LOAD RATING AND STRUCTURAL EVALUATION OF IN-SERVICE, CORRUGATED STEEL STRUCTURES

Load rating, and other structural evaluations of in-service corrugated steel structures, is a two-step process. As with any major structure, both a complete field evaluation of the structure's condition, as well as an analytical evaluation of that structure's load carrying capabilities are required. The analytical evaluation is based on the structure's actual in-service shape and condition, as well as actual field and design loading needs.

• The FHWA CULVERT INSPECTION MANUAL (Ref. 1) provides the field inspection requirements, as well as other guidance and safety concerns.

• The AASHTO STANDARD SPECIFICATION FOR HIGHWAY BRIDGES (Ref. 2) provides the basis for analytical evaluations. The following general outline supports the engineer in combining the two resources for a proper, in-service evaluation or load rating.

I. SURVEY OF FIELD CONDITIONS

(Ref. Report FHWA-IP-86-2; July, 1986)

A. In-Service Dimensions:

1. All structures require that actual, in-service dimensions be recorded throughout their entire length. *Care must be taken to measure the true rise of box culvert and arch structures to avoid inaccuracies due to uneven inverts, bowed or bulged invert plates, burial depth to footings, etc.*
A surveyor's level, string lines across the structure or other equal means are typically necessary for accurate measurements.
These measurements include:

a. Span

b. Rise

c. Symmetry (uniform curvature).
A symmetrical structure has its maximum rise point located above center span.

d. Mid-ordinate of each radius arc segment (for multi radius structure shapes)

2. Unsymmetrical Structures, structures deflected more than 5% from design shape, or those that show localized distortions require that the actual maximum radius be determined in those distorted areas as shown in Appendix B.2. *Use two times the actual maximum radius rather than the span in structural design checks. Typically this provides a conservative evaluation of the structure.*

3. Stability Considerations

a. Continued movement (shape change) of the structure is evidence that the structure requires monitoring and further evaluation of the backfill or foundation conditions.

b. Stability must be investigated where:

1) Actual dimensions show a significant change from design or as built dimensions (i.e., typically more than 5%).

2) Pavement has settled or broken up over or immediately adjacent to the structure.

3) There is evidence of backfill material infiltrating into the structure.

c. Monitoring structures for movement requires repeating the measurements (above) on a regular basis, over a reasonable period of time, using permanently marked measurement points and survey methods accurate to 0.01 ft.

4. Structures with riveted, bolted or welded longitudinal seams must be visually evaluated for proper plate nesting at the laps.

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a. Cusped or open seams may suggest a reduced allowable seam strength.

b. Bolt torque is not critical to seam strength as long as bolts are tight and the plates are properly meshed.

c. Missing bolts, rivets or cracked plates need to be replaced or repaired.

B. Material Evaluation

1. Actual fabricated material in place must be recorded at each measurement location. The plans and specifications typically provide this including:

a. Material thickness in 0.000 inches.

b. Corrugation or rib pitch and depth.

c. For box culverts and other structures with ribs, rib size or type and spacing in the haunch and crown area (as applicable). *Ribs may be provided on the outside, inside or both sides of a box culvert. The external rib spacing can typically be determined by noting the location of the attachment bolts from the interior.*

2. Durability Factors

a. Metal loss evaluation is normally focused on the structure's invert. Visual checks are needed to confirm unusual loss elsewhere.

1) Where the galvanizing is intact and pitting has not occurred, steel structures can typically be assumed to maintain full design properties.

2) If galvanizing or other coating is gone, or abrasion loss of the base metal is evident, but the invert is not perforated, core the structure for a metal thickness evaluation.

3) The occurrence of first perforation from soil side corrosion typically indicates a 13% metal loss in steel structures.

4) For conditions beyond first perforation, a metal loss determination is made by coring the structure.

5) Where significant metal loss is limited to the central portion of the invert, metal loss considerations just above the affected area may be significant to the structural evaluation if the invert is repaired.

6) Where substantial invert perforation has occurred a determination of the degree of structural degradation due to the possible erosion of bedding and backfill materials must be made. Significant loss of bedding and backfill will reduce structural strength and stability quickly. Invert paving or other repair may be warranted. *This paragraph applies to perforations at any location.*

7) Steel box culverts are bending moment design structures.

a) Invert plates are not structural, but bedding and backfill loss considerations apply.

b) Metal loss of the haunch and crown plates typically does not result in an equal reduction in bending strength if external ribs are not similarly affected.

b. Structural Damage, such as dents and tears can be mitigated by bolting or welding a new curved structural member over the damaged section to replace the lost wall area. Appropriate measures must be taken to prevent future loss of bedding or backfill.

C. Footing Evaluation of Arches and Box Culverts on footings or footing pads

1. Undermined footings, due to scour or other attack, must be repaired to provide adequate support for the structure.

2. Repaired footings (and other footings that show signs of significant scour) must be protected from further erosion using means such as:

a. Rip Rap

b. Invert pavement

D. Actual and Design Load Evaluation

1. Height of Cover

a. For a complete structural evaluation determine:

1) Maximum height of cover.

2) Minimum height of cover in areas subject to traffic.

3) Repeat the above for each portion of the structure when dictated by:

a) Structure wall thickness or profile changes.

b) Structure condition changes.

4) For load rating, the above height of cover considerations only apply to areas subject to traffic.

2. Record actual and design loads over the structure.

II. STRUCTURAL EVALUATION

(Ref. AASHTO Standard Specification for Highway Bridges, Division I, Section 12)

Structural evaluation should use A or B, depending on in-service conditions

A. Dimensions for Design

1. For typical structures, use the actual field measured span for calculations.

2. For unsymmetrical structures or those deflected over 5%:

a. Use two times the top radius ($2R_t$) in lieu of span for calculations.

b. Base critical buckling stress calculations on the theoretical design span, reducing the resulting allowable buckling stress by the appropriate multiplier to account for deflection, as shown in Figure B.1.1 in Appendix B.1

3. For all long span structures (horizontal ellipse, low and high profile arches, inverted pear shapes and pear arches), as well as other horizontal ellipses, use two times actual top radius ($2R_t$) in all cases.

4. Box culvert moments are based on the actual span and increased for deflection such that:

a. Crown deflection (reduction in rise) less than 1% of *span*—no increase.

b. Crown deflection (reduction in rise) of 1 to 3% of *span*—increase dead and live load moments by C_H (Ref. 4).

Where: $C_H = 1.15 - \frac{(H-1.4)}{14}$

c. Crown deflection (reduction in rise) greater than 3% of ***span***—special analysis is required.

B. Design Properties

1. Reduce section properties on the basis of metal loss from the materials evaluation.

a. Reduce properties of non-box culvert structures on an equivalent (percent) to metal loss basis. *Where significant metal loss is limited to the bottom quadrant (invert), thrust in this area may be more accurately calculated using ring formulae* (Ref. 5).

b. Box Culverts

1) Invert plates are not structural and do not bear on calculations. However, they must be able to protect against scour.

2) When metal loss is limited to the plate portion of the shell only, reduce moment capacity by interpolating between values from the appropiate tables in Appendix D, using the actual thickness of the plate.

3) When metal loss is uniform over plate and ribs, reduce moment capacity on the basis of the percent of metal loss.

2. Seam Strength depends upon proper nesting and smooth plate alignment as well as sheet or plate gage. *AASHTO requires a seam strength Factor of Safety of 3.0 while other design methods, such as that offered by the American Iron and Steel Institute, require a factor of 2.0. This difference can allow for a reasonable variance of seam characteristics without a practical loss of safety and* *serviceability.*

a. Bolt torque is not critical to strength as long as bolts are tight and the plates are properly nested.

b. Missing bolts should be replaced. They can be accounted for in structural calculations by a ratio of the number of bolts present to the number assumed in tabulated strength values.

c. If there is metal loss in the seam area, reduce seam strength by interpolating between the seam strength for adjacent gage thicknesses vs. actual thickness.

C. Design Calculations

1. Follow AASHTO Bridge Specification Methods as referenced. *Flexibility Factor evaluations, which bear only on installation stiffness, are not applicable since the structure is already in place.*

2. Evaluate each section of the structure along its length.

a. Sections are determined by:

1) Thickness (gage) changes in pipe walls or plates.

2) Changes in shape or material condition.

b. Check each section at points of:

1) Maximum cover

2) Minimum cover in areas subject to traffic. *Minimum cover requirements do not apply in sections without traffic loads.*

3. Where less than minimum cover conditions exist in traffic areas with special backfill materials, load relief slabs, or special design, a special analysis is required.

III. LOAD RATING

(Applicable only to sections carrying traffic. Follow all structure evaluation guidance and base calculations on H20, 32 KIP axle)

A. Basic AASHTO Equations:

Max. Strength = 1.3 [βD + RF (L+I)] - Operating Load

Max. Strength = 1.3 [βD + $\frac{5}{3}$ RF (L+I)] - Inventory Load

1. Where:

a. Maximum Strength is the maximum design strength

b. RF = Rating Factor

c. D = Dead Load

d. L + I = Live Load + Impact

e. 1.3 = Load Factor γ

f. β = Load Factor.
Note: β = 1.0 *for conventional bridges;*
β > 1.0 *for flexible pipes.*

2. For corrugated steel structures

a. Maximum strength is:

1) Max. allowable thrust (T_{cap}) for ring compression structures.

2) Maximum allowable moment (M_{cap}) for box culverts.

b. Dead load is the earth cover load:

1) T_E; earth load thrust for ring compression structures.

2) M_E; earth load bending moment for box culverts.

c. Total earth load, load factor (β x γ) required is:

1) 1.95 for ring compression structures. Therefore, β = 1.5

2) I.50 for box culverts. Therefore, β = 1.15

B. Rating Factors (RF), Ring Compression Structures

1. Operating Load Rating Factor (RF_o) is the lower of the two values based on wall strength or minimum cover requirements.

a. RF_o based on wall strength.

$$RF_{o\text{-}w} = \frac{T_{cap} - 1.95T_E}{1.3T_{(L+I)}}$$

1) T_{cap} equals thrust capacity of the wall. It is the lesser of:

a) Wall Yield Strength = $F_y A$

b) Wall Buckling Strength = $F_{crit} A$

and, for pipes with riveted, welded or bolted seams, a third factor:

c) Seam Strength = 0.67 x (seam strength)

2) T_E equals pipe wall thrust due to earth cover and is the higher value of:

a) $\delta H\ (S/2)$

b) $\delta H\ R_t$

3) $T_{(L + I)}$ equals pipe wall thrust due to live load plus impact (See Appendix C) and is the greater of:

a) $(P_{L + I})S/2$

b) $(P_{L + I})R_t$

b. RF_o based on minimum cover requirements

$$RF_{o\text{-}c} = \frac{H^2}{C(h)^2} \qquad \text{(See Appendix E)}$$

1) H is the lowest actual cover over the structure in a traffic area based on field measurement.

2) h is the AASHTO minimum cover level for the structure (Ref. 2, Sections 12.4.1.5, 12.5.3.3, 12.6.1.5 or 12.7.2.1)

3) C = 2.36 H/S + 0.528 1.0 (See Appendix E)

2. Inventory Load Rating Factor (RF_i) can be determined from the operating load rating Factor (RF_o) or from minimum cover requirements. It is the lowest value of:

a. $RF_i = \frac{3}{5} RF_{o\text{-}w}$

b. $RF_i = \frac{H^2}{h^2}$ (See Appendix E)

1) H is the lowest actual cover over the structure in the traffic area based on field measurement.

2) h is the AASHTO minimum cover level for the structure (Ref. 2, Sections 12.4.1.5, 12.5.3.3, 12.6.1.5, or 12.7.2.1)

C. Rating Factor (RF) for Steel Box Culverts

COMMENTARY: Metal box culverts distribute moment between their haunch and crown on the basis of their relative stiffness (moment capacity). This is accommodated in design by a range of proportioning factors, P, (AASHTO Section 12.8, Table 12.8.4 D) provided in the design specification.

To properly rate a metal box culvert, the value of P selected from the allowable range must assign moment to the haunch and crown such that the same percentage of the available moment capacity of each is utilized. Using that specific value of P, the structure may be rated by load rating either the haunch or the crown.

Where limits on the proportioning factor (P) do not allow for the equal utilization of available haunch and crown moment capacity, load rating must be based on that portion (haunch or crown) that experiences the greatest utilization of its moment capacity. This is done by selecting a proportioning factor (P) at one extreme end of the allowable range such that as much moment as possible is assigned to the under utilized portion (haunch or crown).

1. Operating Load Rating Factor (RF_o)

a. $$RF_o = \frac{M_{cap} - 1.5\, M_E C_H}{1.3\,(M_{L+I})C_H}$$

b. Rating the crown

1) M_{cap} is the moment capacity of the crown (M_p) adjusted for condition factors as shown in the appropiate table in appendix D.

2) M_E is the earth load moment assigned to the crown based on the actual minimum cover in the traffic area as field measured, where:

$M_E = (C_{dl}\ M_{dl}/1.5)P$
(Ref.2, Section 12.8.4.3)

Where: P is the proportioning factor selected as discussed in the commentary.

3) $M_{L+I} = (C_{LL}\ M_{LL}/2)P$
(Ref. 2, Section 12.8.4.3)

Where: P is the proportioning factor selected as discussed in the commentary.

4) C_H is an adjustment factor for the in-service shape:

a) $C_H = 1.0$ if the crown (reduction in rise) is deflected less than 1% of span from design shape.

b) $C_H = 1.15 - \frac{H-1.4}{14} > 1.0$

if crown deflections (reduction in rise) of 1-3 % of span from design shape (Ref. 4).

c) For crown deflections (reduction in rise) exceeding 3% of span, a special analysis is required.

c. Rating the Haunch

1) M_{cap} is the moment capacity of the haunch (M_P) adjusted for condition factors (See Appendix D)

2) M_E is the earth load (dead load) moment assigned to the haunch based on the actual minimum cover in the traffic zone from field measurement:

$M_E = (C_{dl}\ M_{dl} / 1.5)(1-P)$
(Ref. 2, Section 12.8.4.3)

Where: P is the proportioning factor selected as discussed in the commentary.

3) M_{L+I} is the live load plus impact moment assigned to the haunch based on the actual minimum cover in the traffic area (field measurement):

$M_{L+I} = (R_h\ C_{LL}\ M_{LL} / 2)(1-P)$

Where: P is the proportioning factor selected as discussed in the commentary.

4) C_H is an adjustment factor for in-service shape:

a) $C_H = 1.0$ if the crown (reduction in rise) is deflected less than 1% of span from design shape.

b) $C_H = 1.15 - \frac{(H-1.4)}{14}$ Ž 1.0

if crown deflections (reduction in rise) of 1-3% of span from design shape (Ref. 4).

c) For crown deflections (reduction in rise) exceeding 3% of span, a special analysis is required.

2. Inventory Load Rating Factor (RF_i)

$RF_i = \frac{3}{5} RF_o$

D. Loading Rating (Based on H/HS Truck)

1. Operating Loads

a. Axle Load = RF_o (32) (in kips)

b. H/HS Truck = RF_o (GVW)

1) H Truck = RF_o (20) (in tons)

2) HS Truck = RF_o (36) (in tons)

2. Inventory Loads

a. Axle Load = RF_i (32) (in kips)

b. H/HS Truck = RF_i (GVW)

1) H Truck = RF_i (20) (in tons)

2) HS Truck = RF_i (36) (in tons)

IV. APPENDICES

A. NOMENCLATURE

A = Pipe wall cross section area (in^2 /ft.)

C = Minimum cover factor of safety adjustment

C_{dl} = Box culvert dead load adjustment coefficient (AASHTO Section 12.0)

C_H = Box culvert moment adjustment coefficient due to shape

C_{LL} = Box culvert live load adjustment coefficient (AASHTO Section 12.0)

F_y = Material yield strength (psi)

F_{crit} = Critical buckling strength (psi-See AASHTO Section 12)

H = Height of cover (ft.)

h = AASHTO live load minimum cover requirement over structure (ft.)

I = Impact portion of live load (See Appendix C)

M_{cap} = Moment Strenght, M_p (ft - K/ft.)

M_{dl} = AASHTO factored box culvert moment due to dead (earth) load (ft-k/ft.)

M_E = Box culvert moment due to earth load (ft-k/ft.)

M_{L+I} = Box culvert moment due to live load plus impact (ft-k/ft.)

M_{LL} = AASHTO factored box culvert moment due to live load plus impact

P = AASHTO moment proportioning factor for box culverts (AASHTO Section 12.0)

P_D = Pressure at the crown of the pipe due to dead (earth) load (lbs./ft.^{2})

P_{L+I} = Pressure at the crown of the pipe due to live load plus impact (lbs./ft.^{2})

RF = Rating Factor

RF_o = Operating load rating factor

RF_I = Inventor load rating factor

RF_{o-w} = Operating load rating factor based on wall strength

RF_{o-c} = Operating load rating factor based on minimum cover

R_t = Top radius of pipe (ft.)

S = Span of pipe (ft.)

T = Ring compression pipe wall thrust (lbs./ft.)

T_E = Thrust due to dead (earth) loads (lbs./ft.)

T_{cap} = Pipe wall thrust capacity (lbs./ft.)

$T_{(L+I)}$ = Thrust due to live load plus impact (lbs./ft.)

δ = Soil Density (pcf)

B. BUCKLING AND RADIUS

1. Reduction Factor for Buckling Strength (f) Due to Deflection in Round Pipes

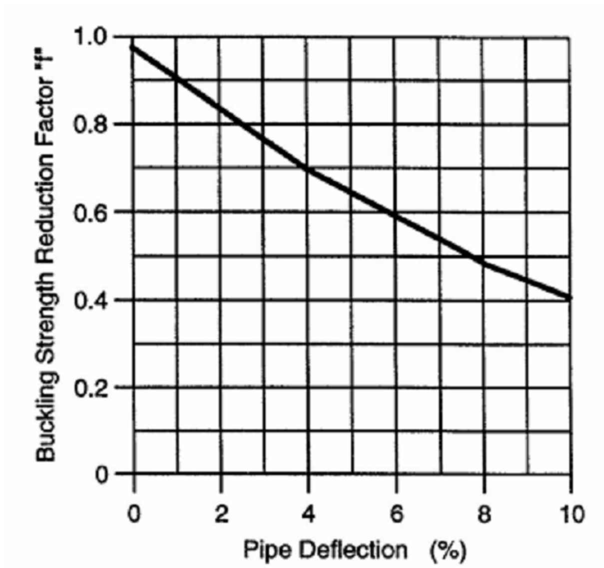
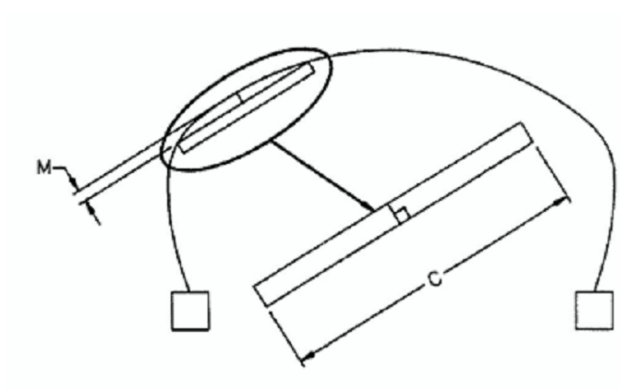


FIG. B.1.1

2. Determining Actual Radius (from field measurement)



Straight edge mid ordinate to check curvature:

$$R = \frac{M}{2} + \frac{C^2}{8M}$$

C = Length of straight edge

M = Mid Ordinate

FIG. B.2.1

APPENDICES (CONTINUED)

C. LIVE LOAD WHEEL PRESSURE FOR DESIGN

1. Although not specified directly, information is given in the AASHTO “Standard Specifications for the Design of Highway Bridges” that can be used to calculate live load pressures.

2. Section 3.30 of the AASHTO specifications assumes a rectangular tire contact pattern with an area of A in square inches equal to 1 percent of the wheel load, P, in pounds. P is 1/2 of the axle load and should include any impact. The contact area is assumed to have a width (w) equal to 2.5 times its length (L) in the direction of traffic. Section 3.8.2.3 provides impact loads (I) for culverts with a cover (H) less than 3 feet according to the following schedule:

H < 1'-0"	I = 30%
1'-1" < H < 2'-0"	I = 20%
2'-1" < H < 2'-11"	I = 10%

3. Section 6.4 of AASHTO provides for the dissipation of live load pressure with depth by assuming that the load is distributed over the base of a truncated prism with side slopes of 1 vertical to 0.875 horizontal.

Table C.3.1 Live Load Pressures for Design (AASHTO)

Height of Cover, ft.	H20 Loading, psf	H25 Loading, psf
1	2270	2580
2	850	1000
3	420	510
4	285	350
5	210	250
6	160	190
7	120	150
8	100	120
9	——	100

Note: Load ratings that exceed H20 by these methods are somewhat conservative in that the footprint dimensions (AASHTO Section 3.30) are not increased for the additional loading.

D. STEEL BOX CULVERT MOMENT STRENGTH

1. 6" x 2" corrugated steel plate shell, 5 x 3 x 1/2 external steel angle rib reinforcements

Moment Strength (M_p; ft-k/ft)

	Steel Shell Thickness (in.)						
Spacing	**0.111**	**0.140**	**0.170**	**0.188**	**0.218**	**0.249**	**0.280**
30"	12.4	13.7	14.9	15.6	16.7	17.7	18.7
24"	14.2	15.7	17.0	17.8	19.0	20.2	21.3
18"	17.2	18.8	20.4	21.4	22.7	24.0	25.3

APPENDICES (CONTINUED)

2. 6" x 2" Corrugated Steel Plate Shell, Corrugated Plate Stiffener Ribs (6" x 3" Corrugation)

Moment Strength (M_p; ft-k/ft)

		Steel Shell Thickness (in.)				
Rib Thicknesses	**Rib Spacing**	**0.111**	**0.140**	**0.170**	**0.188**	**0.218**
0.11"	24" Exterior	6.4	7.3	8.0		
	12" Exterior	9.4	10.7	11.9		
	24" Exterior & Interior	12.0	12.9	13.8		
0.140"	24" Exterior	7.4	8.4	9.2	9.9	
	12" Exterior	11.1	12.5	13.7	14.5	
	24" Exterior & Interior	14.6	15.6	16.6	17.2	
0.170"	24" Exterior	8.3	9.5	10.4	11.0	11.8
	12" Exterior	12.0	14.4	15.2	16.2	17.5
	24" Exterior & Interior	17.5	18.3	19.0	19.5	20.3
0.188"	24" Exterior		10.1	11.1	11.7	12.6
	12" Exterior		14.7	16.2	17.2	18.6
	24" Exterior & Interior		20.0	20.8	21.3	22.0
0.218"	24" Exterior			12.1	12.8	14.2
	12" Exterior			17.7	18.8	20.2
	24" Exterior & Interior			23.6	24.0	24.8
0.249	24" Exterior				13.9	15.1
	12" Exterior				20.0	21.9
	24" Exterior & Interior				26.8	27.6

3. 15" x 5-1/2" Corrugated Steel Pipe Shell (No Rib Reinforcements) *Material with corrugation crests or valleys that have been crimped or otherwise embossed to facilitate curving, do not apply.*

Moment Strength (M_p; ft-k/ft)

	Steel Shell Thickness (in.)							
	0.140	**0.170**	**0.188**	**0.218**	**0.249**	**0.280**	**0.318**	**0.377**
M_p (Ft-k/ft)	10.8	13.2	14.8	17.3	19.8	22.3	25.3	30.4

APPENDICES (CONTINUED)

E. RF LIMIT FOR MINIMUM OR NEAR MINIMUM COVER RING COMPRESSIONS STRUCTURES.

1. Plastic Moment Strength Minimum Cover Requirements (Ref. 6)

$M_p = K_3 \left(\frac{S}{H}\right)^2$ The value of the coefficient K_3 is defined as: $K_3 = \frac{AL\ d\ F_p}{c}$

In which:

M_p = plastic moment capacity (K ft/ft) (see table page ••)
S = span (ft)
H = Cover depth over crown (ft)
AL = axle load for design vehicle (Kips). AL is the load supported on a single axle or on tandem axles if the spacing between the axles is less than one-third the span of the culvert.
d = corrugation depth = .2083 ft. (2.5")
F_p = factor of safety against the development of a plastic hinge, dimensionless. See figures below.
c = coefficient with units of length, whose value depends on the degree of compaction of the backfill
c = 69 ft for RC - 90% Std. AASHTO
c = 115 ft for RC - 95% Std. AASHTO

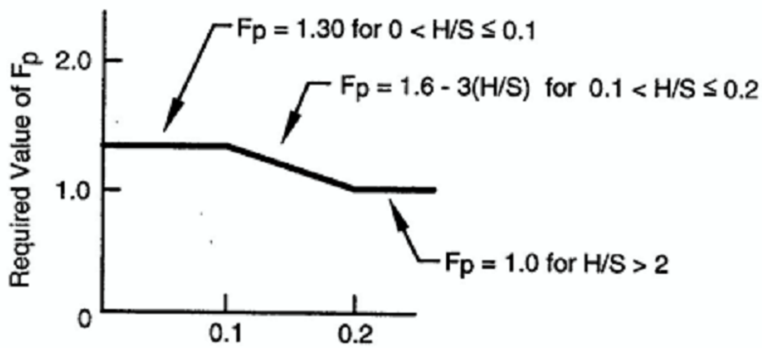


FIG. E.1.1 Cover Ratio (H/S)
Required values of F_p for construction vehicle loads.
(Loads not repetitive over full life of structure)

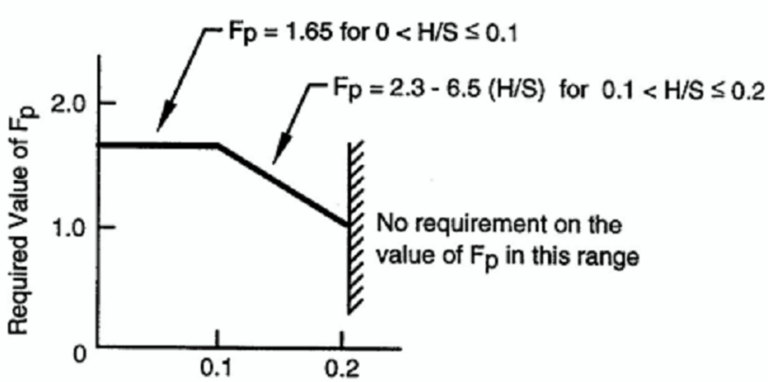


FIG. E.1.2 Cover Ratio (H/S)
Required values for design vehicle loads which are repetitive over full life of structure.

APPENDICES (CONTINUED)

2. RF Limit Development

2.1 AASHTO minimum cover limits are span/8 for H20 live loads.

2.2 The required Factors of Safety F_p, for minimum covers of span/8 are:

F_p = 1.488 (for Inventory Loads – Fig. E.1.2)

F_p = 1.225 (for Operating Loads – Fig. E.1.1)

F_p operating/F_p inventory = 0.823

2.3 Basic equations in E.1, for a given structure and backfill condition, require minimum cover levels that increase linearly with increasing axle loads such that

$$M_p = K_3 \left(\frac{S}{H}\right)^2 = \frac{AL\ d\ F_p}{c} \left(\frac{S}{H}\right)^2$$

2.4 To maintain the Factor of Safety when axle loads are increased:

$$\frac{AL\ d\ F_p}{c} \left(\frac{S}{h}\right)^2 = \frac{RF\ (AL)\ d\ F_p}{c} \left(\frac{S}{H}\right)^2$$

$RF = \frac{H^2}{h^2}$ Inventory loads, based on cover

2.5 To reduce the Factor of Safety for occasional (operating) loads, Figure E 2.5.1 has been developed from F_p values in E.1.

$y = mx+b \rightarrow C = 2.36 \frac{H}{S} + .528 \leq 1.0$

$RF = \frac{H^2}{Ch^2}$ Operating loads based on cover

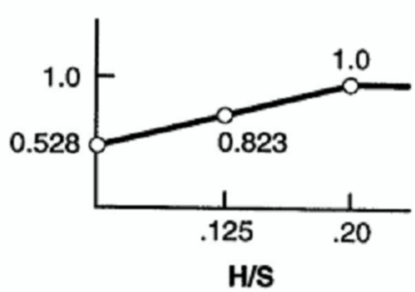


FIG. E.2.5.1 F_p Inventory / F_p Operating

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