIGAN, Steven P. Beck, David Juntunen
MINNESOTA, Daniel L. Dorgan, Kevin Western
MISSISSIPPI, Mitchell K. Carr, B. Keith Carr
MISSOURI, Dennis Heckman, Michael Harms
MONTANA, Kent M. Barnes
NEBRASKA, Mark J. Traynowicz, Mark Ahlman, Fouad Jaber
NEVADA, Mark P. Elicegui, Todd Stefonowicz
NEW HAMPSHIRE, Mark W. Richardson, David L. Scott
NEW JERSEY, Richard W. Dunne
NEW MEXICO, Raymond M. Trujillo, Jimmy D. Camp
NEW YORK, George A. Christian, Donald F. Dwyer, Arthur P. Yannotti
NORTH CAROLINA, Greg R. Perfetti
NORTH DAKOTA, Terrence R. Udland
OHIO, Timothy J. Keller, Jawdat Siddiqi
OKLAHOMA, Robert J. Rusch, Gregory D. Allen, John A. Schmiedel
OREGON, Bruce V. Johnson, Hormoz Seradj
PENNSYLVANIA, Thomas P. Macioce, Harold C. "Hal" Rogers, Jr., Lou Ruzzi
PUERTO RICO, (Vacant)
RHODE ISLAND, David Fish
SOUTH CAROLINA, Barry W. Bowers, Jeff Sizemore
SOUTH DAKOTA, Kevin Goeden
TENNESSEE, Edward P. Wasserman
TEXAS, David P. Hohmann, Keith L. Ramsey
U.S. DOT, M. Myint Lwin, Firas I. Sheikh Ibrahim
UTAH, (Vacant)
VERMONT, Wayne B. Symonds
VIRGINIA, Malcolm T. Kerley, Kendal Walus, Prasad L. Nallapaneni, Julius F. J. Volgyi, Jr.
WASHINGTON, Jugesh Kapur, Tony M. Allen, Bijan Khaleghi
WEST VIRGINIA, Gregory Bailey, James D. Shook
WISCONSIN, Scot Becker, Beth A. Cannestra, William Dreher
WYOMING, Gregg C. Fredrick, Keith R. Fulton

GOLDEN GATE BRIDGE, Kary H. Witt
N.J. TURNPIKE AUTHORITY, Richard J. Raczynski
N.Y. STATE BRIDGE AUTHORITY, William J. Moreau
PENN. TURNPIKE COMMISSION, James L. Stump

U.S. ARMY CORPS OF ENGINEERS—DEPARTMENT OF THE ARMY, Christopher H. Westbrook
U.S. COAST GUARD, Hala Elgaaly
U.S. DEPARTMENT OF AGRICULTURE—FOREST SERVICE, John R. Kattell, Scott F. Mitchell

ALBERTA, Tom Loo
NEW BRUNSWICK, Doug Noble
NOVA SCOTIA, Mark Pertus
ONTARIO, Bala Tharmabala
SASKATCHEWAN, Howard Yea

TRANSPORTATION RESEARCH BOARD—
Waseem Dekelbab

FOREWORD TO FHWA MANUAL

The Federal Highways Administration *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 Specifications* and the *AASHTO LRFD Bridge 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; and 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

ACKNOWLEDGMENTS

AASHTO's *Technical Manual for Design and Construction of Road Tunnels—Civil Elements* was originally published by FHWA in May 2009 (FHWA-NHI-09-010) and revised in December 2009 (FHWA-NHI-10-034). This AASHTO June 2010 edition incorporates graphic and editorial improvement, as well as minor technical revisions. The development of this manual was led by Principal Investigators including C. Jeremy Hung, P.E.; J. Monsees, Ph.D., P.E., N. Munfakh, P.E., and J. Wisniewski, P.E. of Parsons Brinckerhoff, Inc., funded by the National Highway Institute, and supported by Parsons Brinckerhoff, Inc., as well as numerous authors and reviewers acknowledged hereafter including the following primary authors from Parsons Brinckerhoff, Inc. (PB), and Gall Zeidler Consultants, LLC:

Chapter 1—Planning: Nasri Munfah and Christian Ingerslev

Chapter 2—Geometrical Configuration: Christian Ingerslev and Jeremy Hung

Chapter 3—Geotechnical Investigation: Jeremy Hung and Raymond Castelli

Chapter 4—Geotechnical Report: Raymond Castelli and Jeremy Hung

Chapter 5—Cut-and-Cover Tunnels: John Wisniewski and Nasri Munfah

Chapter 6—Rock Tunneling: James Monsees and Sunghoon Choi

Chapter 7—Soft Ground Tunneling: James Monsees

Chapter 8—Difficult Ground Tunneling: James Monsees and Terrence McCusker (Consultant)

Chapter 9—Sequential Excavation Method: Vojtech Gall and Kurt Zeidler

Chapter 10—Tunneling Lining: John Wisniewski

Chapter 11—Immersed Tunnels: Christian Ingerslev and Nasri Munfah

Chapter 12—Jacked Box Tunneling: Philip Rice and Jeremy Hung

Chapter 13—Seismic Considerations: Jaw-Nan (Joe) Wang

Chapter 14—Construction Engineering: Thomas Peyton

Chapter 15—Geotechnical and Structural Instrumentation: Charles Daugherty and Doug Anderson

Chapter 16—Tunnel Rehabilitation: Henry Russell

The Principal Investigators would like to especially acknowledge the support of the FHWA Task Manager, Firas Ibrahim, and the reviews and recommendations provided by the FHWA technical reviewers including Jesus Rohena, Jerry DiMaggio, Steven Ernst, and Peter Osborn. Furthermore, the reviews and contributions of the following members of the AASHTO T-20 Tunnel Committee are also acknowledged:

- Kevin Thompson, Chair, California Department of Transportation
- Bruce Johnson, Vice Chair, Oregon Department of Transportation
- Donald Dwyer, New York State Department of Transportation
- Louis Ruzzi, Pennsylvania Department of Transportation
- Prasad Nallapaneni, Virginia Department of Transportation
- Michael Salamon, Colorado Department of Transportation
- Bijan Khaleghi, Washington Department of Transportation
- Alexander Bardow, Massachusetts Highway Department
- Dharam Pal, The Port Authority of New York and New Jersey
- Moe Amini, California Department of Transportation
- Harry Capers, Arora and Associates, P.C.

The Principal Investigators and authors would like to express our special thanks to Dr. George Munfakh of PB for his continuing support, advice, and encouragement.

We further acknowledge the support of Gene McCormick of PB and the contributions and reviews from Sunghoon Choi, Joe O'Carroll, Doug Anderson, Kyle Ott, Frank Pepe, and Bill Hansmire of PB; Dr. Andrzej Nowak of University of Nebraska; and Tony Ricci and Nabil Hourani of the Massachusetts Highway Department.

Chapter 8 is an update of Chapter 8, "Tunneling in Difficult Ground," of the *Tunnel Engineering Handbook*, Second Edition, by Terrence G. McCusker (Bickel, et al., 1996). The Principal Investigators appreciate PB's providing the original manuscript for the chapter.

In addition, we appreciate the information provided by Herrenknecht AG, the Robbins Company, and several other manufacturers and contractors from the tunneling industry.

Lastly, the Principal Investigators and authors would like to extend our gratitude to the support provided by a number of professionals from PB and Gall Zeidler Consultants, LLC including Taehyun Moon, Kevin Doherty, Mitchell Fong, Rudy Holley, Benny Louie, Tim O'Brien, and Dominic Reda for their assistance; Jose Morales and Jeff Waclawski for graphic support; and finally Amy Pavlakovich, Lauren Chu, Alejandra Morales, Mary Halliburton, and Maria Roberts for their assistance and overall word processing and compiling.

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 a 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.

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, 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), also 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 the 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 and blast operation, and 5) groundwater movement due to changes in the water percolation pattern.

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

AASHTO Publications Staff
May 2010

TABLE OF CONTENTS

LIST OF APPENDICES

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
Planning

1.1—INTRODUCTION

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

Road tunnels are feasible alternatives to cross a water body or traverse through physical barriers such as mountains, existing roadways, railroads, or facilities, or to satisfy environmental or ecological requirements. In addition, road tunnels are viable means to minimize potential environmental impact, such as traffic congestion, pedestrian movement, air quality, noise pollution, or visual intrusion; to protect areas of special cultural or historical value, such as conservation of districts, buildings, or private properties; or for other sustainability reasons, such as to avoid the impact on natural habitat or reduce disturbance to surface land. Figure 1.1-1 shows the portal for the Glenwood Canyon Reverse Curve Tunnel—twin 4,000-ft long tunnels carrying a critical section of I-70 unobtrusively through Colorado's scenic Glenwood Canyon.

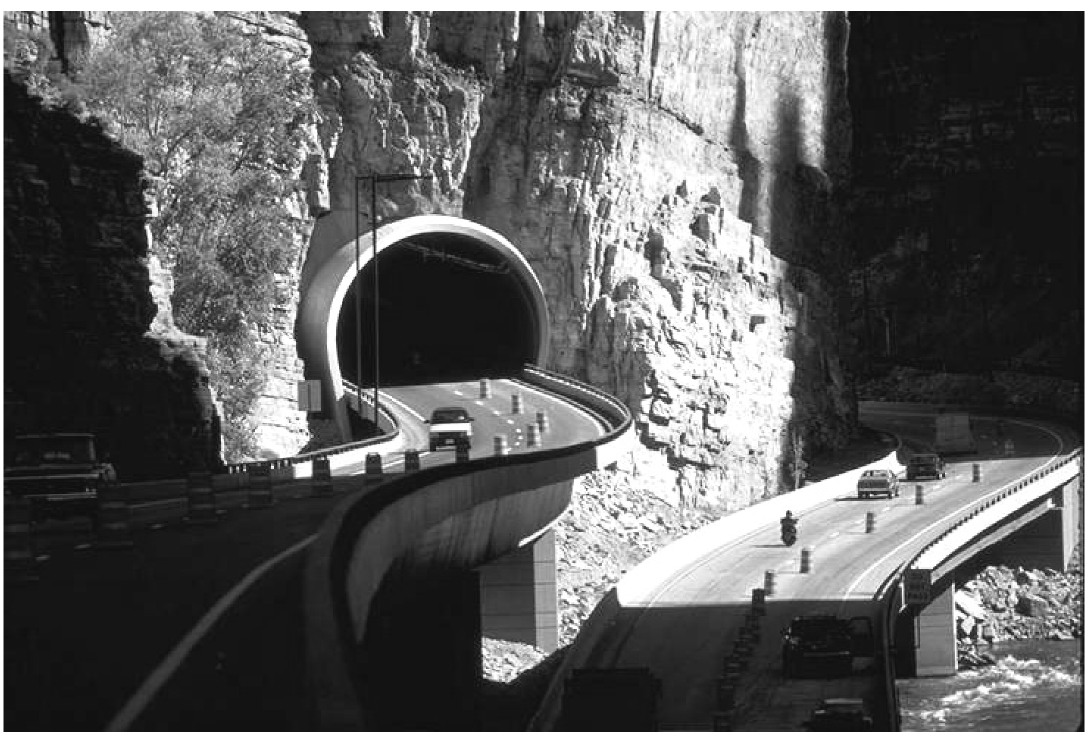

Figure 1.1-1—Glenwood Canyon Reverse Curve Tunnel