SECTION 16 - STEEL TUNNEL LINER PLATES

16.1 GENERAL AND NOTATIONS

16.1.1 General

16.1.1.1 These criteria cover the design of coldformed panel steel tunnel liner plates. The minimum thickness shall be as determined by design in accordance with Articles 16.2, 3, 4, 5, and 6. 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.

16.1.1.2 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.

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

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

16.1.2 Notations

A = cross-sectional area of liner plates (Article 16.3.4)
C_d = coefficient for tunnel liner, used in Marston's formula (Article 16.2.4)
D = horizontal diameter or span of the tunnel (Article 16.2.4)
D = pipe diameter (Article 16.3.3)
D_c = critical pipe diameter (Article 16.3.4)
E = modulus of elasticity (Article 16.3.3)
FS = factor of safety for buckling (Article 16.3.4)
f_c = buckling stress (Article 16.3.4)
f_u = minimum specified tensile strength (Article 16.3.4)
H = height of soil over the top of the tunnel (Article 16.2.4)
I = moment of inertia (Article 16.3.3)
k = parameter dependent on the value of the friction angle (Article 16.3.4)
P = external load on tunnel liner (Article 16.2.1)
P_d = vertical load at the level of the top of the tunnel liner due to dead load (Article 16.2.1)
P_l = vertical load at the level of the top of the tunnel liner due to live load (Article 16.2.1)
r = radius of gyration (Article 16.3.4)
T = thrust per unit length (Article 16.3.4)
W = total (moist) unit weight of soil (Article 16.2.4)
$ø$ = friction angle of soil (Article 16.3.4.1)

16.2 LOADS

16.2.1 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:

$$P = P_l + P_d \qquad (16\text{-}1)$$

where:

P = the external load on the tunnel liner;
P_l = the vertical load at the level of the top of the tunnel liner due to live loads;
P_d = the vertical load at the level of the top of the tunnel liner due to dead load.

16.2.2 For an H 20 load, values of P_l are approximately the following:

H(ft.)	4	5	6	7	8	9	10
P_l (lb. per sq.ft.)	375	260	190	140	110	90	75

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

16.2.4 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:

$$P_d = C_d WD \qquad (16\text{-}2)$$

where:

C_d = coefficient for tunnel liner, Figure 16.2.3A;
W = total (moist) unit weight of soil;
D = horizontal diameter or span of the tunnel;
H = height of soil over the top of the tunnel.

16.3 DESIGN

16.3.1 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.

16.3.2 Joint Strength

16.3.2.1 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 pounds per linear foot is:

$$T = PD/2 \qquad (16\text{-}3)$$

where P = load as defined in Article 16.2, and D = diameter or span in feet.

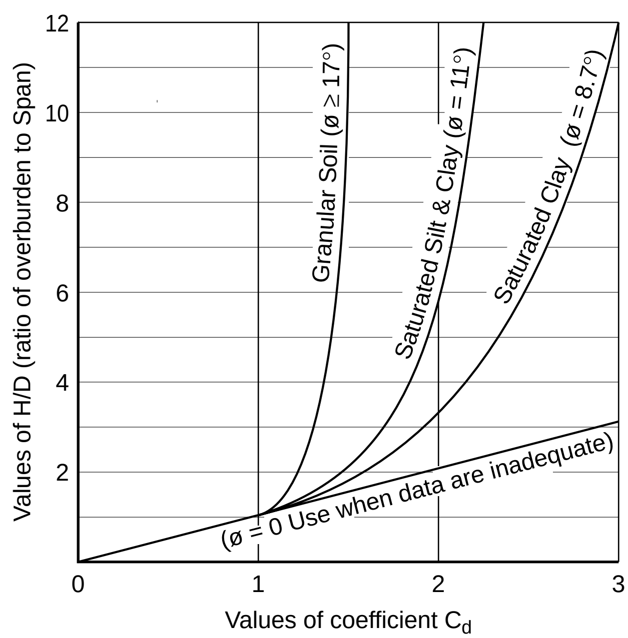

FIGURE 16.2.3A. Diagram for Coefficient C_d for Tunnels in Soil (ϕ = Friction Angle)

16.3.2.2 The ultimate design longitudinal seam strengths are:

TABLE 16.3.2.2

Ultimate Seam Strength of Liner Plates		
Plate Thickness (in.)	Ultimate Strength (kips/ft.)	
	2-Flange	4-Flange
0.075	20.0	—
0.105	30.0	26.0
0.135	47.0	43.0
0.164	55.0	50.0
0.179	62.0	54.0
0.209	87.0	67.0
0.239	92.0	81.0
0.313	—	115.0
0.375	—	119.0

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

16.3.3 Minimum Stiffness for Installation

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

16.3.3.1 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 on this factor should be based on intimate knowledge of the project and practical experience.

16.3.3.2 The minimum stiffness for installation is determined by the formula:

$$\text{Minimum stiffness} = EI/D^2 \qquad (16\text{-}4)$$

where:

D = diameter in inches;
E = modulus of elasticity, psi (29×10^6);
I = moment of inertia, inches to the fourth power per inch.

For 2-Flange (EI/D^2) = 50 minimum
For 4-Flange (EI/D^2) = 111 minimum

16.3.4 Critical Buckling of Liner Plate Wall

16.3.4.1 Wall bucking stresses are determined from the following formulae:

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

(16-5)

For diameters greater than D_c:

$$f_c = \frac{12E}{(kD/r)^2} \text{ in psi} \qquad (16\text{-}6)$$

where:

D_c = $(r/k)\sqrt{24E/f_u}$ = critical pipe diameter in inches; (16-7)
f_u = minimum specified tensile strength in pounds per square inch;
f_c = buckling stress in pounds per square inch, not to exceed minimum specified yield strength;
D = pipe diameter in inches;
r = radius of gyration of section in inches per foot;
E = modulus of elasticity in pounds per square inch.

k will vary from 0.22 for soils with ϕ>15 to 0.44 for soils ϕ<15.

16.3.4.2 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.

$$T = \frac{f_c A}{FS} \qquad (16\text{-}8)$$

where:

T = thrust per linear foot from Article 16.3.2;
A = effective cross-sectional area of liner plate in square inches per foot;
FS = factor of safety for buckling.

16.3.5 Deflection or Flattening

16.3.5.1 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.

16.3.5.2 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.

16.4 CHEMICAL AND MECHANICAL REQUIREMENTS

16.4.1 Chemical Composition

Base metal shall conform to ASTM A 569.

16.4.2 Minimum Mechanical Properties of Flat Plate before Cold Forming

Tensile strength	=	42,000 psi
Yield strength	=	28,000 psi
Elongation, 2 inches	=	30 percent

16.4.3 Dimensions and Tolerances

Nominal plate dimensions shall provide the section properties shown in Article 16.5. Thickness tolerances shall conform to Paragraph 14 of AASHTO M 167.

16.5 SECTION PROPERTIES

The section properties per inch of plate width, based on the average of one ring of linear plates, shall conform to the following:

TABLE 16.5A Section Properties for Four Flange Liner Plate

Gage	Thickness (in.)	Area ($in.^2/in.$)	Effective Area ($in.^2/in.$)	Moment of Inertia ($in.^4/in.$)
12	0.105	0.133	0.067	0.042
11	0.1196	0.152	0.076	0.049
10	0.135	0.170	0.085	0.055
8	0.164	0.209	0.105	0.070
7	0.179	0.227	0.114	0.075
5	0.209	0.264	0.132	0.087
3	0.239	0.300	0.150	0.120
1/4	0.250	0.309	0.155	0.101
5/16	0.3125	0.386	0.193	0.123
3/8	0.375	0.460	0.230	0.143

TABLE 16.5B Section Properties for Two Flange Liner Plates

Thickness (in.)	Effective Area ($in.^2/in.$)	Moment of Inertia ($in.^4/in.$)
0.075	0.096	0.034
0.105	0.135	0.049
0.135	0.174	0.064
0.164	0.213	0.079
0.179	0.233	0.087
0.209	0.272	0.103
0.239	0.312	0.118

16.6 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.

16.7 BOLTS

16.7.1 Bolts and nuts used with lapped seams shall be not less than $^5/_8$ inch in diameter. The bolts shall conform to the specifications of ASTM A 449 for plate thickness equal to or greater than 0.209 inches and A 307 for plate thickness less than 0.209 inches. The nut shall conform to ASTM A 307, Grade A.

16.7.2 Circumferential seam bolts shall be A 307 or better for all plate thicknesses.

16.7.3 Bolts and nuts used with four flanged plates shall be not less than $^1/_2$ inch in diameter for plate thicknesses to and including 0.179 inches and not less than $^5/_8$ inch in diameter for plates of greater thickness. The bolts and nuts shall be quick acting coarse thread and shall conform to ASTM A 307, Grade A.

16.8 SAFETY FACTORS

Longitudinal test seam strength	=	3
Pipe Wall Buckling	=	2