IN-LB Inch-Pound Units

SI International System of Units

Guide for Precast Concrete Tunnel Segments

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

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Guide for Precast Concrete Tunnel Segments

Reported by ACI Committee 533

David Wan, Chair

Mehdi Bakhshi[*†]
George F. Baty
Harry A. Chambers[‡]
Benjamin Lavon
James Lewis
Donald F. Meinheit
Brian D. Miller
Verya Nasri[†]
Karen Polanco
Larbi M. Sennour
Venkatesh Seshappa
Michael H. Weber
Dennis M. Wittry
Wael A Zatar

*Chair of task group who prepared this report.
†Members who prepared this report.
‡Deceased.

Consulting Members

Aaron W. Fink
Sidney Freedman
Ava Shypula
Weilan Song

The worldwide trend in construction is toward mechanization and automation. This trend has led to continued rapid progress of mechanized tunneling. Advantages over conventional tunnel construction methods include, but are not limited to, occupational health and safety, faster advance rates, and reducing construction labor requirements. Mechanized tunneling in soft ground using tunnel boring machines is often associated with installing precast concrete segmental lining. However, very little industry-wide guidance has been provided by practice and code organizations. This document provides guidelines for precast concrete tunnel segments, including the most recent developments and practical experience, in addition to information on all aspects of design and construction. These guidelines are based on the knowledge and the experience gained on numerous precast tunnel projects in the United States, and available national and international guidelines often used as industry references.

Keywords: design; durability; fiber; gasket; joint; lining; precast; segment; tolerance; tunnel.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Precast concrete segments are installed to support the excavation behind the tunnel boring machine (TBM) in soft ground, weak rock, and fractured hard rock applications. As shown in Fig. 1.1, the TBM advances by reacting against the completed rings of precast concrete segments that typically provide both the initial and final ground support as part of a one-pass lining system. These segments are designed to resist the permanent loads from the ground and groundwater as well as the temporary loads from production, transportation, and construction. Currently, very little guidance is provided for tunnel designers and contractors by local or international authorities, and there is an acute need for a document to clearly highlight the practical design principles, advances in construction, and the research needs in this area. Tunnel segments are generally reinforced to resist the tensile and compressive stresses at the ultimate limit states (ULS) and the serviceability limit state (SLS). Special attention is paid in this document to common methods in ULS and SLS designs of these elements. In addition, detailed design considerations are presented, such as concrete strength and reinforcement. Gasket design as sealing elements against groundwater inflow, connection devices, and fastening systems are introduced, followed by segment tolerances, measurement, and dimensional control systems.

1.2—Scope

This document provides analysis, design, and construction guidelines exclusively for one-pass precast segmental lining that is installed almost instantaneously with excavation inside TBM shields only a few yards behind the TBM cutterhead. Linings that are installed long after passing of an open-mode TBM, cast-in-place concrete linings, and segments of other materials such as steel and cast-iron segments do not fall within the scope of this guideline. Two-pass lining systems, which are no longer popular in modern tunnels, are not specifically discussed but can still benefit from the guidelines. More information about the two-pass linings can be found in ITA WG2 guidelines. This guideline provides methods of design and construction for TBM tunneling in soft ground as well as weak and fractured hard rock tunneling. The guidelines and recommendations in this document can be applied to tunnels of different types, such as road, railway, and subway tunnels; headrace, water supply, and waste water tunnels; and service, gas pipeline, and

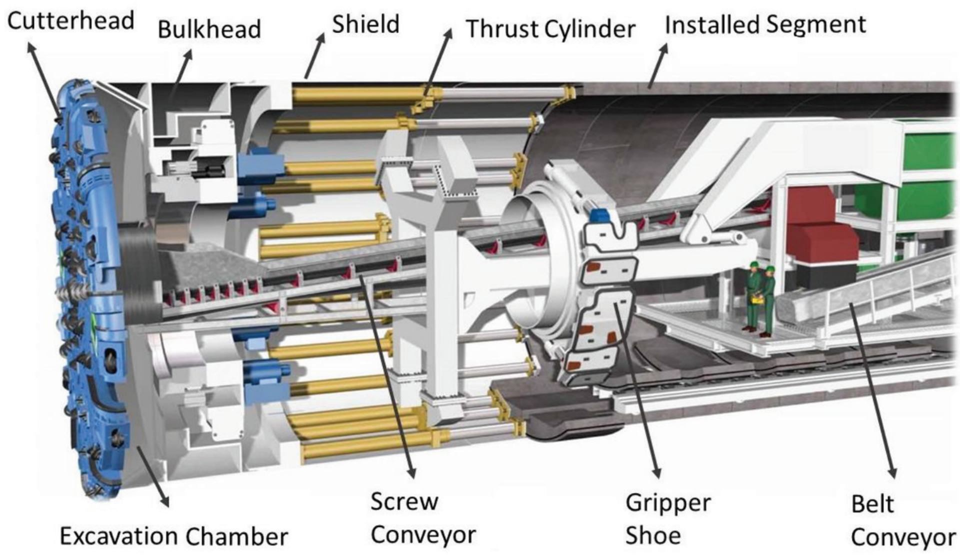

Fig. 1.1—Main parts of a typical TBM of earth-pressure balance (EPB) type, which is used for soft ground tunneling.

power cable tunnels. The structural design part of this document pertains to procedures for designing concrete tunnel segments to withstand the commonly encountered temporary and permanent load cases occurring during the production, transportation, construction, and final service phases. The procedure was developed based on global practice and review of major available design codes, standards, and guidelines related to precast segments in tunneling and concrete industries. The construction aspects presented in this guideline including segmental ring geometry and systems, gasket systems, and connection devices, and segment tolerances reflect global practice perspectives such as ACI 544.7R, AFTES:2005, BS PAS 8810:2016, DAUB:2013, JSCE 2007, LTA 2010, ÖVBB 2011, and STUVAtec:2005. This document does not address the actions of thermal variations, fire loads and explosion, or internal loads such as train loads within the tunnels. While some structural design parts of this guideline may only consider the procedures adopted by ACI, they can be extended to other structural codes such as BS EN 1992-1-1:2004.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = effective tension area of concrete around reinforcing bar divided by number of steel bars, in.^{2} (mm^2)

A_d = load distribution area inside segment under thrust jack forces, in.^{2} (mm^2)

A_g = gross area of concrete section, in.^{2} (mm^2)

A_j = area of contact zone between jack shoes and the segment face, in.^{2} (mm^2)

A_s = area of reinforcing bars, in.^{2} (mm^2)

a = distance from edge of vacuum lift pad to edge of segment in the load case of stripping (demolding), or dimension of final spreading surface under thrust jack forces, in. (mm)

a_l = transverse length of contact zone between jack shoes and the segment face, in. (mm)

a_t = transverse length of stress distribution zone at the centerline of segment under thrust jack forces, in. (mm)

b = width of tunnel segment or width of tested specimen, ft (m)

C_c = compression force in the concrete section, lbf (N)

C_t = tensile force in the section due to fiber reinforcement, lbf (N)

D_e = external diameters of the tunnel segmental lining, ft (m)

D_i = internal diameter of the tunnel segmental lining, ft (m)

d = thickness of tested specimen, or total width of the segment cross section, in. (mm)

d_1 = length of load transfer zone for the case of longitudinal joint bursting load, in. (mm)

d_{burst} = centroidal distance of bursting force from the face of section, in. (mm)

d_c = concrete cover over reinforcing bar, in. (mm)

d_k = width of the hinge joint or thickness of contact surface between segment joints for the case of longitudinal joint bursting load, in. (mm)

d_s = distributed width of stress block inside the segment for the case of longitudinal joint bursting, in. (mm)

E = modulus of elasticity of concrete, psi (MPa)

E_r = modulus of elasticity of surrounding ground, psi (MPa)

E_s = stiffness modulus of the surrounding ground determined by oedometer test, psi (MPa); or modulus of elasticity of reinforcing bar, psi (MPa)

EH = horizontal earth pressure, psi (MPa)

EV = vertical earth pressure, psi (MPa)

e = eccentricity, in. (mm)

e_{anc} = eccentricity of jack pads with respect to the centroid of cross section, or maximum total eccentricity in longitudinal joints consisting of force eccentricity and eccentricity of load transfer area, in. (mm)

F = forces acting on bottom segment due to self-weight of segments positioned above when segments are piled up within one stack during storage or transportation phases, lbf (N)
F_{sd} = bursting tensile forces developed close to longitudinal joints, lbf (N)
$F_{sd,r}$ = spalling tensile forces developed close to longitudinal joints, lbf (N)
$F_{sd,2}$ = secondary tensile forces developed close to longitudinal joints, lbf (N)
f_1 = first peak flexural strength, psi (MPa)
f_{bot} = stress at the extreme bottom fiber of concrete section, psi (MPa)
f_c' = specified compressive strength of concrete segment, psi (MPa)
f_{co}' = compressive strength of partially loaded concrete surface, psi (MPa)
f_{cd} = concrete design compressive strength according to BS EN 1992-1-1:2004, psi (MPa)
f_{ctd} = fiber-reinforced concrete design tensile strength, psi (MPa)
$f_{ct,eff}$ = concrete tensile strength, psi (MPa)
f^D_{150} = residual flexural strength at net deflection of L/150, psi (MPa)
f^D_{600} = residual flexural strength at net deflection of L/600, psi (MPa)
f'^D_{150} = specified residual flexural strength at net deflection of L/150, psi (MPa)
f'^D_{600} = specified residual flexural strength at net deflection of L/600, psi (MPa)
f^D_{150r} = required average residual flexural strength at net deflection of L/150, psi (MPa)
f^D_{600r} = required average residual flexural strength at net deflection of L/600, psi (MPa)
f_{Ftu} = fiber-reinforced concrete tensile strength at ultimate limit state, psi (MPa)
f_{R1} = residual flexural strength of FRC beam corresponding to crack mouth opening displacement of 0.02 in. (0.5 mm), psi (MPa)
f_{R3} = residual flexural strength of fiber-reinforced concrete beam corresponding to crack mouth opening displacement of 0.1 in. (2.5 mm), psi (MPa)
f_s = stress in reinforcing bar, psi (MPa)
f_t = specified splitting tensile strength, psi (MPa)
f_y = yield stress of required reinforcing bars, psi (MPa)
g = self-weight of the segments per unit length, lbf/in. (N/mm)
H = overburden depth, ft (m)
H_w = groundwater depth, ft (m)
h = thickness of tunnel segment, in. (mm)
h_{anc} = length of contact zone between jack shoes and the segment face, in. (mm)
I = moment of inertia of FRC segment, in.^{4} (mm^4)
J = tunnel boring machine thrust jack forces, kip (kN)
k = coefficient of subgrade reaction or subgrade reaction modulus, lb/ft^3 (kg/m^3)
k_{jr} = Janssen rotational spring stiffness in longitudinal joints, lb.in./rad (N.mm/rad)
k_r = radial component of subgrade reaction modulus or stiffness of radial springs simulating ground-structure interaction, lb/ft^3 (kg/m^3)
k_t = subgrade reaction modulus in the tangential direction, lb/ft^3 (kg/m^3); or in crack width analysis, a factor depending on the duration of loading (0.6 for short-term loading and 0.4 for long-term loading)
k_θ = tangential component of subgrade reaction modulus or stiffness of tangential springs simulating ground-structure interaction, lb/ft^3 (kg/m^3)
L = distance between the supports, in. (mm)
l_t = full length of contact area between segments in longitudinal joints, in. (mm)
$M_{distortion}$ = bending moment due to additional distortion effect, lbf.ft (N.m)
M_n = nominal resistance bending moment, lbf.ft (N.m)
N = axial hoop force in segments, lbf (N)
N_{Ed} = maximum normal force due to permanent ground, groundwater, and surcharge loads, lbf (N)
n = number of segments per ring excluding the key segment ($n \geq 4$); or number of layers of tensile reinforcing bar in crack with analysis
P_0 = surcharge load, lbf (N)
P_{e1} = vertical earth pressure at crown of lining applied to the elastic equation method, psi (MPa)
P_{e2} = vertical earth pressure at invert of lining applied to the elastic equation method, psi (MPa)
P_g = segment dead load, psi (MPa)
P_{gr} = radial grouting pressure, psi (MPa)
P_{pu} = factored jacking force applied on each jack pad in circumferential joints, or maximum factored normal force from the final service loads transferred in longitudinal joints, psi (MPa)
P_{w1} = vertical water pressure at crown of lining applied to the elastic equation method, psi (MPa)
P_{w2} = vertical water pressure at invert of lining applied to the elastic equation method, psi (MPa)
q_{e1} = horizontal earth pressure at crown of lining applied to the elastic equation method, psi (MPa)
q_{e2} = horizontal earth pressure at invert of lining applied to the elastic equation method, psi (MPa)
q_{w1} = horizontal water pressure at crown of lining applied to the elastic equation method, psi (MPa)
q_{w2} = horizontal water pressure at invert of lining applied to the elastic equation method, psi (MPa)
R = radius from centerline of lining, ft (m)
r_o = radius of excavated tunnel, ft (m)
S = distance between stack supports and free edge of segments in the load case of segment storage, ft (m)
s = maximum reinforcing bar spacing, in. (mm)
$s_{r,max}$ = maximum crack spacing, mm
s_s = sample standard deviations of test results
T_{burst} = bursting force, lbf (N)
WA_p = groundwater pressure, psi (MPa)

w = segment self-weight, lb/ft (kg/m); or maximum crack width, in. (mm)
y = distance from extreme tension fiber to the neutral axis, in. (mm)
y_c = distance from extreme compression fiber to centroid of equivalent compression force in the section, in. (mm)
β = dimension of the loaded surface under thrust jack forces according to Iyengar diagram, in. (mm); or in crack width analysis ratio of the distance between neutral axis and tension face to the distance between neutral axis and centroid of reinforcing bar
$\Delta P_{g,\ invert}$ = vertical gradient of radial grout pressure between the crown and invert of tunnel, psi (MPa)
δ = displacement of lining applied to the elastic equation method, in. (mm)
δ_d = diametrical distortion, in. (mm)
ε'_{csd} = compressive strain due to shrinkage and creep equal to 150×10^{-6}
ε_{cu} = ultimate tensile strain
ε_{tu} = ultimate compressive strain
ϕ = strength reduction factor; or reinforcing bar diameter, in. (mm)
γ = material safety factor
λ = slenderness defined as the ratio between the developed segment lengths and its thickness
θ = angle from crown in the elastic equation method, or rotation in the longitudinal Janssen joint, radians
$\rho_{concrete}$ = specific weight of concrete, lb/ft^3 (kg/m^3)
ρ_{eq} = equivalent specific weight of grout, lb/ft^3 (kg/m^3)
$\sigma_{c,j}$ = compressive stresses developed under jack pads because of axial effects of thrust jack forces, psi (MPa)
σ_{cm} = fully spread compressive stress in method of the Iyengar diagram, psi (MPa)
σ_{cx} = bursting tensile stresses using the Iyengar diagram, psi (MPa)
σ_p = specified post-crack residual tensile strength of fiber-reinforced concrete (FRC) segment, psi (MPa)
τ_{yield} = shear yield strength of grout, psi (MPa)

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

annular gap—space between the surrounding ground and the outer surface of the segments.

circumferential joint—joint approximately perpendicular to the tunnel axis between two adjacent segment rings.

connections—devices for temporary or permanent attachment of two segments or segment rings in the longitudinal and circumferential joints.

counter key segments—two segments installed adjacent to key segment with at least one tapered joint with respect to tunnel longitudinal axis in plan view.

crosscut—connecting structure between two tunnel tubes or between a tunnel tube and the ground surface or a shaft, with special passages in the connecting area of the main tube.

crown—highest part of a tunnel in cross section.

earth-pressure balance tunnel boring machine—one type of tunnel boring machine used in soft ground tunneling; uses a screw conveyor and with controlling muck removal from the excavation chamber, the earth pressure in the chamber is maintained to balance the face pressure.

extrados—outer surface of the segment or the segment ring on the side in contact with the ground.

gasket—sealing system consisting of sealing strips placed in one or more layers around the individual segment, ensuring permanent sealing of the tunnel tube against the ingress of water from the surrounding ground.

guiding rod—segment accessories in the shape of rods, often 1 to 2 in. (25 to 50 mm) in diameter; placed in longitudinal joints along the centroid of two adjacent segments to fulfill the functions of guidance and locking adjacent segments during installation of a full ring inside tunnel boring machine shield.

ground—soil, rock, and fill into which the tunnel is placed.

intrados—inner surface of the segment or the segment ring on the tunnel side.

invert—lowest part of a tunnel in cross section.

joint misalignment—eccentricity between end of two segments at longitudinal or circumferential joints that results in limited contact areas between segment ends at joints.

key segment—last installed segment of a ring with a trapezoidal shape in plan view, which is often smaller than and accounted for as a proportion of ordinary segments such as one-third, two-thirds, or half.

longitudinal joint—joint between adjacent segments in a ring with an axis parallel to the longitudinal axis of tunnel; also known as radial joint.

one-pass lining—all static and structural requirements of the tunnel lining are handled by the segmental ring; no further internal lining is installed that contributes to load bearing or sealing.

ovalization—deformation of an initially circular segmental ring; for example, to a vertical or horizontal oval shape due to earth pressure, grout pressure, segment self-weight, or uplift.

packer—semi-rigid boards made of polyethylene or fortified asphalt core pressed between two layers of weatherproofed fiberglass plies or timber materials that are placed between tunnel segmental ring joins; they are used to relieve the stresses between segments and therefore prevent cracking and spalling. Packers are not used as often in modern segmental lining construction.

portal—entrance from the ground surface to a tunnel.

reverse key segment—first installed segment of a ring, in rectangular or trapezoidal shape, located opposite to key segment in segmental ring side view and often placed on or very close to tunnel invert.

ring width (ring length)—dimension of the segment ring in its center axis in the longitudinal direction of the tunnel.

segment—curved prefabricated elements that make up a ring of support or lining.

segment thickness—radial distance between the inner and outer sides of a segment.

shield—steel tube, usually cylindrical, shaped to fit the excavation line of a tunnel.

soft ground—residual soil or deteriorated rock with limited compressive strength and stand-up time.

springline—opposite ends of the horizontal centerline of tunnel.

tail void—annular space between the outside diameter of the shield and the outside of the segmental lining.

tunnel boring machine—consisting of a cutterhead, shield, and gantries used to excavate tunnels with a circular or rectangular cross section through different rock and soil strata, and to install the tunnel lining at the end of the shield.

tunnel boring machine backup—area behind tunnel boring machine shields in the shape of an equipment train that is used for providing a final staging area for feeding segments to the installation erectors as well as housing tunnel boring machine ancillary equipment such as transformers, power supply, hydraulic pumps, control room, ventilation, trail skin grouting, and spoil (muck) removal systems needed for the tunnel boring machine operation.

test ring—complete segment ring, usually assembled in horizontal orientation in segment precast plant, for test purposes.

thrust jacks—hydraulic jacks serving to transmit the thrust forces of the tunnel boring machine to the segment ring, facilitate installation, or both.

tunnel cover—perpendicular distance to nearest ground surface from the tunnel exterior.

two-pass lining—tunnel lining consisting of two shells with different structural and constructional requirements that are produced in independent operations and with different construction methods.

CHAPTER 3—DESIGN PHILOSOPHY AND SEGMENTAL RING GEOMETRY

3.1—Load and resistance factor design

The design engineer should use load and resistance factor design (LRFD) method to design concrete precast tunnel segments. LRFD is a design philosophy that takes into account the variability in the prediction of loads and the variability in the properties of structural elements. LRFD employs specified limit states to achieve its objectives of constructability, safety, and serviceability. In BS EN 1992-1-1:2004, this is defined as limit state design.

Even though force effects may often be determined using elastic analyses, the resistance of elements using LRFD design methods is determined on the basis of inelastic behavior. Concrete precast tunnel segments should be designed using load factors and strength reduction factors specified in concrete design codes such as ACI 318. For load cases not covered in these codes, load factors, load combinations, and strength reduction factors from other resources such as ACI 544.7R or AASHTO DCRT-1 can be used.

3.2—Governing load cases and load factors

The current practice in the tunnel industry is to design segmental tunnel linings for the following load cases, which occur during segment manufacturing, transportation, installation, and service conditions:

a) Production and transient stages
- i. Segment stripping (demolding)
- ii. Segment storage
- iii. Segment transportation
- iv. Segment handling

b) Construction stages
- i. Tunnel boring machine (TBM) thrust jack forces
- ii. Tail skin back grouting pressure
- iii. Localized back grouting (secondary grouting) pressure

c) Service stages
- i. Ground pressure, groundwater pressure, and surcharge loads
- ii. Longitudinal joint bursting load
- iii. Loads induced due to additional distortion
- iv. Other loads (for example, earthquake, fire and explosion, TBM load of upper tunnel to lower tunnel in case of stacked arrangement of tunnels, aerodynamic loads, mechanical and electrical loads, railway loads, temperature load, and loads during segmental ring erection)

In the strength design procedure, the required strength (U), also known as required design strength, is expressed in terms of factored loads such as the ones shown in Table 3.2 for presented governing load cases. Note that this table provides comprehensive factored load combinations for a specific case of tunnel segments. If different load factors are provided by the local codes, they should be used in place of the factors in this table. In this document, aforementioned load cases are divided into three categories: production and transient loads, construction loads, and service loads. The resulting axial forces, bending moments, and shear forces are used to design concrete and reinforcement.

3.3—Design approach

A common design approach for concrete tunnel segments starts with selecting an appropriate geometry, including thickness, width, and length of segments with respect to the size and loadings of the tunnel. Considering specified compressive strength (f_c') and type and amount of reinforcement, the design strength of segments is compared with required strength against all critical load cases. Methods of calculation for required strength against these load cases will be explained in the following chapters. The geometry, compressive strength, and reinforcement of segments should be specified to provide sufficient design strength against all load cases as well as satisfying all service conditions. The design procedure starts with initial considerations for a segmental ring system and geometry that is discussed in the following section and further checked against the demand of different loadings.

Table 3.2—Required strength (*U*) for governing load cases (ACI 544.7R)

Load case	Required strength (U)
Load Case 1: stripping (demolding)	$U = 1.4w$
Load Case 2: storage	$U = 1.4(w \pm F)$
Load Case 3: transportation	$U = 1.4(w \pm F)$
Load Case 4: handling	$U = 1.4w$
Load Case 5: thrust jack forces	$U = 1.0J$ (1.2 if maximum machine thrust is unknown)
Load Case 6: tail skin grouting	$U = 1.25(w \pm P_{gr})$
Load Case 7: secondary grouting	$U = 1.25(w \pm P_{gr})$
Load Case 8: earth pressure and groundwater load	$U = 1.25(w \pm WA_p) \pm 1.35(EH + EV) \pm 1.5P_0$
Load Case 9: longitudinal joint bursting	$U = 1.25(w \pm WA_p) \pm 1.35(EH + EV) \pm 1.5P_0$
Load Case 10: additional distortion	$U = 1.4M_{distortion}$

3.4—Segmental ring geometry and systems

Segmental tunnel linings installed in the rear of the TBM shield are generally in the shape of circular rings. The size of the ring is defined by the internal diameter, thickness, and length of the ring. Other important design considerations include ring systems, ring configurations in terms of number of segments that form a complete ring, geometries of individual segments, and geometry and tapering of key segments (Bakhshi and Nasri 2018b).

3.4.1 *Internal diameter of the bored tunnel*—The dimensions of the tunnel inner section should be determined considering the internal space required during the service, which depends on the intended use of the tunnel. For the railroad and subway tunnels, the inner dimensions of tunnels in a single-track case are generally governed by the train clearance envelope (clearance gauge), track structure, drainage trough, structure of the overhead catenary contact line stays, and emergency evacuation corridor (egress space). In a double track and twin tunnel cases, tunnel inner dimensions are additionally governed by distance between the centers of tracks and the cross passageway. The internal diameter of the tunnel is first set by obtaining a circle that satisfies these conditions. Then, the electrical equipment, water pipes, and other equipment are installed in the unoccupied space inside this circle. Sufficient ventilation space is generally provided if egress space and cross passageways are allocated (RTRI 2008), but this needs to be verified. For the road tunnels, the geometrical configuration of the tunnel cross section should satisfy the required horizontal and vertical traffic clearances; shoulders or sidewalks/curbs; barriers; fans and suitable spaces for ventilation, lights, traffic control system, and fire life safety systems including water supply pipes for firefighting, cabinets for hose reels, fire extinguishers, and emergency telephones. As shown in Fig. 3.4.1, the smallest tunnel encircling these clearances and elements are considered as the minimum internal tunnel diameter. The available spaces in a circular cross section can be used to house other required elements for road tunnels including tunnel drainage, tunnel utilities and power, signals and signs above roadway lanes, CCTV surveillance cameras, communication antenna and equipment, and monitoring equipment of noxious emissions and visibility (AASHTO DCRT-1). If the

(a)

(b)

Fig. 3.4.1—Schematics of interior space of TBM-bored road tunnels: (a) typical section; and (b) section at low-point pump station.