CHAPTER 11

TUNNEL LINER PLATE

INTRODUCTION

The open-trench method of placing underground conduits is commonly used on new construction of culverts, sewers and underpasses. Interference with traffic, as well as inconvenience to and disruption of business or industry, is an undesirable and costly consequence of open-trench construction. Tunneling is a practical alternative.

Over 50 years of field experience with strong, lightweight steel liner plates has popularized the tunneling method of construction. These plates, along with modern excavating and material handling equipment, and increasing knowledge of effective soil stabilization techniques, have led to many thousands of feet of small tunneling projects completed each year.

Compared to open trench installations, tunneling with steel liner plates results in less excavation and less backfilling. Expensive pavements and utilities need not be removed and replaced. The cost associated with future maintenance, resulting from street or track settlement, can be avoided.

Liner plate tunnel entrance.

GENERAL APPLICATIONS

Uses of steel liner plates include conduits under railways, highways and streets. These conduits are used as culverts, storm drains, sanitary sewers, and as underpasses for pedestrians, livestock, aggregate conveyors, utility lines, and vehicles. Other applications are: lining failing masonry and concrete structures such as culverts and sewers; highway and railway tunnels; mine and sewer entry shafts; utility tunnels; and foundation caissons for bridges and buildings.

Liner plates may act as a temporary or secondary liner to be lined by other materials. They also serve alone as the permanent or primary liner; as the conduit itself. Installation and assembly can be done entirely from inside a liner plate structure.

Non-tunneling uses of steel liner plates include storage bins, surge tanks and small retaining walls.

Twin lining.

DESIGN

The following is based on Section l6 Steel Tunnel Liner Plates taken from the AASHTO Standard Specifications for Highway Bridges. A significant number of editorial revisions have been made to reflect Canadian standard practice. The article numbers have therefore been revised to avoid confusing the text presented here with the AASHTO Standard.

1 GENERAL AND NOTATIONS

1.1 General

1.1.1 These criteria cover the design of cold-formed panel steel tunnel liner plates. The minimum thickness shall be as determined by design in accordance with Articles 2, 3, 4, 5, and 6 and the construction shall conform to the AASHTO Standard Specifications for Highway Bridges, Section 26-Division II. The supporting capacity of a nonrigid tunnel lining such as a steel liner plate results from its ability to deflect under load, so that side restraint developed by the lateral resistance of the soil constrains further deflection. Deflection thus tends to equalize radial pressures and to load the tunnel liner as a compression ring.

1.1.2 The load to be carried by the tunnel liner is a function of the type of soil. In a granular soil, with little or no cohesion, the load is a function of the angle of internal friction of the soil and the diameter of the tunnel being constructed. In cohesive soils such as clays and silty clays the load to be carried by the tunnel liner is dependent on the shearing strength of the soil above the roof of the tunnel.

1.1.3 A subsurface exploration program and appropriate soil tests should be performed at each installation before undertaking a design.

1.1.4 Nothing included in this section shall be interpreted as prohibiting the use of new developments where usefulness can be substantiated.

1.2 Notations

A = cross-sectional area of liner plates (Article 3.4)
C_d = coefficient for tunnel liner, used in Marston's formula (Article 2.4)
D = horizontal diameter or span of the tunnel (Article 2.4)
D_c = critical diameter (Article 3.4)
E = modulus of elasticity (Article 3.3)
FS = factor of safety for buckling (Article 3.4)
f_c = buckling stress (Article 3.4)
f_u = minimum specified tensile strength (Article 3.4)
H = height of soil over the top of the tunnel (Article 2.4)
I = moment of inertia (Article 3.3)
k = parameter dependent on the value of the friction angle (Article 3.4)
P = external load on tunnel liner (Article 2.1)
P_d = vertical load at the level of the top of the tunnel liner due to dead load (Article 2.1)
P_1 = vertical load at the level of the top of the tunnel liner due to live load (Article 2.1)
r = radius of gyration (Article 3.4)
T = thrust per unit length (Article 3.2)
T_{max} = maximum allowable thrust (Article 3.4)
W = total (moist) unit weight of soil (Article 2.4)
ø = friction angle of soil (Article 3.4.1)

2 LOADS

2.1 External load on a circular tunnel liner made up of tunnel liner plates may be predicted by various methods including actual tests. In cases where more precise methods of analysis are not employed, the external load P can be predicted by the following:

(a) If the grouting pressure is greater than the computed external load, the external load P on the tunnel liner shall be the grouting pressure.

(b) In general the external load can be computed by the formula

$$P = P_1 + P_d$$

where: P = the external load on the tunnel liner, kPa
P_1 = the vertical load at the level of the top of the tunnel liner due to live loads, kPa
P_d = the vertical load at the level of the top of the tunnel liner due to dead load, kPa.

2.2 For an H-20 load, values of P_1 are approximately the following:

H (m)	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
P_1 (kPa)	25.0	17.3	12.8	9.9	7.7	6.0	5.0	4.2	3.6

For an E-80* load, values of P_1 are approximately the following:

H (m)	1.00	1.20	1.50	2.00	3.00	4.00	6.00	8.00	10.00
P_1 (kPa)	147.0	133.0	115.0	91.0	53.0	34.0	15.0	7.0	3.0

* AREMA Manual for Railway Engineering, Chapter 1.

2.3 Values of P_d may be calculated using Marston's formula for load or any other suitable method.

2.4 In the absence of adequate borings and soil tests, the full overburden height should be the basis for P_d in the tunnel liner plate design.

The following is one form of Marston's formula:

$$P_d = C_d W D$$

where: C_d = coefficient for tunnel liner, Figure 11.1
W = total (moist) unit weight of soil, kN/m^3
D = horizontal diameter or span of the tunnel, m
H = height of soil over the top of the tunnel, m

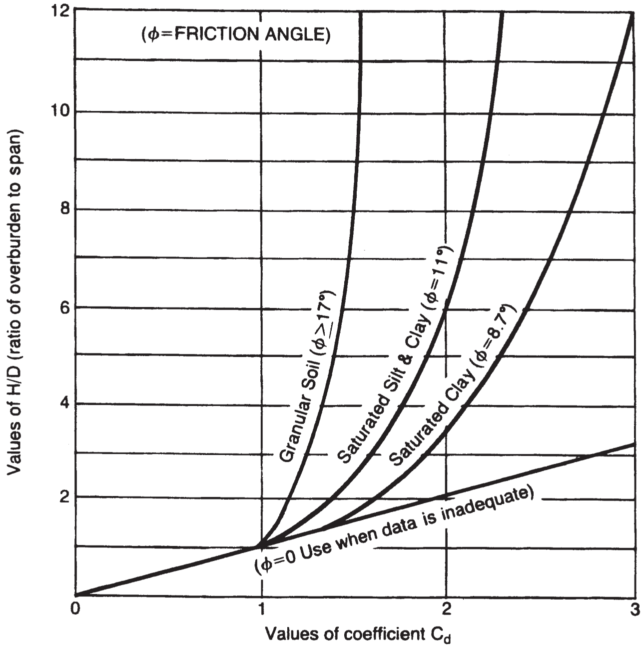


Figure 11.1 Diagram for coefficient C_d for tunnels in soil.

3 DESIGN

3.1 Criteria

The following criteria must be considered in the design of liner plates:

(a) Joint strength.
(b) Minimum stiffness for installation.
(c) Critical buckling of liner plate wall.
(d) Deflection or flattening of tunnel section.

3.2 Joint Strength

3.2.1 The seam strength of liner plates must be sufficient to withstand the thrust developed from the total load supported by the liner plate. This thrust, T, in kN/m is:

$$T = PD/2$$

where: P = load as defined in Article 2, kPa;
D = diameter or span, m.

3.2.2 The ultimate design longitudinal seam strengths are shown in Table 11.1.

3.2.3 The thrust, T, multiplied by the safety factor, should not exceed the ultimate seam strength.

3.3 Minimum Stiffness for Installation

3.3.1 The liner plate ring shall have enough rigidity to resist the unbalanced loads of normal construction: grouting pressure, local slough-ins, and miscellaneous concentrated loads.

The minimum stiffness required for these loads can be expressed for convenience by the formula below. It must be recognized, however, that the limiting values given here are only recommended minima. Actual job conditions may require higher values (greater effective stiffness). Final determination of this factor should be based on intimate knowledge of the project and practical experience.

3.3.2 The stiffness for installation is determined by the formula:

$$\text{Stiffness} = EI/D^2$$

where: D = diameter, mm
E = modulus of elasticity, MPa (200,000)
I = moment of inertia, mm^4/mm

The required minimum stiffness based on 2-flange liner plates is

$$(EI/D^2) \geq 8.76$$

3.4 Critical Buckling of Liner Plate Wall

3.4.1 Wall buckling stresses are determined from the following formulae:

For diameters less than D_c, the ring compression stress at which buckling becomes critical is:

$$f_c = f_u - \left[\frac{f_u^2}{48E} \times \left(\frac{kD}{r}\right)^2\right] \text{, MPa}$$

For diameters greater than D_c:

$$f_c = \frac{12E}{\left(\frac{kD}{r}\right)^2} \text{, MPa}$$

where: $D_c = \frac{r}{k}\sqrt{\frac{24E}{f_u}}$ = critical diameter, mm
f_u = minimum specified tensile strength, MPa
f_c = buckling stress in MPa, not to exceed minimum specified yield strength
D = pipe diameter, mm
r = radius of gyration of section in mm
E = modulus of elasticity, MPa

The parameter k will vary from 0.22 for soils with ø >15˚ to 0.44 for soils with ø <15˚.

3.4.2 Design for buckling is accomplished by limiting the ring compression thrust T to the buckling stress multiplied by the effective cross-sectional area of the liner plate divided by the factor of safety.

$$T_{max} = \frac{f_c A}{FS}$$

where: T_{max} = maximum allowable thrust, kN/m
A = effective cross-sectional area of the liner plate, mm^2/mm
FS = factor of safety for buckling

3.5 Deflection or Flattening

3.5.1 Deflection of a tunnel depends significantly on the amount of over-excavation of the bore and is affected by delay in backpacking or inadequate backpacking. The magnitude of deflection is not primarily a function of soil modulus or the liner plate properties, so it cannot be computed with usual deflection formulae.

3.5.2 Where the tunnel clearances are important, the designer should oversize the structure to provide for a normal deflection. Good construction methods should result in deflections of not more than 3 percent of the normal diameter.

4 CHEMICAL AND MECHANICAL REQUIREMENTS

4.1 Chemical Composition
Base metal shall conform to ASTM A 569.

4.2 Minimum Mechanical Properties of Flat Plate before Cold Forming

Tensile strength	=	290 MPa
Yield strength	=	195 MPa
Elongation, 50 mm	=	30 percent

4.3 Dimensions and Tolerances
Nominal plate dimensions shall provide the section properties shown in Article 5. Thickness tolerances shall conform to Paragraph 14 of AASHTO M 167.

5 SECTION PROPERTIES
The section properties, based on the average of one ring of liner plates, shall conform to those shown in Table 11.2.

6 COATINGS
Steel tunnel liner plates shall be of heavier gage or thickness or protected by coatings or other means when required for resistance to abrasion or corrosion.

7 BOLTS

7.1 Bolts and nuts used with lapped seams shall be not less than 16 mm in diameter. The bolts shall conform to the specifications of ASTM A 449 for plate thickness equal to or greater than 5.0 mm and A 307 for plate thickness less than 5.0 mm. The nut shall conform to ASTM A 563, Grade A.

8 SAFETY FACTORS

Longitudinal seam strength	= 3
Pipe wall buckling	= 2

DESIGN CONSIDERATIONS

The AASHTO specification provides a design to carry the final loads on the steel liner. While the design follows conventional ring compression theory, actual soil loads depend on the bridging characteristics of the soil as well as the diameter and depth of the tunnel. Soil loads for tunneling conditions are typically much lower than for cut and cover conditions, and can be determined using Marston loading theory based on the friction angle ø, or shear strength, of the soil (Article 2.4). Sufficient subsurface investigation is necessary to determine actual soil conditions and to ensure adequate depth for soil bridging in shallow tunnels.

Liner plates are typically backgrouted, or backpacked with granular materials, to fill the overbore. These materials provide buckling support for the steel liner plate and help to ensure a more even distribution of the loads.

While attention is directed to the final loads for design, construction loads are often the controlling factor. Unbalanced loads due to possible soil sloughing or rock falls, especially in soft ground or hand mined conditions and before the liner is complete or backgrouted, can control the liner plate thickness.

During this period the liner plate ring stiffness and bending strength are a prime consideration. The minimum AASHTO stiffness value provides for adequate assembly (Article 3.3.2). No specific minimum factor of safety has been established for stiffness (Article 8), but rather the allowable or minimum stiffness is based on experience. Final determination of the minimum required stiffness (Article 3.3.1) should be based on in depth knowledge of the project, ground conditions, experience and tunneling techniques.

The material mechanical requirements listed in the specification (Article 4.2) are for virgin material prior to cold forming. The typical values used for design, which reflect the cold work of forming, are:

f_y = minimum specified yield strength = 230 MPa

f_u = minimum specified tensile strength = 310 MPa

Four radius liner plate shape for lining an old concrete shape.

PRODUCT DETAILS

Two-flange liner plates are supplied with deep corrugations running through lapped end joints (Figure 11.2). The ultimate longitudinal seam strengths are shown in Table 11.1. Dimensions, physical properties and thicknesses are given in Table 11.2. These section properties are reproduced from the manufacturer's data.

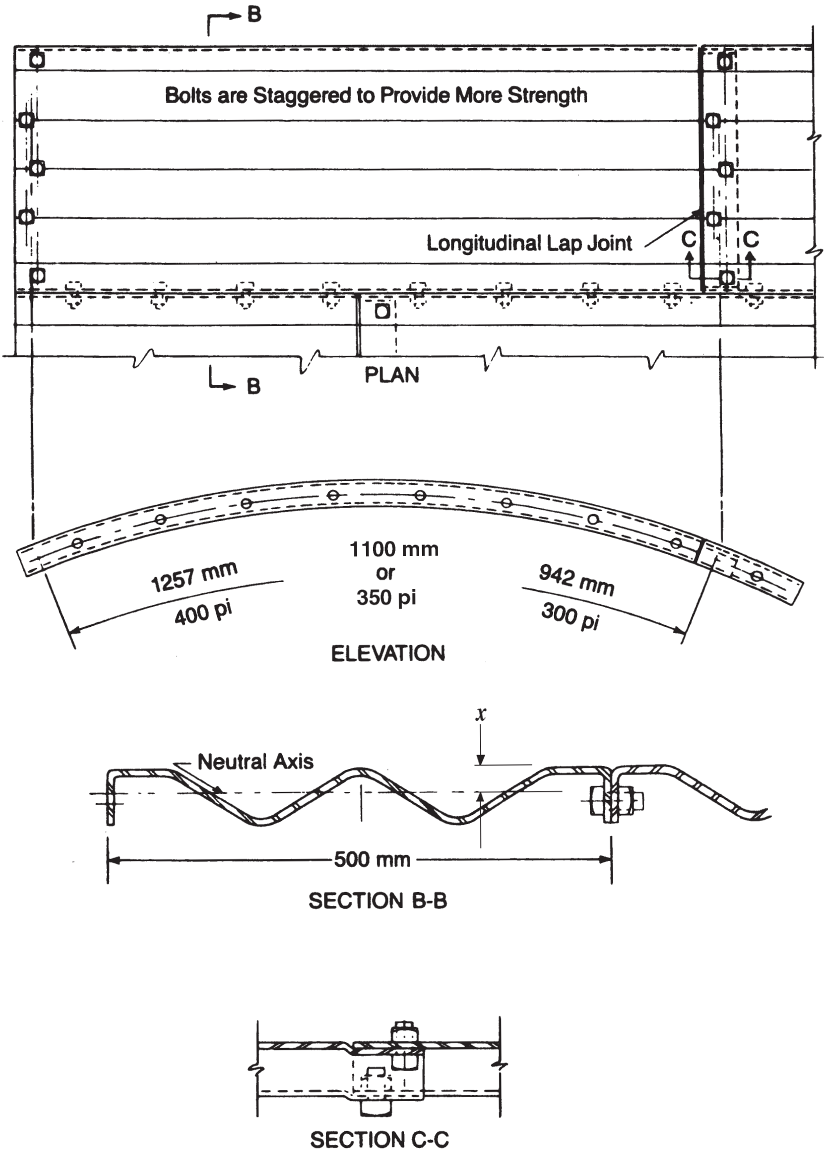


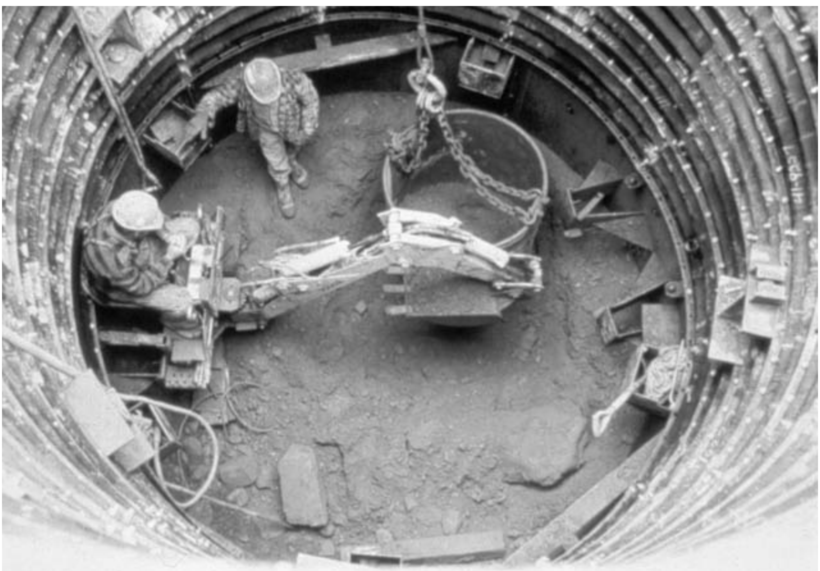
Figure 11.2 Details of 2-flange liner plate.

Table 11.1 Ultimate longitudinal seam strength of liner plates

Plate Thickness	Ultimate Strength
mm	kN/m
3.0	497
4.0	802
5.0	1117
6.0	1246

Table 11.2 Sectional properties and weights of 2-Flange lap-joint steel liner plates

Uncoated Thickness T mm	Area of Section A mm^2/mm	Moment of inertia I mm^4/mm	Section Modulus S mm^3/mm		Radius of Gyration r mm	Neutral Axis to Outer Face x mm	Approximate Plate Weights Including Bolts, kg		
			Outer	Inner			300 Pi mm Plate	350 Pi mm Plate	400 Pi mm Plate
3.0	3.522	1198.77	52.32	37.42	17.84	22.910	15.73	18.13	20.53
4.0	4.776	1634.48	69.39	50.38	17.89	23.556	20.98	24.18	27.37
5.0	5.970	2054.55	85.00	62.58	17.94	24.172	26.22	30.22	34.21
6.0	7.164	2480.01	100.04	74.67	18.00	24.789	31.46	36.26	41.05



Liner plate shaft construction.

INSTALLATION NOTES

Steel liner plates are installed to support the soil exposed by tunneling operations. The outside shape of the liner plates should fit closely to the excavated opening.

Where too much soil is removed, the annular space between the plates and the soil should be backfilled promptly or temporary supports should be used and the space should be grouted. When soil conditions are such that the soil may slough or rock falls are possible prior to grouting, a liner plate thickness must be selected to support these loads with an adequate factor of safety on bending stiffness. Backfill may consist of pneumatically placed pea gravel, lean grout, sand, or other suitable material.

Some of the liner plates should be provided with grout holes. A sufficient number should be installed so that grouting can be done effectively at various locations around the liner periphery. Grout or backfill should be kept as close to the tunnel face as possible. When grout is used for backfill, it should be injected in lower holes first, followed by higher holes as the space is filled. Plugs, preferably threaded, should be installed in holes after their use.

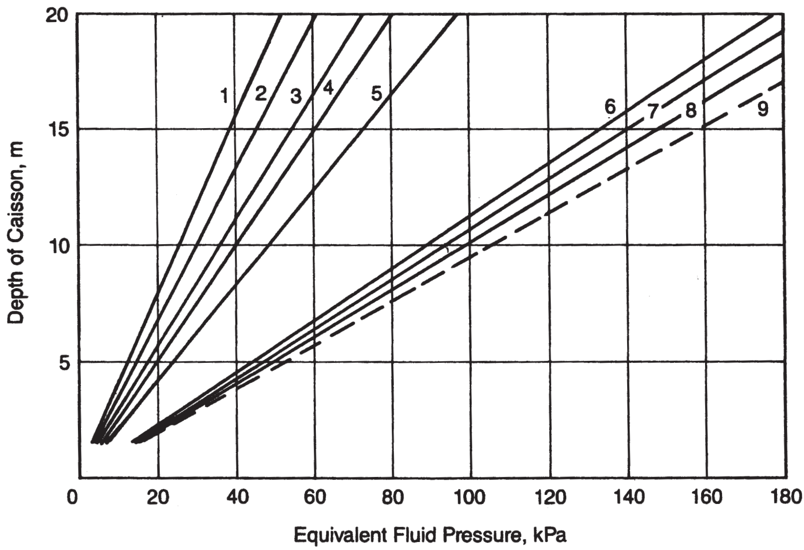
With extremely heavy loads, or a tunnel or shaft too large for practical use of liner plates alone, reinforcing I-Beam rings may be used. In unstable soils, where the soil will not remain in place long enough to excavate for a liner plate, the soil can be controlled with steel poling plates, wood spiling boards, or a shield and breast boards at the tunnel face. Chemical stabilization of the soil is also practical in some cases. Tunneling machines are useful for long tunnels in uniform soils.

Liner plate shaft construction.

CAISSON DESIGN

The load to be carried by a caisson may be computed by known methods. The horizontal pressure at a specified depth is determined and multiplied by one-half the caisson diameter.

Estimated unit pressures for some soils are shown in Figure 11.3. These equivalent fluid pressures assume that pressure increases uniformly with depth and have been calculated using typical properties for the type of soil described. Actual pressures on the backfilled caisson will vary from those in Figure 11.3 depending on the actual soil properties. Unbalanced loads, due to soil sloughing prior to backfill, may result in the critical design loading. In that case, an adequate factor of safety on bending stiffness must be used.



1) Clay: Lumpy and dry
   Earth: Loose and either dry or slightly moist
2) Earth: Fairly moist and packed
3) Earth: Perfectly dry and packed
4) Clay, sand and gravel mixture
5) Drained river sand
6) Earth: Soft flowing mud
7) Clay: Damp and plastic
8) Earth: Soft, packed mud
9) Hydrostatic pressure of water

Figure 11.3 Equivalent fluid pressure for caisson construction.

Example

Soil: Damp plastic clay
Depth of caisson: 10 m
Diameter of caisson: 6 m

From the graph (Figure 11.3, curve 7) the equivalent fluid pressure is 94 kPa. The resulting thrust is given by:

$$T = \frac{PD}{2} = \frac{94\,(6)}{2} = 282 \text{ kN/m}$$

The ultimate longitudinal seam strength for 5.0 mm thick plates is 1117 kN/m. The resulting factor of safety is:

$$FS = \frac{1117}{282} = 3.96$$

Since this is greater than the required 3.0, the 5.0 mm thick plate meets the seam strength requirement.

For the caisson, the critical diameter is:

$$D_c = \frac{r}{k}\sqrt{\frac{24\,E}{f_u}} = \frac{17.94}{0.44}\sqrt{\frac{24(200\,000)}{310}} = 5074 \text{ mm}$$

Since the diameter of the caisson is larger than the critical diameter, the buckling stress is:

$$f_c = \frac{12\,E}{\left(\frac{kD}{r}\right)^2} = \frac{12\,(200\,000)}{\left[\frac{0.44\,(6\,000)}{17.94}\right]^2} = 110.8 \text{ MPa}$$

The maximum allowable thrust is:

$$T_{max} = \frac{f_c A}{FS} = \frac{110.8\,(5.970)}{2} = 330.7 \text{ kN/m}$$

Since this is greater than the calculated thrust, the caisson will resist buckling.

The stiffness of the caisson is given by:

$$\frac{EI}{D^2} = \frac{200\,000(2054.55)}{(6000)^2} = 11.41$$

Since this is greater than the minimum requirement described in 3.3.2, the installation stiffness requirement is satisfied.

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