2024 PIPE SCHOOL
STRENGTH. RESILIENCE. SUSTAINABILITY.

Box Culvert Design

Brian S. Jenner, P.E.

Rinker Materials

Box Culvert Design

Outline

- Basics
  - Introduction to Culverts
  - Structural Model
  - Demand
  - Capacity
  - Load Rating
- Advanced Topics
  - Flexible Foundations
  - Seismic
- Eriksson Culvert Design

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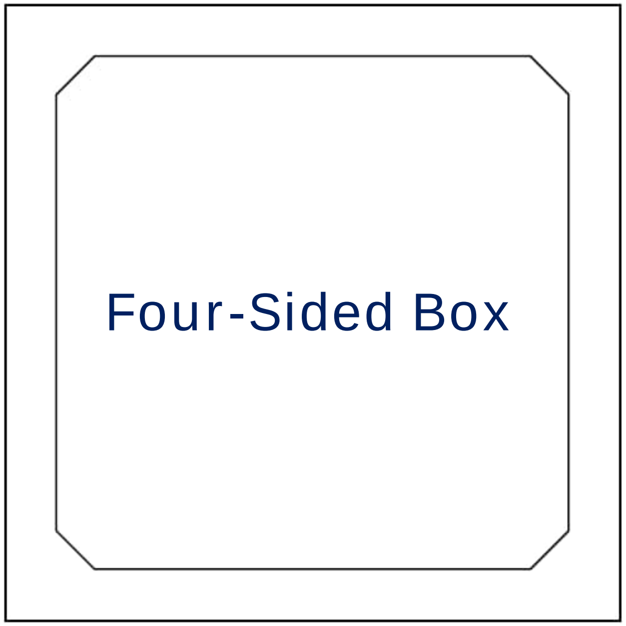
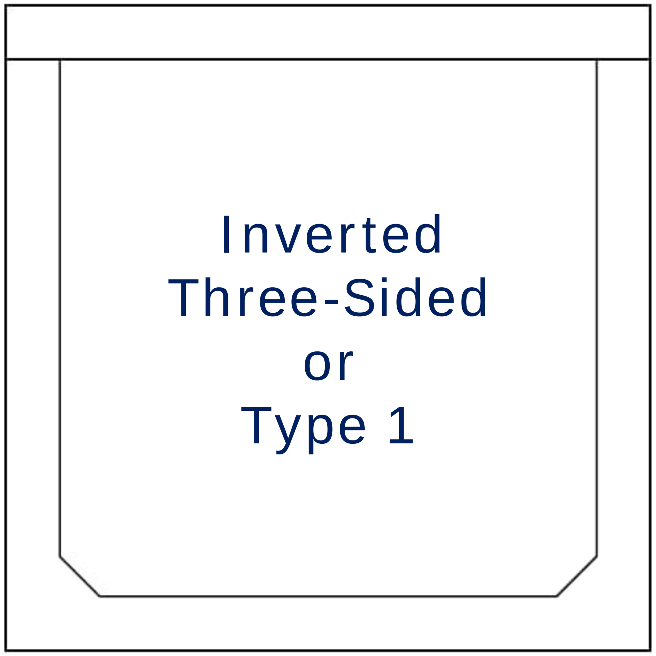
Introduction to Culverts

- Culvert Types



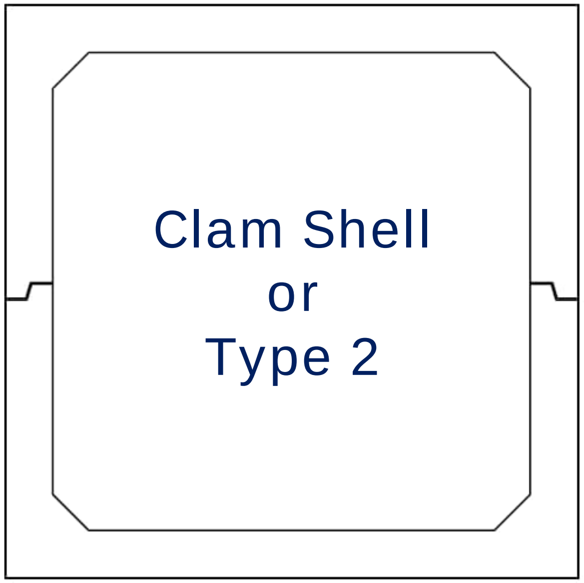
Introduction to Culverts

- Culvert Types



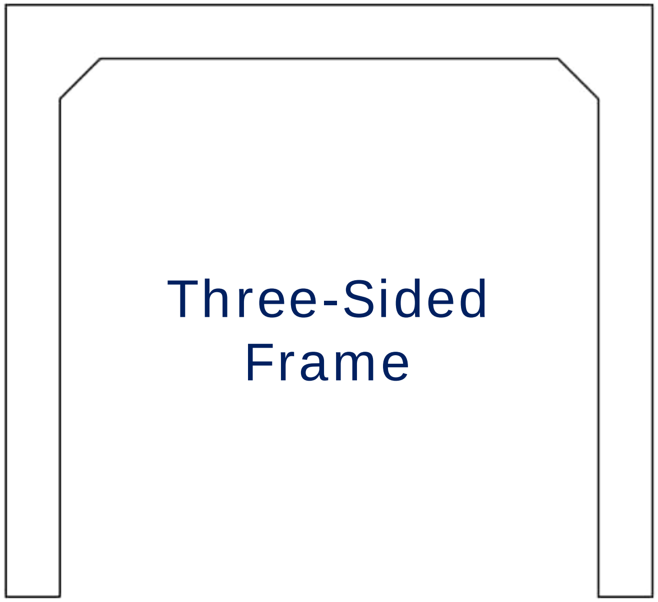
Introduction to Culverts

- Culvert Types



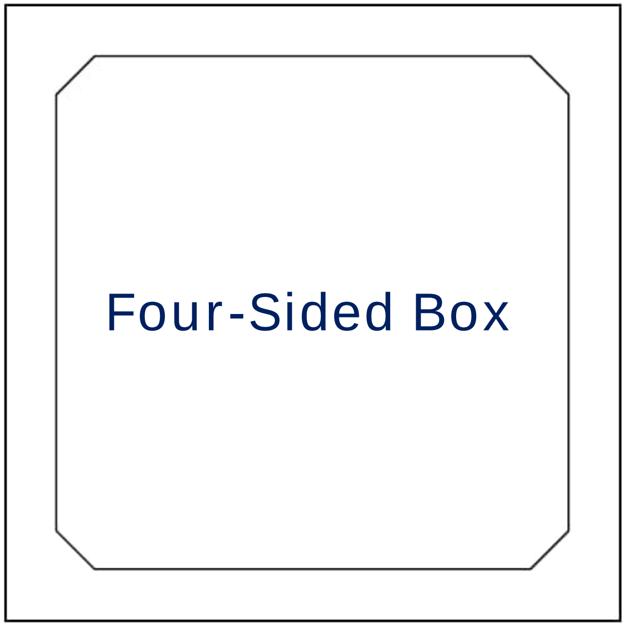
Introduction to Culverts

- Culvert Types



Introduction to Culverts

- Four-Sided Box Culvert



Introduction to Culverts

- Governing Specifications
  - AASHTO LRFD Bridge Design Specifications
  - AREMA (Railroads)
  - ASTM (C1577)

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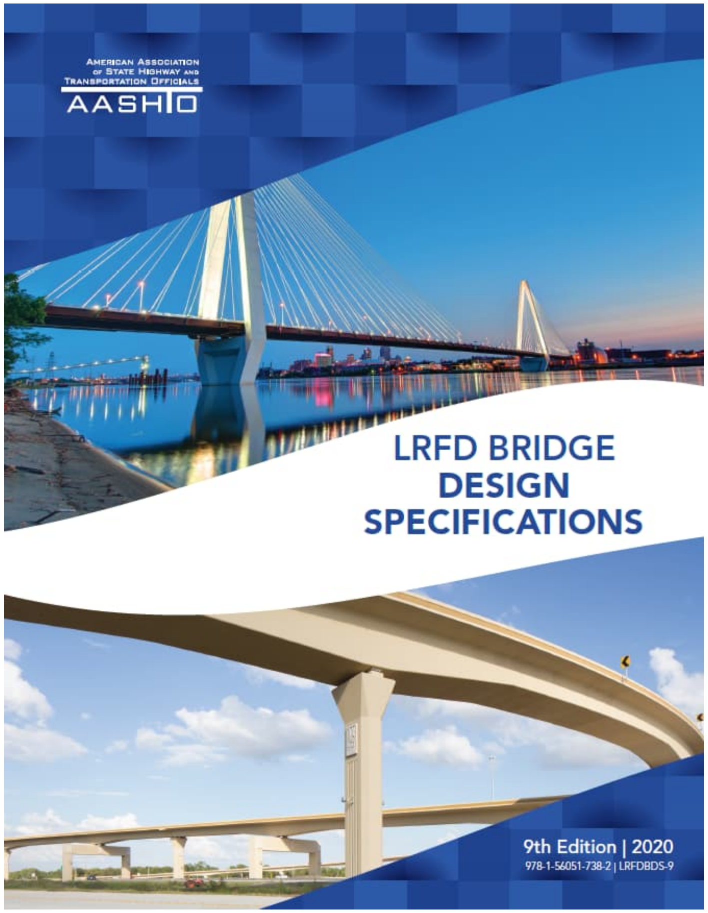
Introduction to Culverts

➢ Governing Specifications

- AASHTO LRFD Bridge Design Specifications
- AREMA (Railroads)
- ASTM (C1577)



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Introduction to Culverts

- Governing Specifications
  - AASHTO LRFD Bridge Design Specifications
    - ✓ Section 1 Introduction
    - ✓ Section 3 Loads and Load Factors
    - ✓ Section 4 Structural Analysis and Evaluation
    - ✓ Section 5 Concrete Structures
    - ✓ Section 12 Buried Structures and Tunnel Liner
  - ASTM
    - ✓ C1577 Standard Specification for Precast Reinforced Concrete Monolithic Box Sections for Culverts, Storm Drains, and Sewers Designed According to AASHTO LRFD

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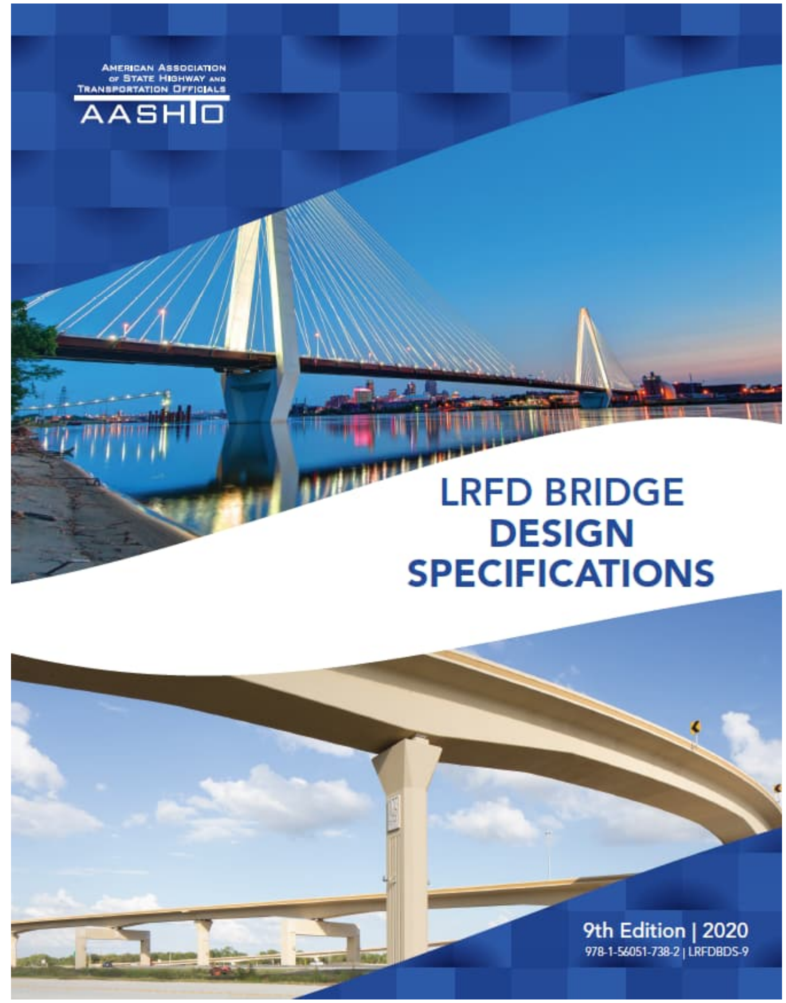
Introduction to Culverts

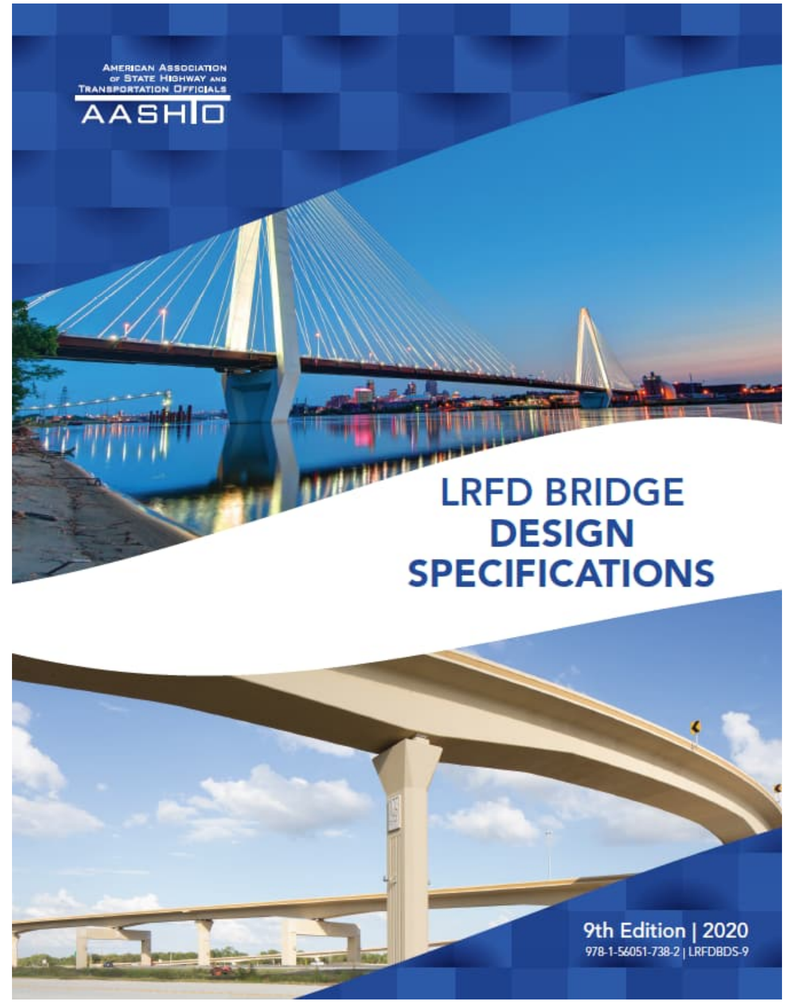
- Governing Specifications
  - AASHTO LRFD

$$\sum \eta_i \gamma_i Q_i \leq \phi R_n = R_r \qquad (1.3.2.1\text{-}1)$$



Introduction to Culverts

- Governing Specifications
  - AASHTO LRFD



$$\sum \eta_i \gamma_i Q_i \le \phi R_n = R_r \qquad (1.3.2.1\text{-}1)$$

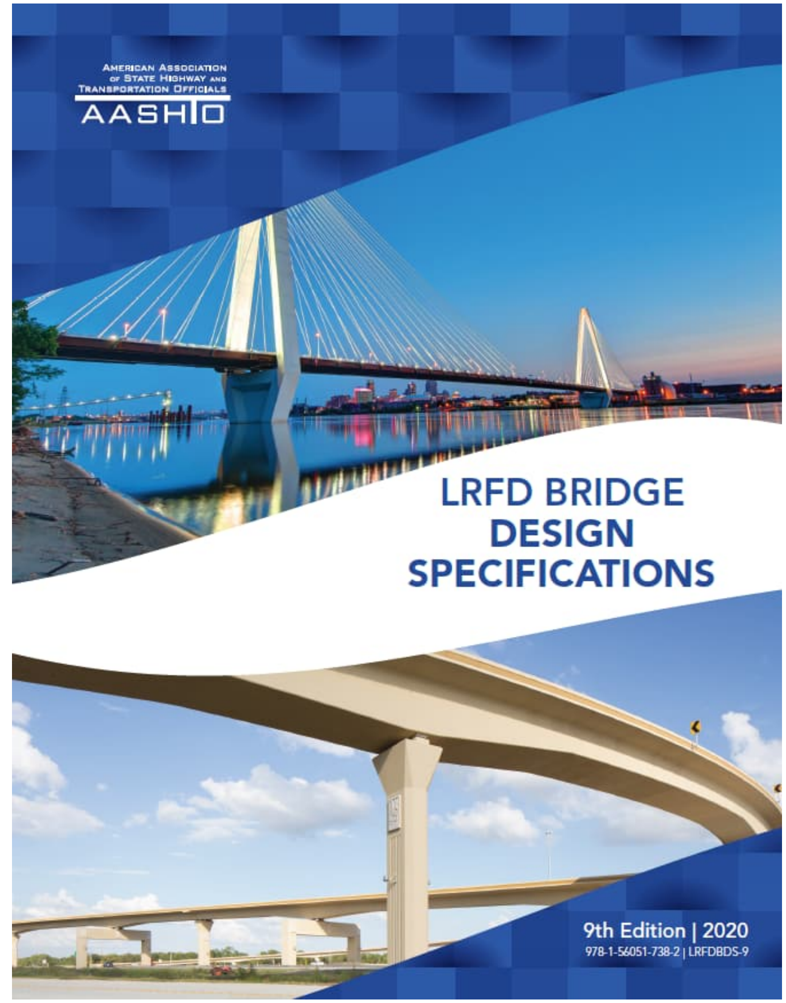
Demand ≤ Capacity

Introduction to Culverts

- Governing Specifications
  - AASHTO LRFD

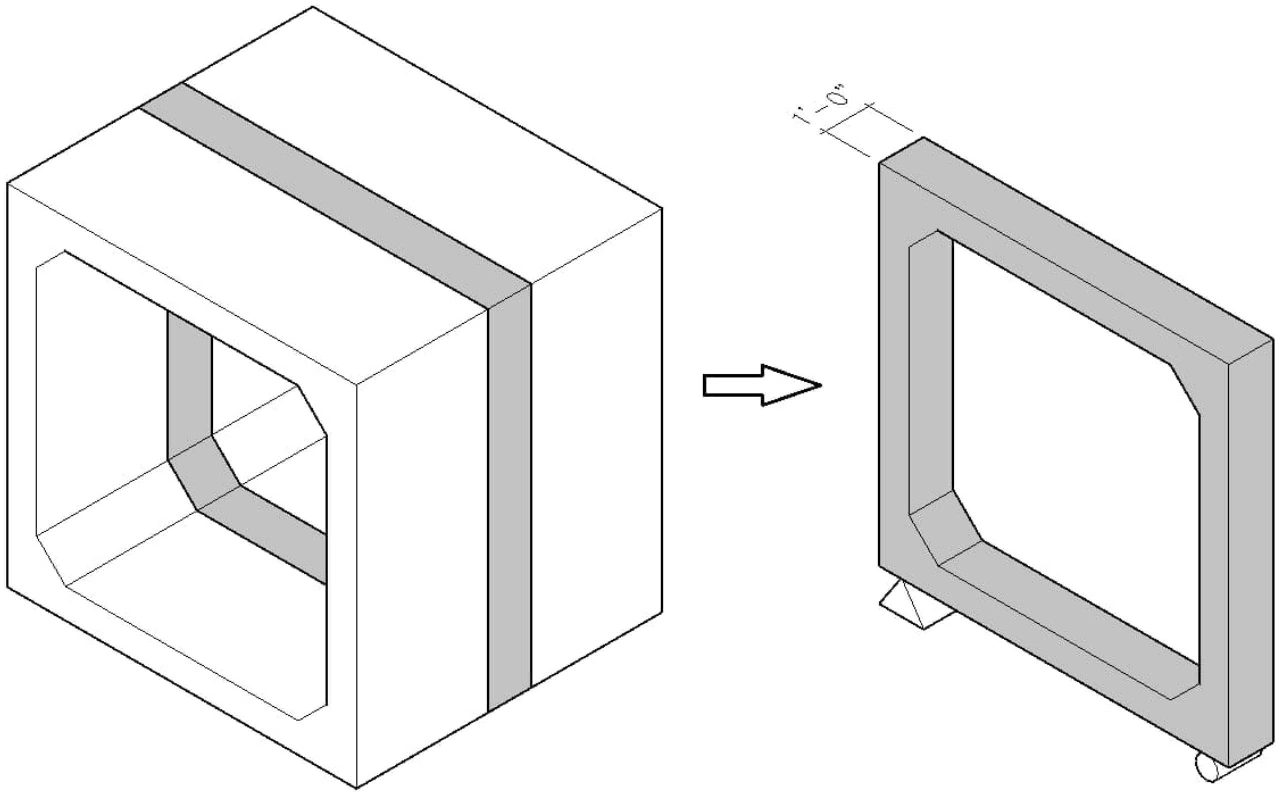
$$\sum \eta_i \gamma_i Q_i \le \phi R_n = R_r \qquad (1.3.2.1\text{-}1)$$

Demand ≤ Capacity



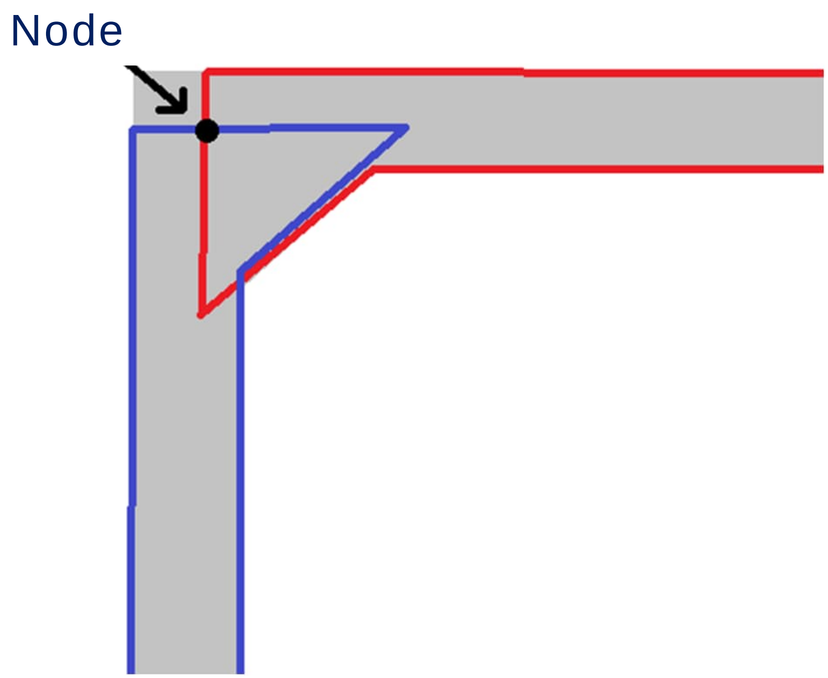
Structural Model

- Per Unit Length Basis



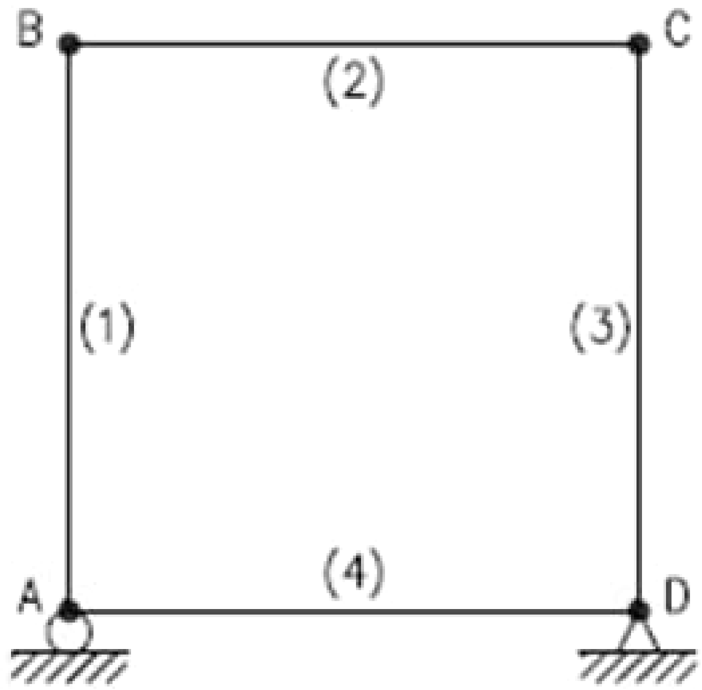
Structural Model

- Haunches in the Structural Model
  - Allowed, but not required
  - Redistributes forces in structure
  - Can use the effects of haunches in either or both the slabs and the walls



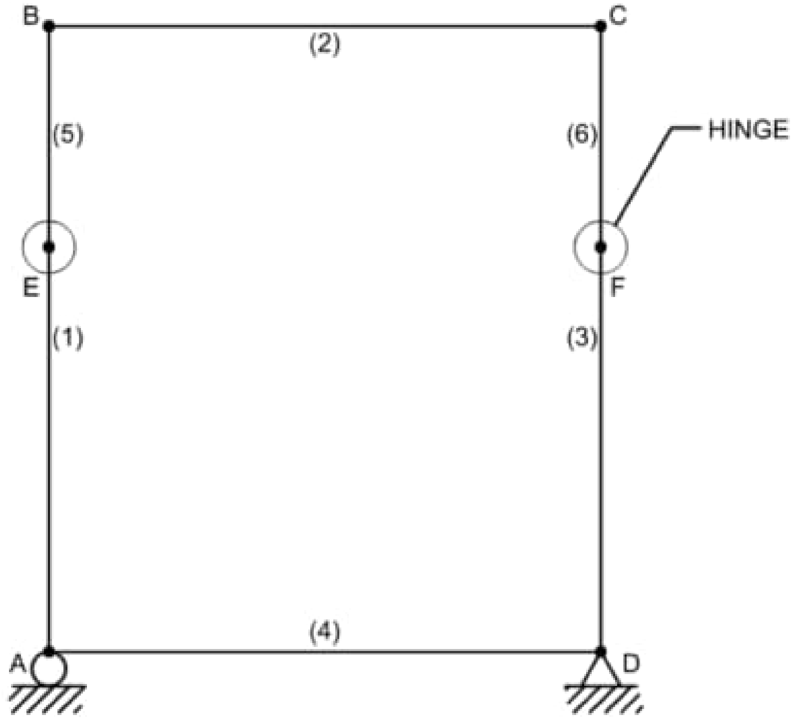
Structural Model

- Boundary Conditions – Four-Sided Box Culvert



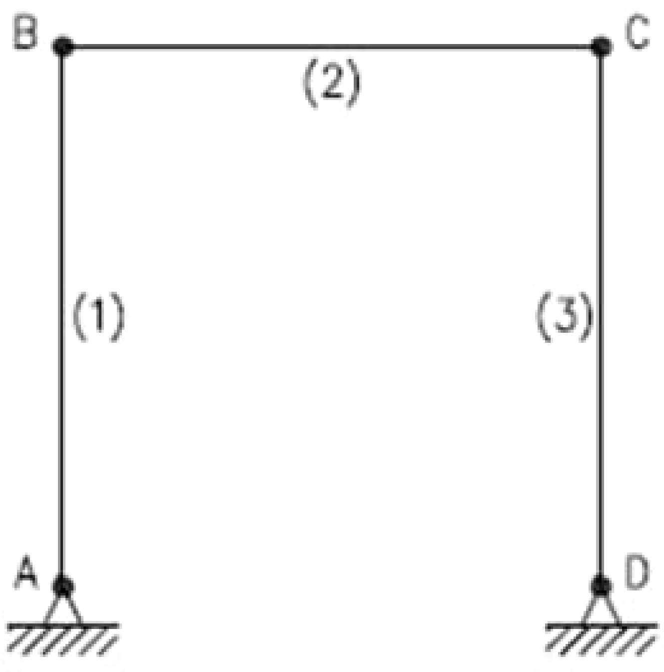
Structural Model

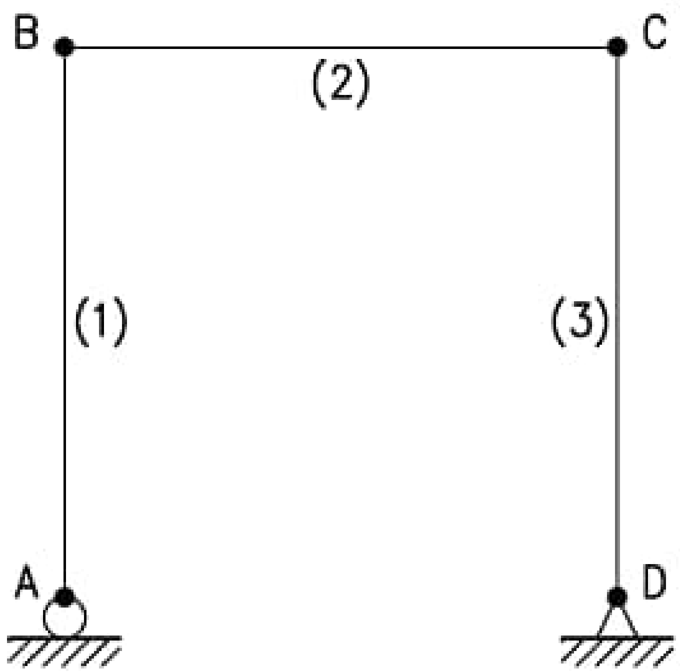
- Boundary Conditions – Type 1 and Type 2 Culverts



Structural Model

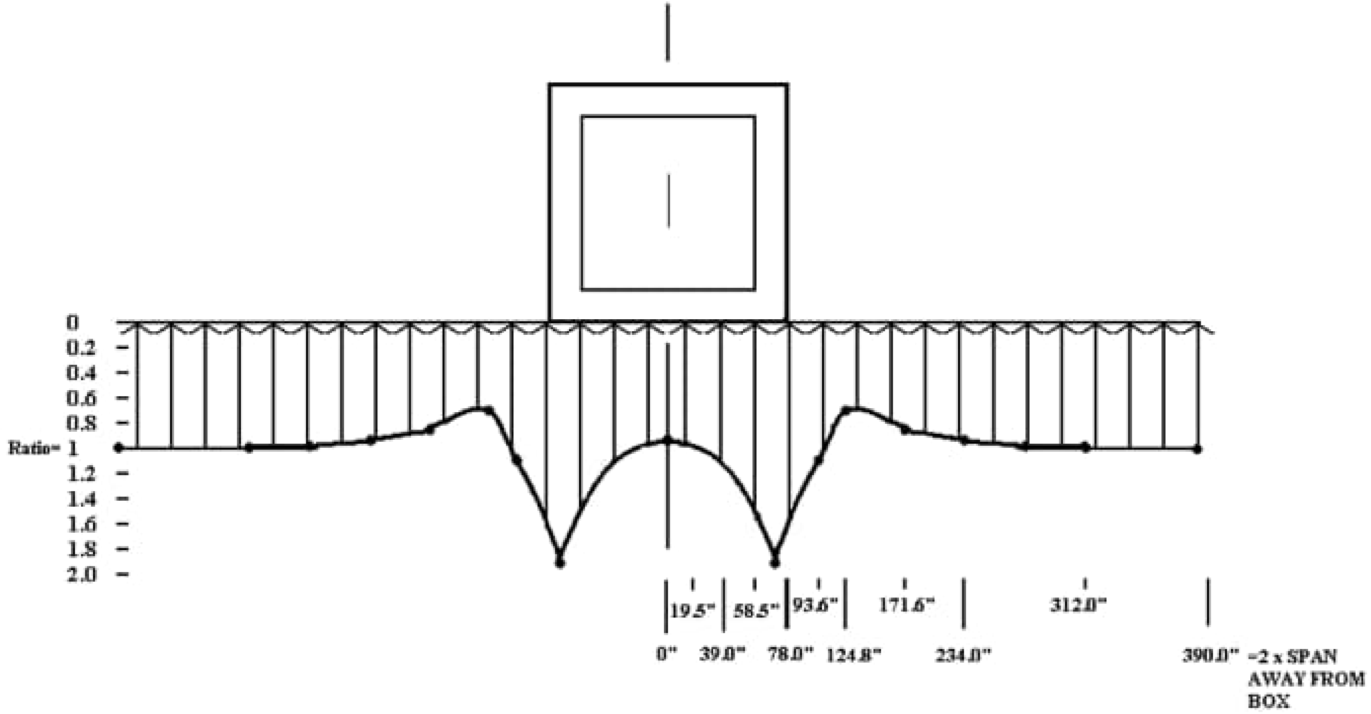
- Boundary Conditions – Three-Sided Culverts





Structural Model

- Bottom Slab



Structural Model

- Bottom Slab
  - As per code, we can assume a linearly varying stress distribution

10.6.5—Structural Design

The structural design of footings shall comply with the requirements given in Section 5.

For structural design of an eccentrically loaded foundation, a triangular or trapezoidal contact stress distribution based on factored loads shall be used for footings bearing on all soil and rock conditions.

C10.6.5

For purposes of structural design, it is usually assumed that the bearing stress varies linearly across the bottom of the footing. This assumption results in the slightly conservative triangular or trapezoidal contact stress distribution.

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Structural Model

- Bottom Slab
  - Implies a rigid foundation
  - Probably OK for Precast Box Culverts of typical dimensions

10.6.5—Structural Design

The structural design of footings shall comply with the requirements given in Section 5.

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C10.6.5

For purposes of structural design, it is usually assumed that the bearing stress varies linearly across the bottom of the footing. This assumption results in the slightly conservative triangular or trapezoidal contact stress distribution.

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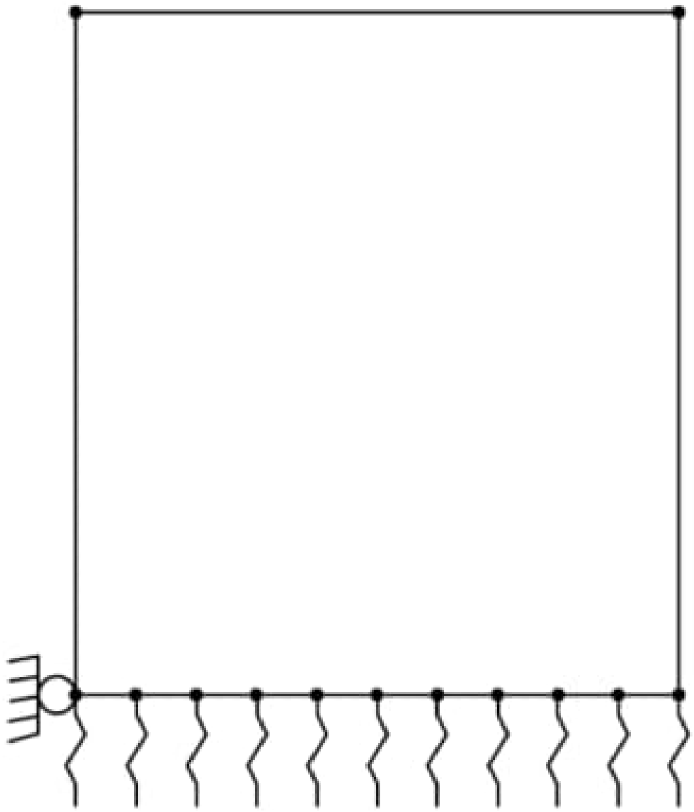
Structural Model

➢ Bottom Slab

- We could also assume a flexible foundation



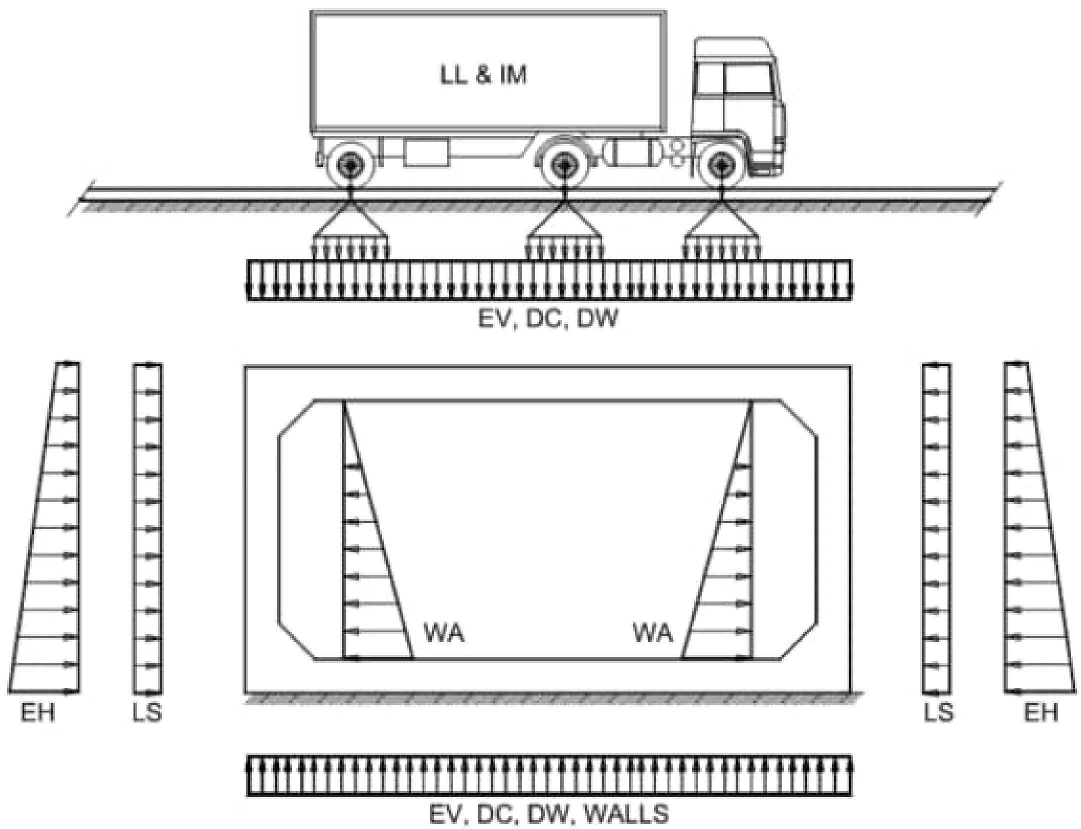
Demand Side

$$\sum \eta_i \gamma_i Q_i \leq \phi R_n = R_r$$

Demand ≤ Capacity

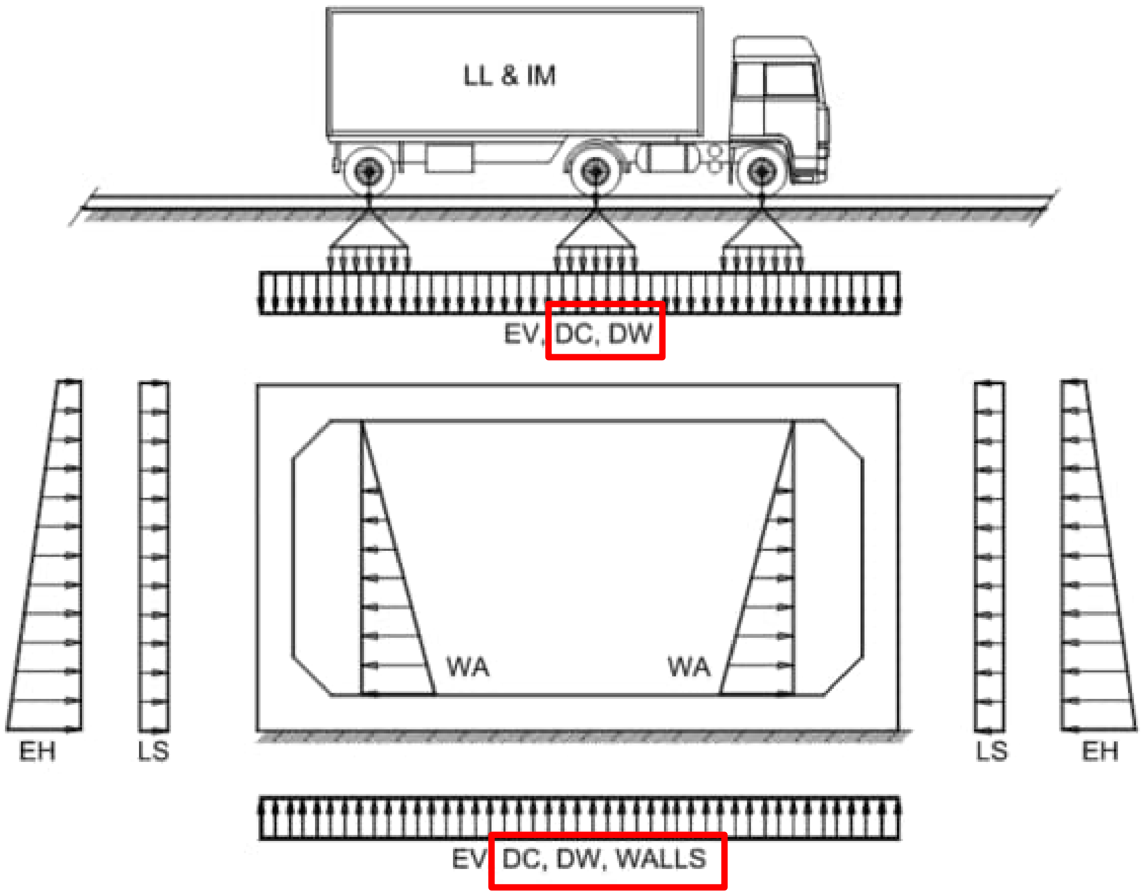
Demand Side

- Applied Loads
  - LL + IM = Live Load + Impact
  - EV = Vertical Soil Load
  - DC = Self Weight
  - DW = Wearing Surface
  - EH = Horizontal Soil Load
  - WA = Internal Fluid Pressure
  - LS = Live Load Surcharge



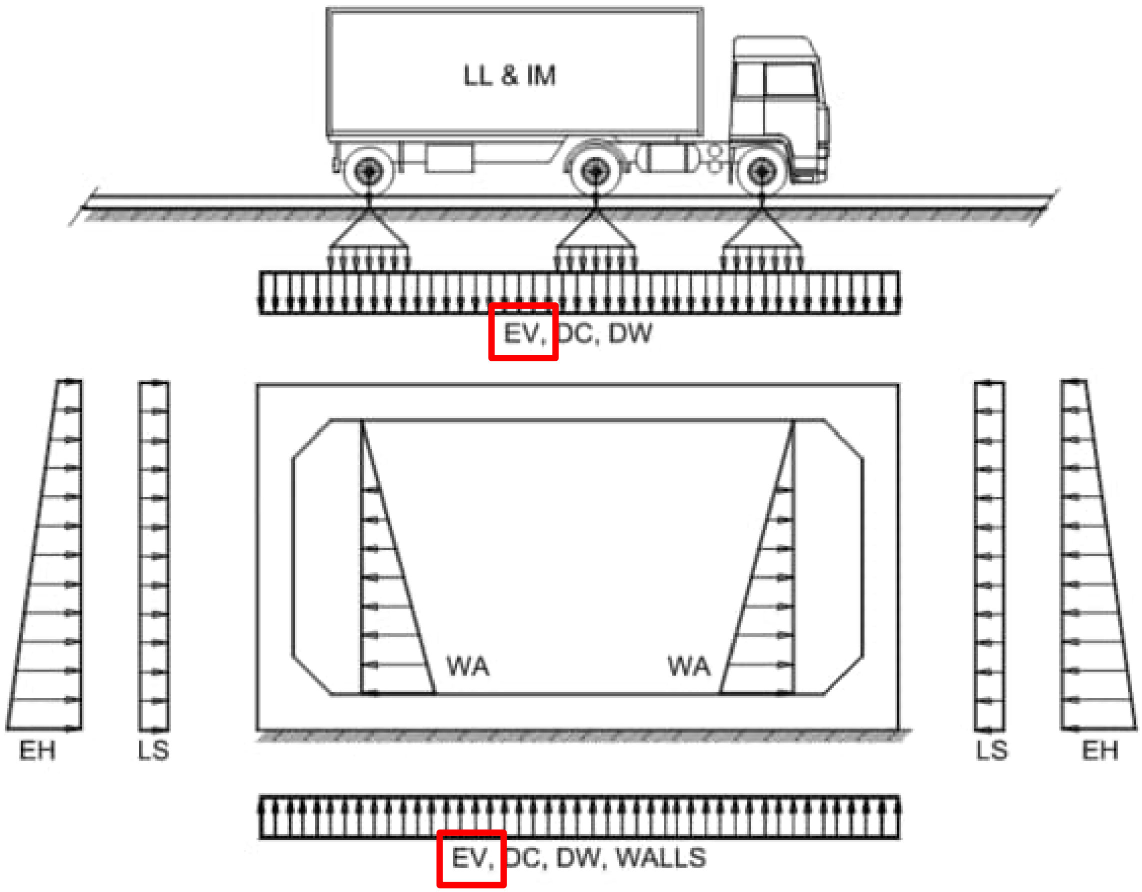
Demand Side

- Self Weight (DC)
- Wearing Surface (DW)



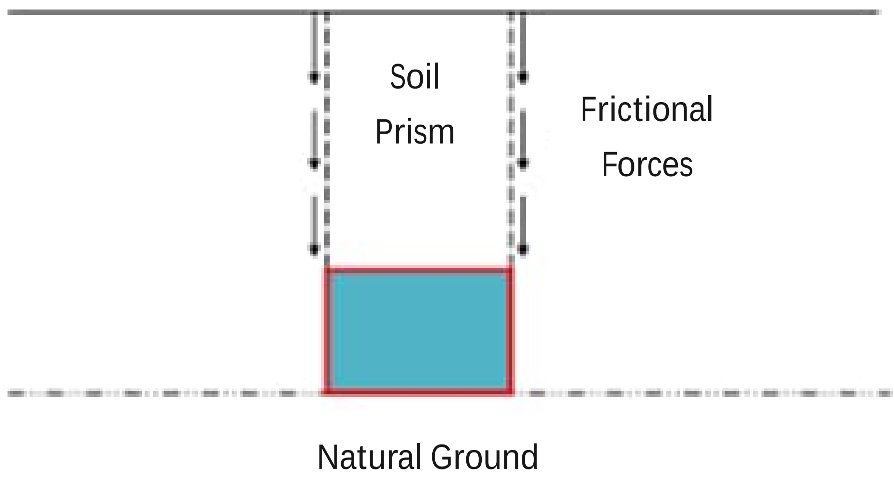
Demand Side

- Vertical Soil Load (EV)



Demand Side

- Vertical Soil Load (EV)
  - Embankment Installation
  - Soil-Structure Interaction



Demand Side

- Vertical Soil Load (EV)
  - Vertical Arching Factor

12.11.2.2—Modification of Earth Loads for Soil–Structure Interaction

12.11.2.2.1—Embankment and Trench Conditions

In lieu of a more refined analysis, the total unfactored earth load, W_E, acting on the culvert may be taken as:

- For embankment installations:

$$W_E = F_e \gamma_s B_c H \qquad (12.11.2.2.1\text{-}1)$$

in which:

$$F_e = 1 + 0.20\frac{H}{B_c} \qquad (12.11.2.2.1\text{-}2)$$

F_e shall not exceed 1.15 for installations with compacted fill along the sides of the box section, or 1.40 for installations with uncompacted fill along the sides of the box section.

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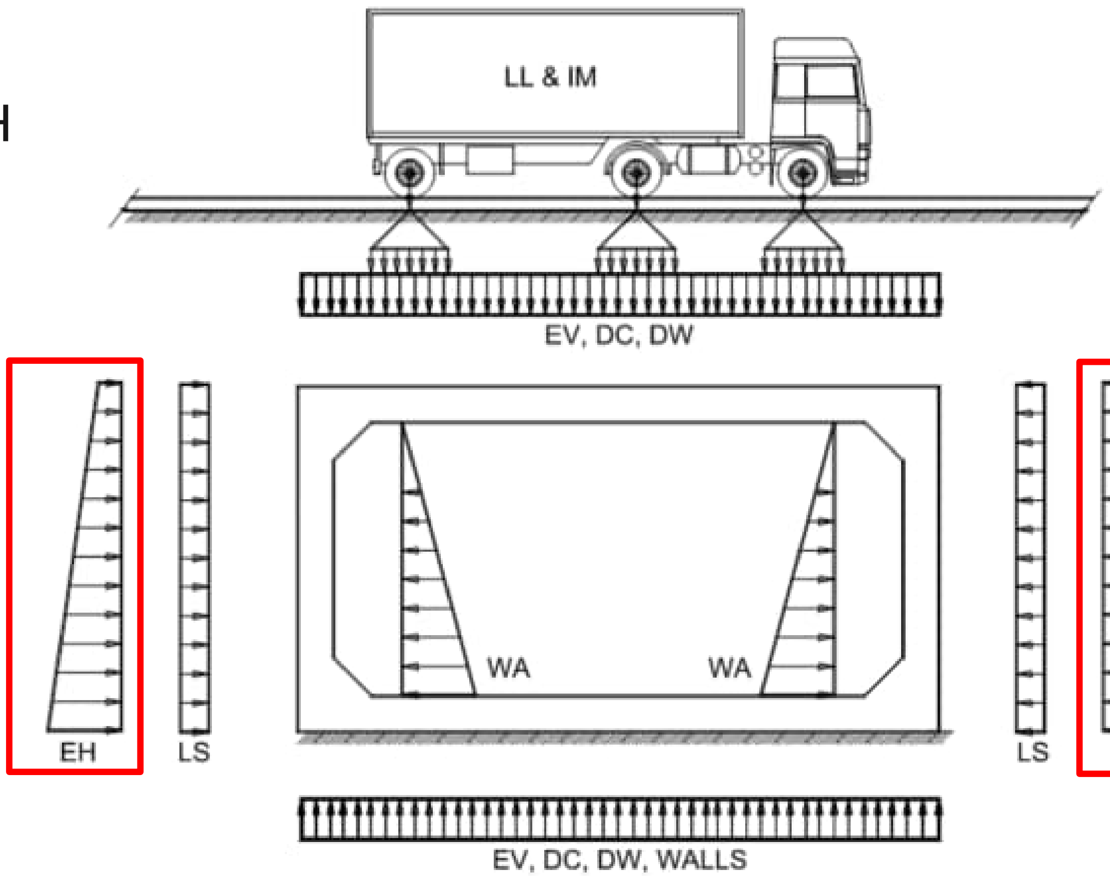
Demand Side

- Horizontal Soil Load (EH



Demand Side

- Horizontal Soil Load (EH)
  - Equivalent Fluid Pressure Method

$$p = k\gamma_s z \qquad (3.11.5.1\text{-}1)$$

Demand Side

- Horizontal Soil Load (EH)
  - Equivalent Fluid Pressure Method

$$p = k\gamma_s z \qquad (3.11.5.1\text{-}1)$$

Soil Condition	Average ‘k’ values
Active	1/3
At-Rest	1/2
Passive	3

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Demand Side

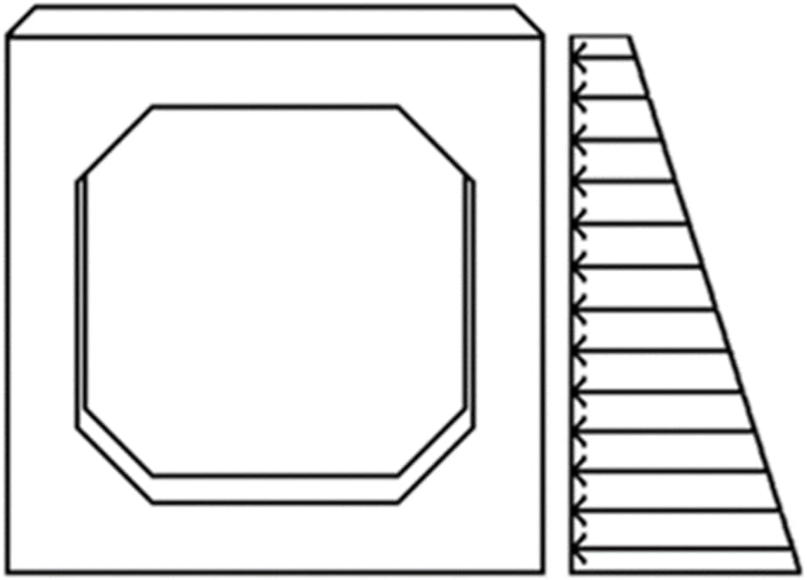
- Horizontal Soil Load (EH)
  - Equivalent Fluid Pressure Method
  - AASHTO recommends “at-rest” pressure

C3.11.1

Walls that can tolerate little or no movement should be designed for at-rest earth pressure.

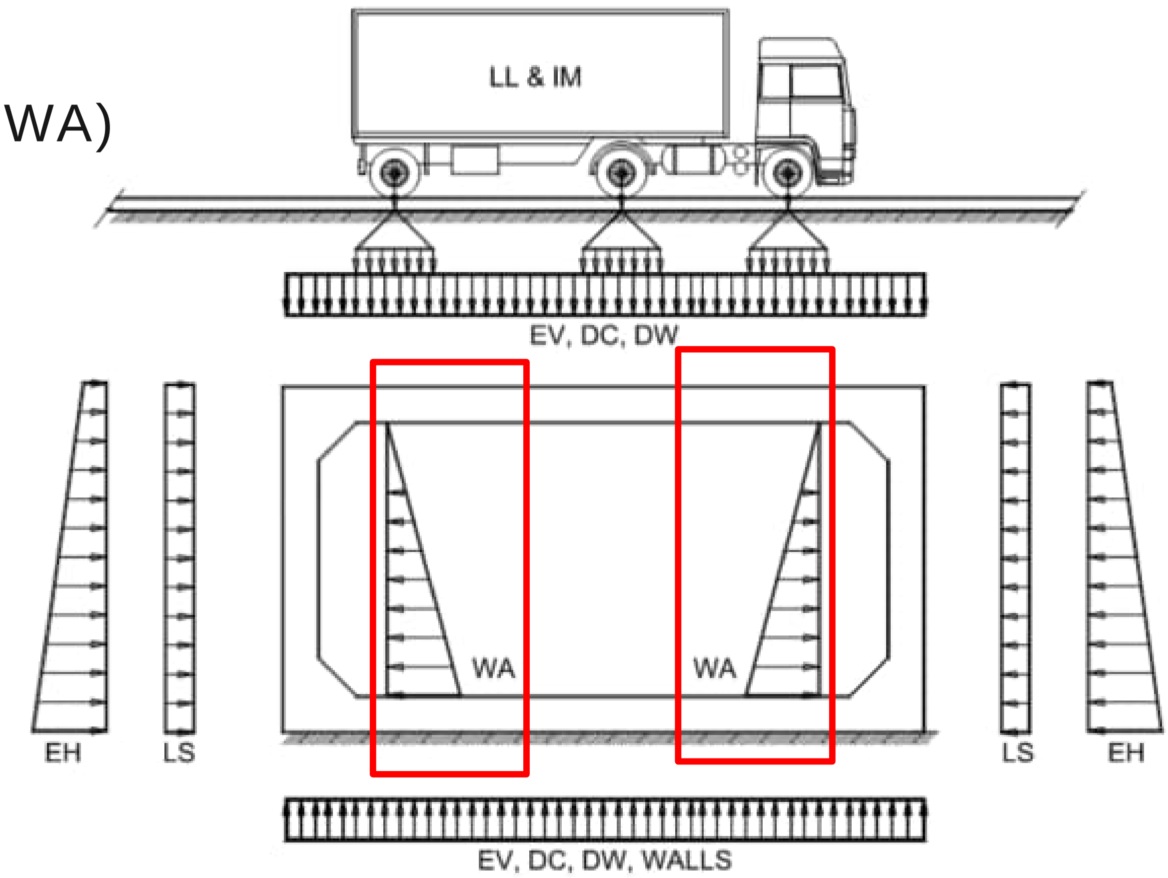
Demand Side

- Horizontal Soil Load (EH)
  - Equivalent Fluid Pressure Method
  - AASHTO recommends “at-rest” pressure



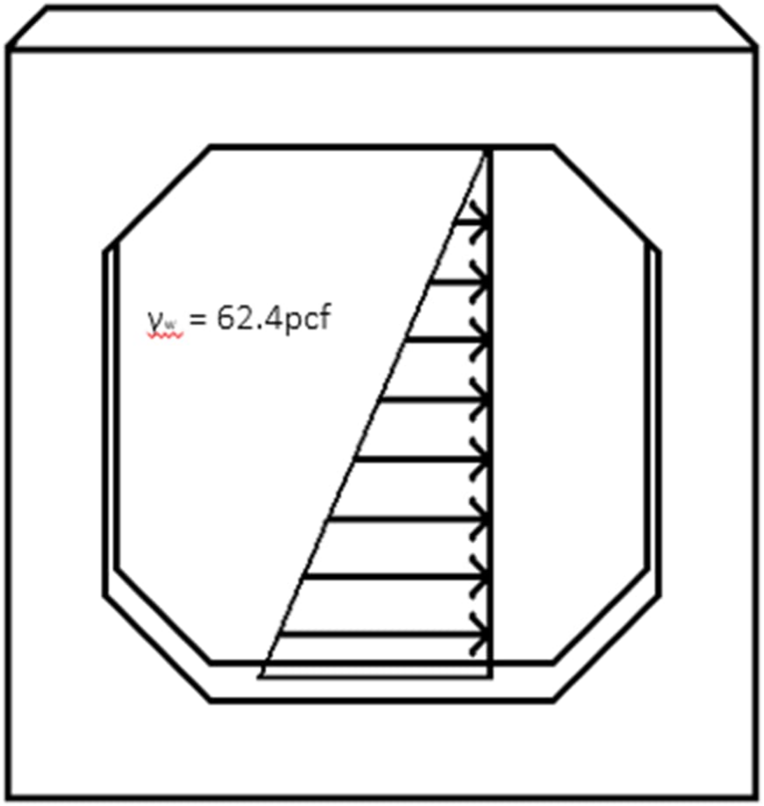
Demand Side

- Internal Fluid Pressure (WA)



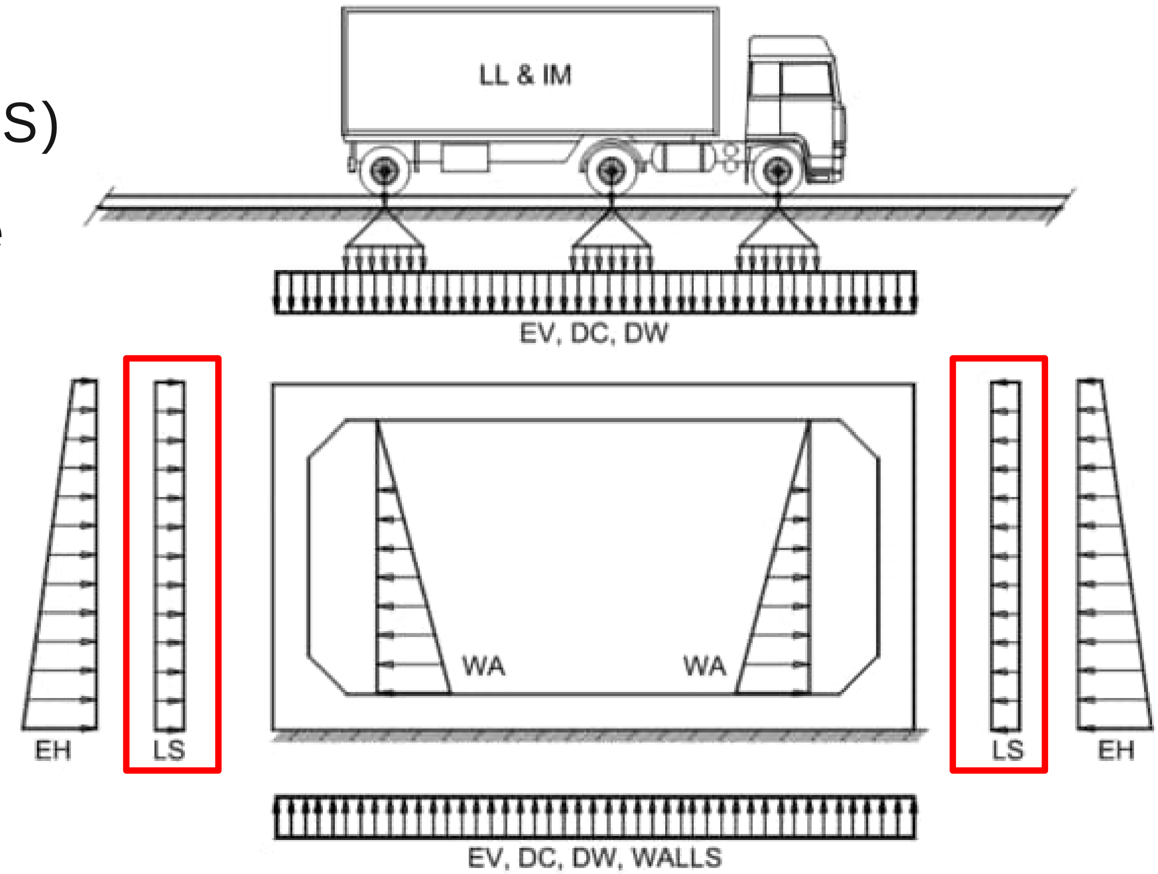
Demand Side

- Internal Fluid Pressure (WA)
  - Weight of fluid running through box



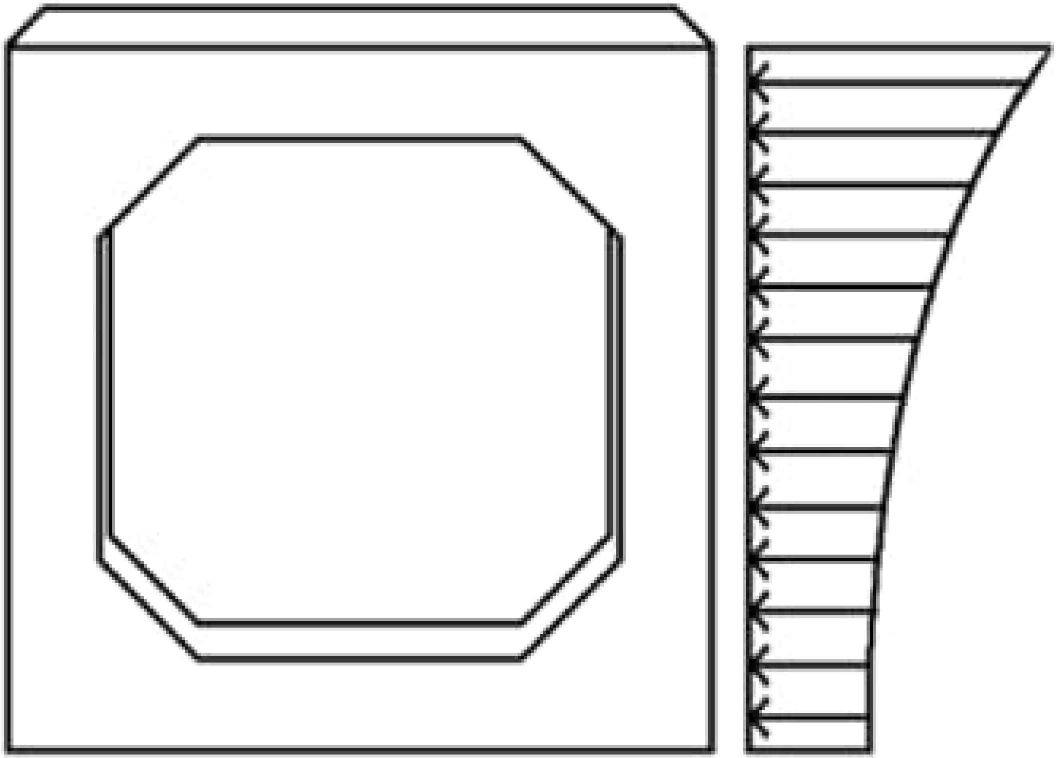
Demand Side

- Live Load Surcharge (LS)
  - Approaching Vehicle



Demand Side

- Live Load Surcharge (LS)
  - Approaching Vehicle
  - Boussinesq distribution



Demand Side

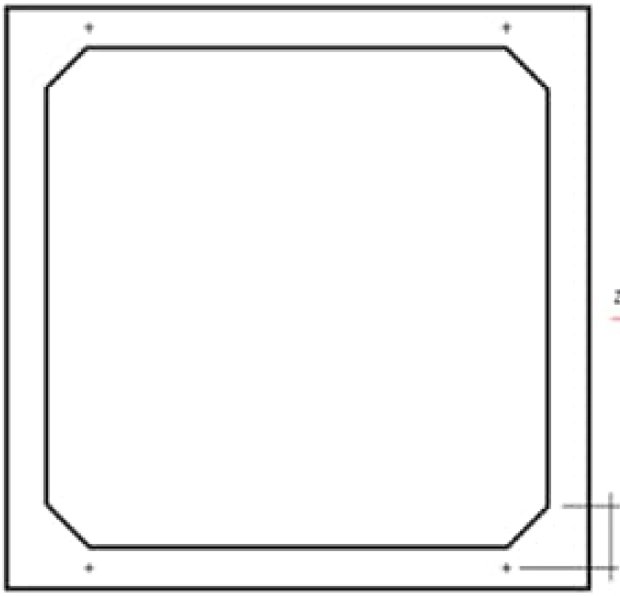
- Live Load Surcharge (LS)
  - Approaching Vehicle
  - Boussinesq distribution

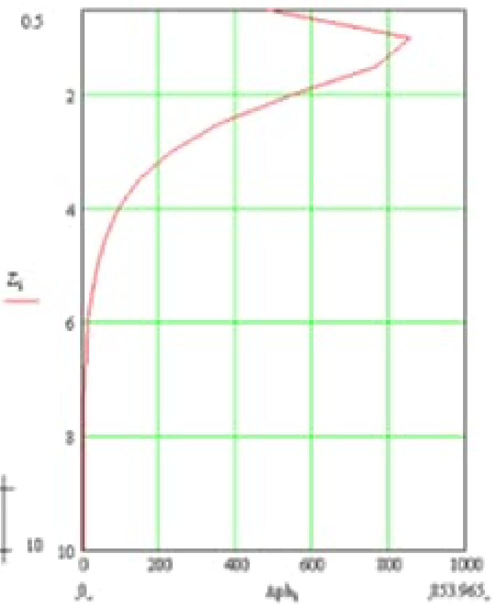
The horizontal pressure, Δ_{ph} in ksf, on a wall resulting from a point load may be taken as:

$$\Delta_{ph} = \frac{P}{\pi R^2}\left[\frac{3ZX^2}{R^3} - \frac{R(1-2\nu)}{R+Z}\right] \qquad (3.11.6.2\text{-}2)$$

Demand Side

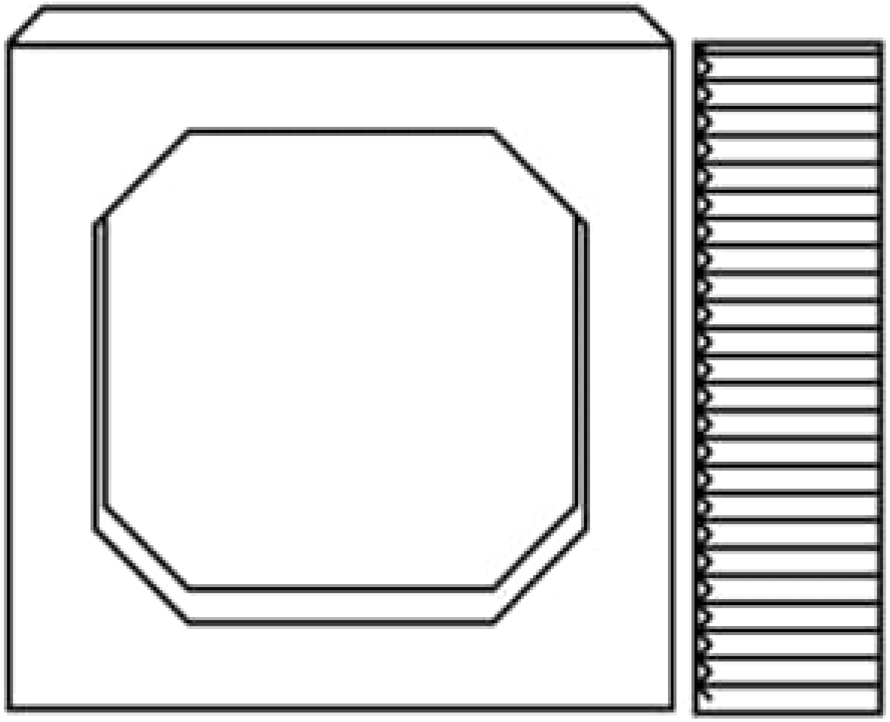
- Live Load Surcharge (LS)
    - Approaching Vehicle
    - Boussinesq distribution





Demand Side

- Live Load Surcharge (LS)
  - Approaching Vehicle
  - Boussinesq distribution
  - AASHTO allows uniform distribution



Demand Side

- Live Load Surcharge (LS)
  - Approaching Vehicle
  - Boussinesq distribution
  - AASHTO allows uniform distribution

Equivalent heights of soil, h_{eq}, for highway loadings on abutments and retaining walls may be taken from Tables 3.11.6.4-1 and 3.11.6.4-2. Linear interpolation shall be used for intermediate wall heights.

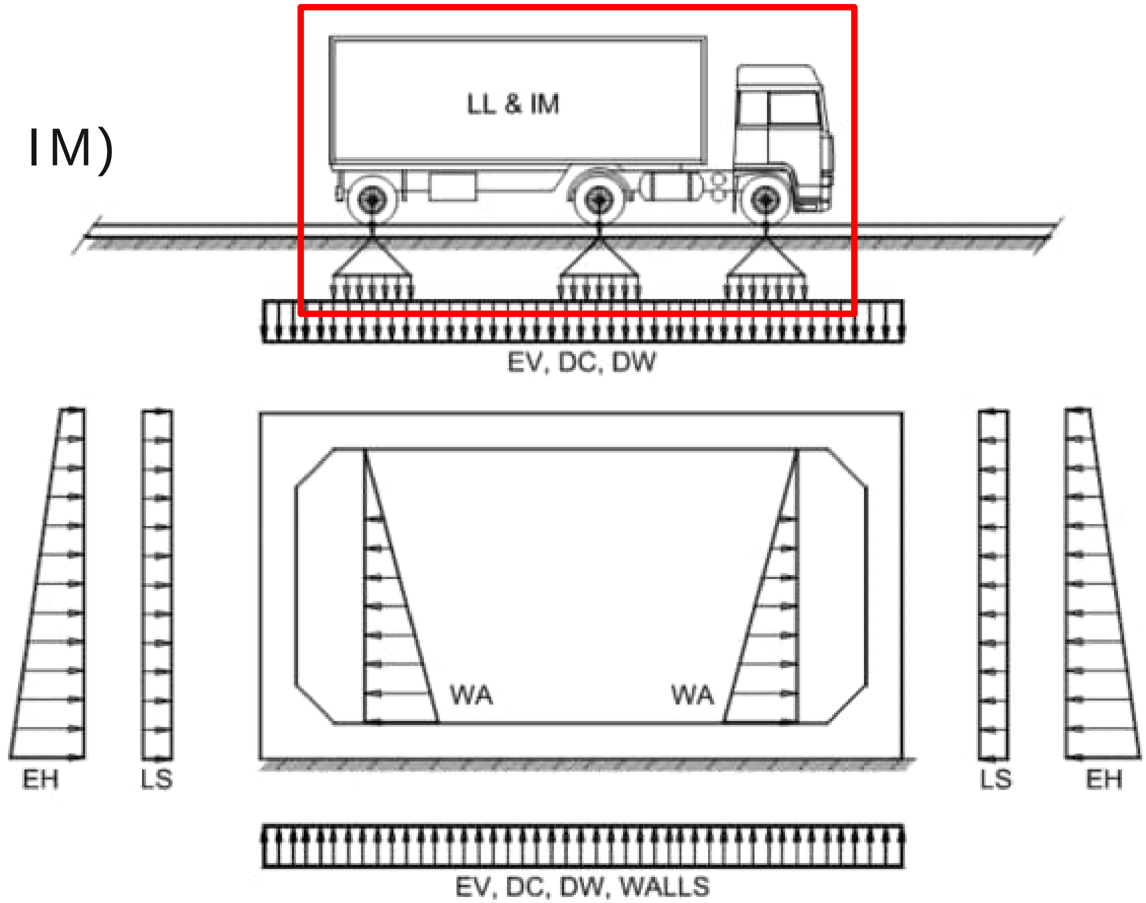
The wall height shall be taken as the distance between the surface of the backfill and the bottom of the footing along the pressure surface being considered.

Table 3.11.6.4-1—Equivalent Height of Soil for Vehicular Loading on Abutments Perpendicular to Traffic

Abutment Height (ft)	h_{eq} (ft)
5.0	4.0
10.0	3.0
≥20.0	2.0

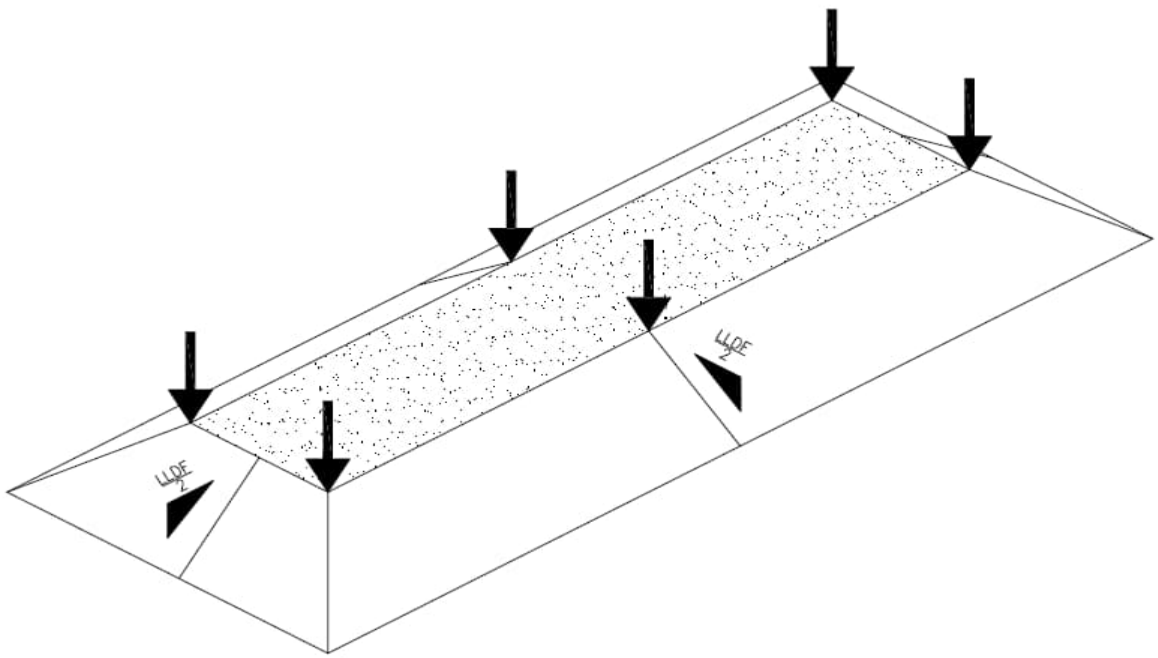
Demand Side

➢ Live Load + Impact (LL + IM)



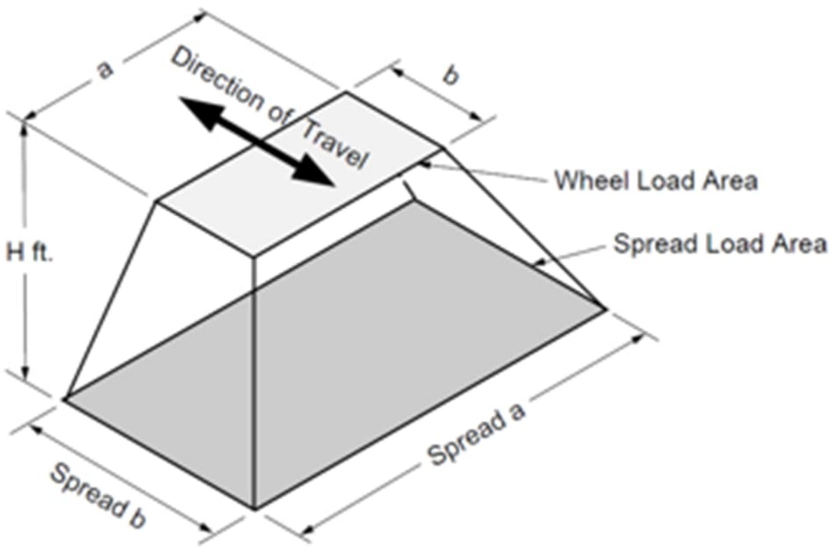
Demand Side

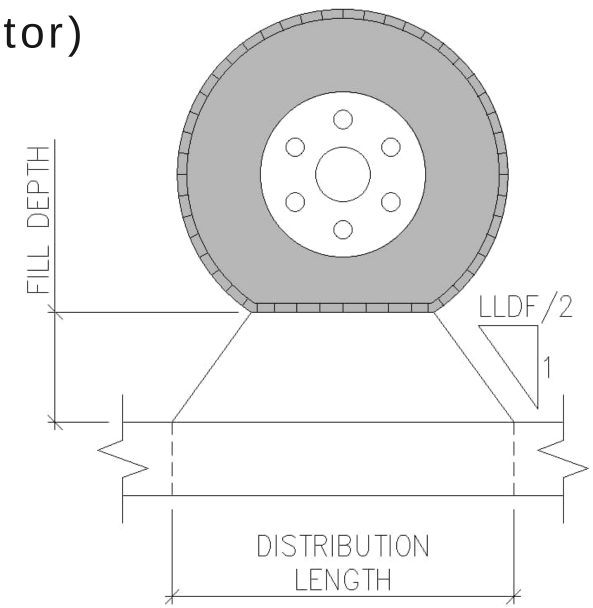
- Live Loads (Moving Loads)



Demand Side

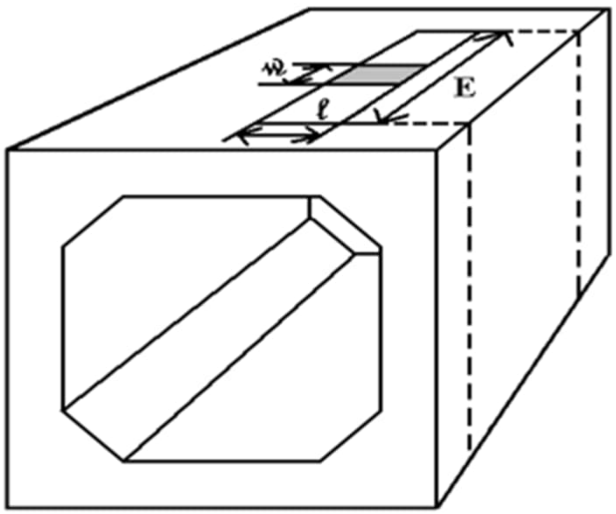
- Live Loads (Moving Loads)
  - Distribution through earth fills
  - LLDF (Live Load Distribution Factor or Slope Factor)





Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For < 2’ of fill we get to distribute the load through the top slab
  - For traffic parallel to the span



E = 96 +1.44 (s) ;
E in inches, s in feet

Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For < 2' of fill we get to distribute the load through the top slab
  - For traffic parallel to the span – only need to check one lane

4.6.2.10—Equivalent Strip Widths for Box Culverts

4.6.2.10.1—General

This Article shall be applied to box culverts with depths of fill less than 2.0 ft.

4.6.2.10.2—Case 1: Traffic Travels Parallel to Span

When traffic travels primarily parallel to the span, culverts shall be analyzed for a single loaded lane with the single lane multiple presence factor.

Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For < 2’ of fill we get to distribute the load through the top slab
  - For traffic parallel to the span – only need to check one lane

Table 4.6.2.1.3-1—Equivalent Strips

Type of Deck	Direction of Primary Strip Relative to Traffic	Width of Primary Strip (in.)
Concrete:		
• Cast-in-place	Overhang	$45.0 + 10.0X$
	Either Parallel or Perpendicular	$+M$: $26.0 + 6.6S$ $-M$: $48.0 + 3.0S$
• Cast-in-place with stay-in-place concrete formwork	Either Parallel or Perpendicular	$+M$: $26.0 + 6.6S$ $-M$: $48.0 + 3.0S$
• Precast, post-tensioned	Either Parallel or Perpendicular	$+M$: $26.0 + 6.6S$ $-M$: $48.0 + 3.0S$

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Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For < 2’ of fill we get to distribute the load through the top slab
  - For traffic perpendicular to the span – number of lanes?

???

Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For < 2’ of fill we get to distribute the load through the top slab
  - Don’t forget to add distribution steel in the top slab

Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For >= 2' of fill
    - Distribution equations are basically the same regardless of traffic direction

$$A_{LL} = l_w w_w \qquad (3.6.1.2.6a\text{-}1)$$

3.6.1.2.6b—Traffic Parallel to the Culvert Span

$$H_{int} = \frac{s_w - \frac{w_t}{12} - \frac{0.06D_i}{12}}{LLDF} \qquad (3.6.1.2.6b\text{-}1)$$

$$w_w = \frac{w_t}{12} + LLDF(H) + 0.06\frac{D_i}{12} \qquad (3.6.1.2.6b\text{-}2)$$

$$w_w = \frac{w_t}{12} + s_w + LLDF(H) + 0.06\frac{D_i}{12} \qquad (3.6.1.2.6b\text{-}3)$$

3.6.1.2.6c—Traffic Perpendicular to the Culvert Span

$$H_{int\text{-}p} = \frac{s_a - \frac{l_t}{12}}{LLDF} \qquad (3.6.1.2.6b\text{-}4)$$

$$l_w = \frac{l_t}{12} + LLDF(H) \qquad (3.6.1.2.6b\text{-}5)$$

$$l_w = \frac{l_t}{12} + s_a + LLDF(H) \qquad (3.6.1.2.6b\text{-}6)$$

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Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For >= 2' of fill the distribution equations are basically the same regardless of traffic direction
  - For traffic parallel to the span – only check one lane

3.6.1.2.6—Distribution of Wheel Load through Earth Fills

3.6.1.2.6a—General

For traffic parallel to the span, culverts shall be analyzed for a single loaded lane with the single lane multiple presence factor. For traffic perpendicular to the culvert span, analysis shall include consideration of multiple lane loadings with appropriate multiple presence factors. Only the axle loads of the design truck or design tandem of Articles 3.6.1.2.2 and 3.6.1.2.3, respectively shall be applied as live load on culverts, regardless of traffic orientation.

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Demand Side

- Live Loads (Moving Loads)
  - Distribution through earth fills
  - For >= 2' of fill the distribution equations are basically the same regardless of traffic direction
  - For traffic perpendicular to the span – number of lanes?

???

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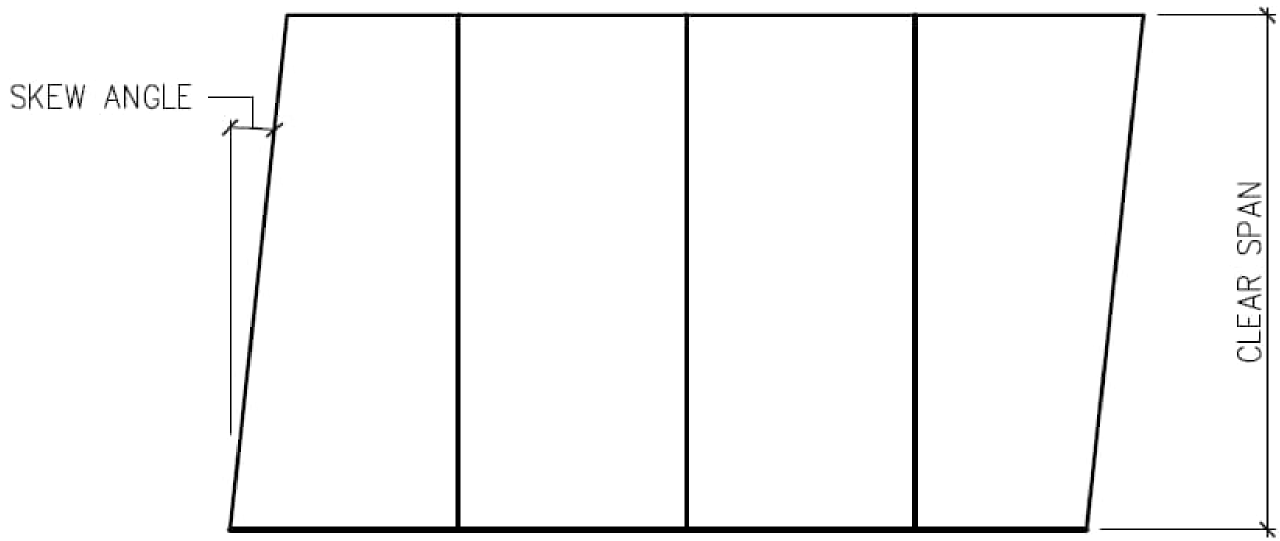
Demand Side

- Live Loads (Moving Loads)
  - Skewed Culverts – 2 cases with one subcase
  - Applicable up to 5’ of soil depth

Demand Side

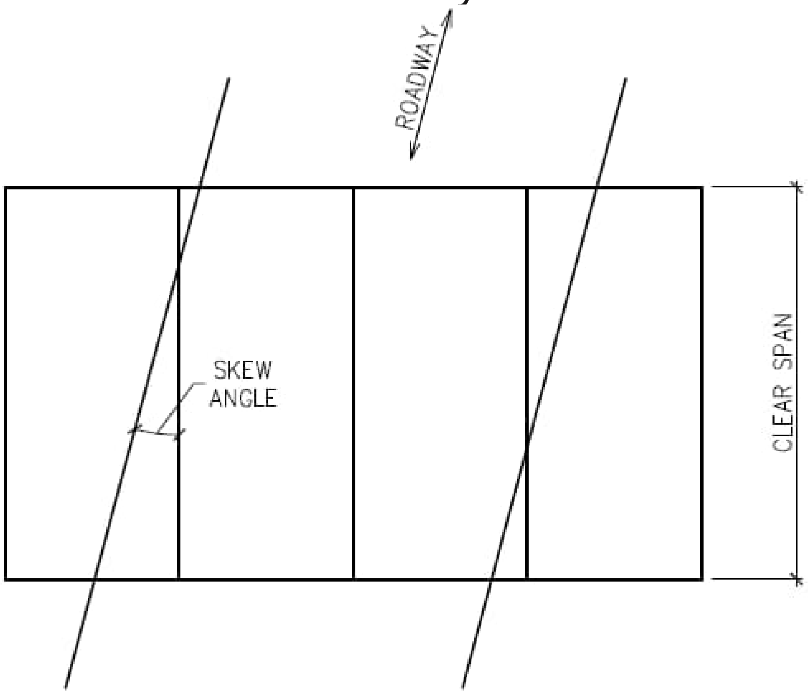
➢ Live Loads (Moving Loads)

- Skewed Culverts – 2 cases with one subcase
- Case 1 – Only the exterior culvert is skewed



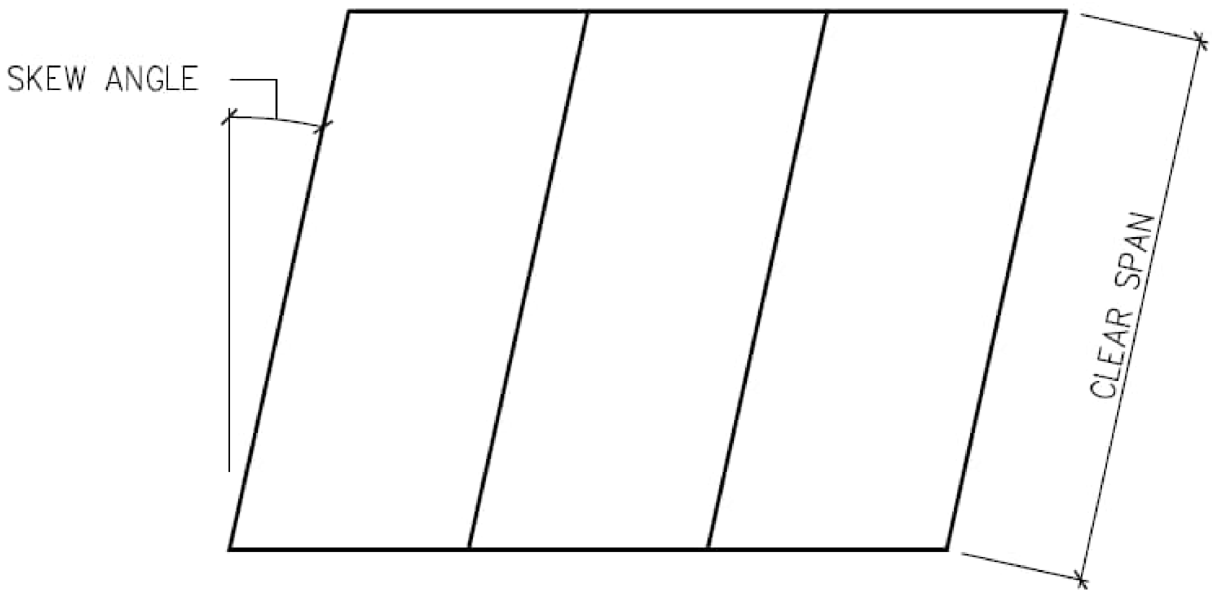
Demand Side

- Live Loads (Moving Loads)
  - Skewed Culverts – 2 cases with one subcase
  - Case 1a – Straight culvert with skewed roadway



Demand Side

- Live Loads (Moving Loads)
  - Skewed Culverts – 2 cases with 1 subcase
  - Case 2 – All culverts are skewed

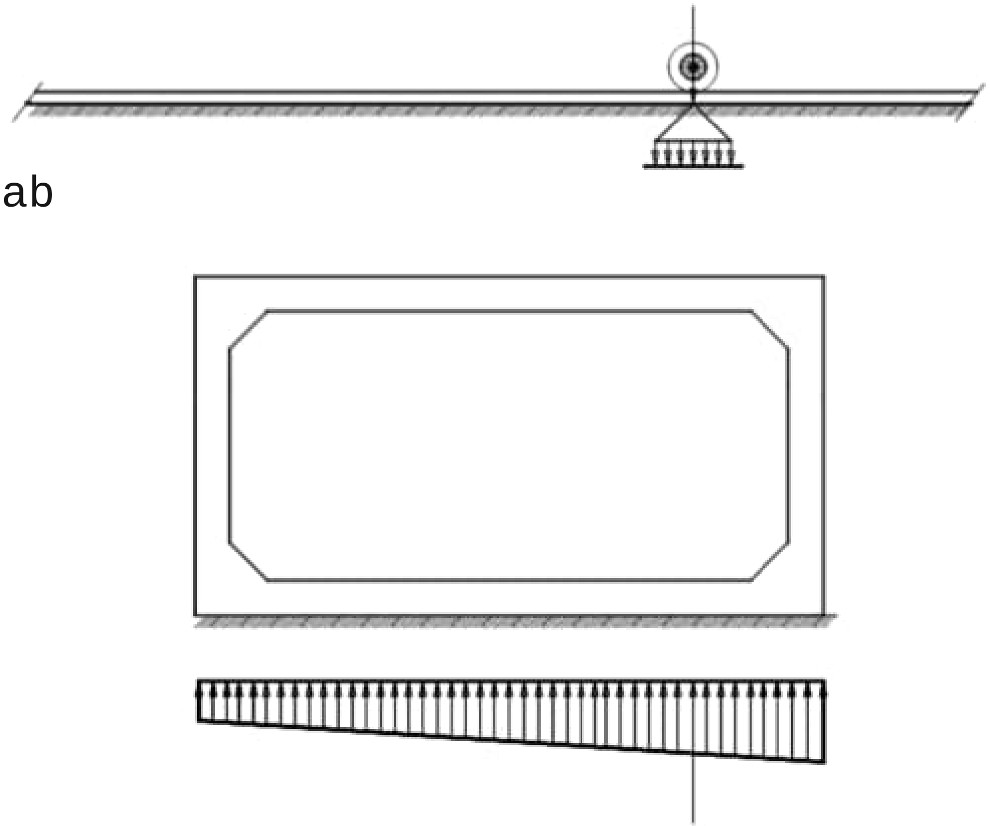


Demand Side

- Live Loads (Moving Loads)
  - Effect of moving load on bottom slab
  - Two options available

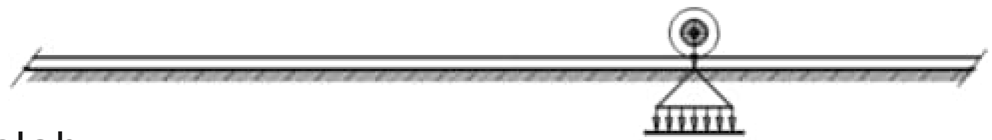
Demand Side

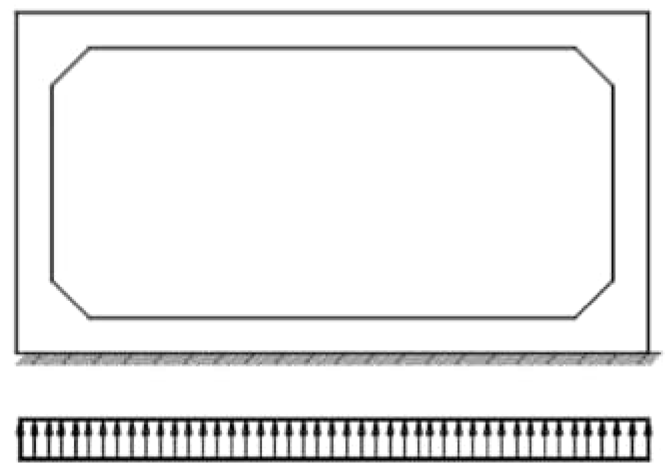
- Live Loads (Moving Loads)
  - Effect of moving loads on bottom slab
  - Two options available



Demand Side

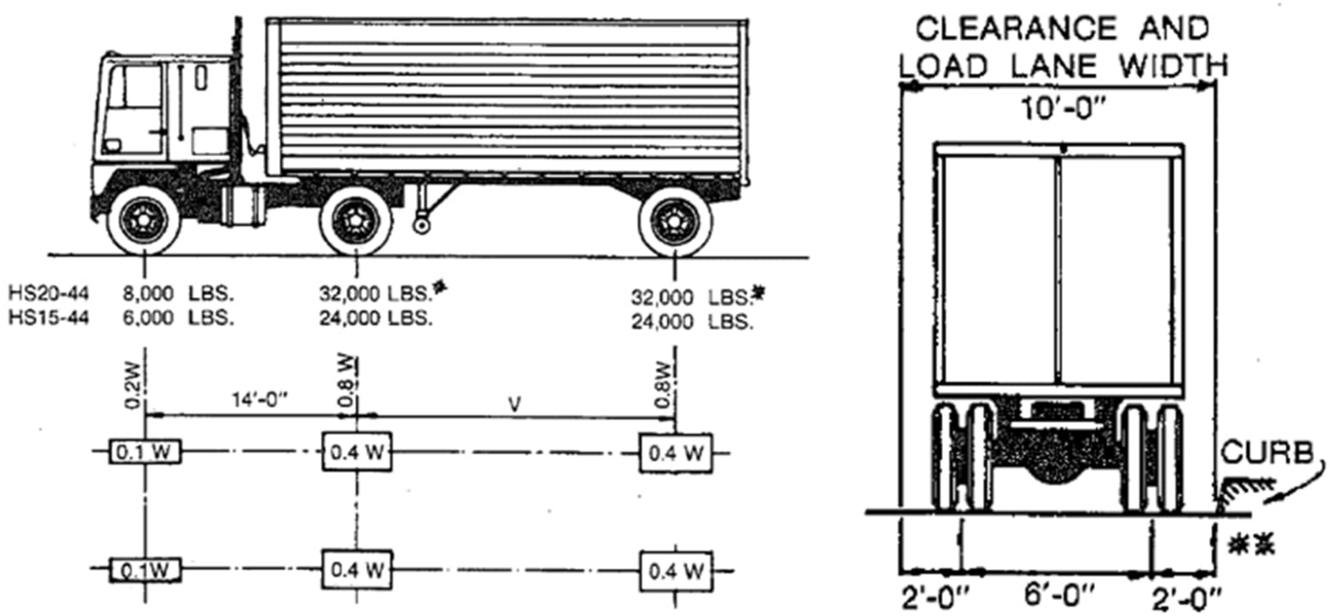
- Live Loads (Moving Loads)
  - Effect of moving loads on bottom slab
  - Two options available





Demand Side

- Live Loads (Moving Loads)
  - Truck Types
    - Design – HL-93



Demand Side

- Live Loads (Moving Loads)
  - Lane Loads

3.6.1.2.6—Distribution of Wheel Load through Earth Fills

3.6.1.2.6a—General

For traffic parallel to the span, culverts shall be analyzed for a single loaded lane with the single lane multiple presence factor. For traffic perpendicular to the culvert span, analysis shall include consideration of multiple lane loadings with appropriate multiple presence factors. Only the axle loads of the design truck or design tandem of Articles 3.6.1.2.2 and 3.6.1.2.3, respectively shall be applied as live load on culverts, regardless of traffic orientation.

Demand Side

- Live Loads (Moving Loads)
  - Truck Types
    - Design – HL-93
    - Permit
    - Legal

Demand Side

- Live Loads (Moving Loads)
  - Multiple Presence Factor (MPF)

Table 3.6.1.1.2-1—Multiple Presence Factors, *m*

Number of Loaded Lanes	Multiple Presence Factors, *m*
1	1.20
2	1.00
3	0.85
>3	0.65

Demand Side

- Live Loads (Moving Loads)
  - Multiple Presence Factor (MPF)
  - Impact Factor (IM) or Dynamic Load Allowance (DLA)

3.6.2.2—Buried Components

The dynamic load allowance for culverts and other buried structures covered by Section 12, in percent, shall be taken as:

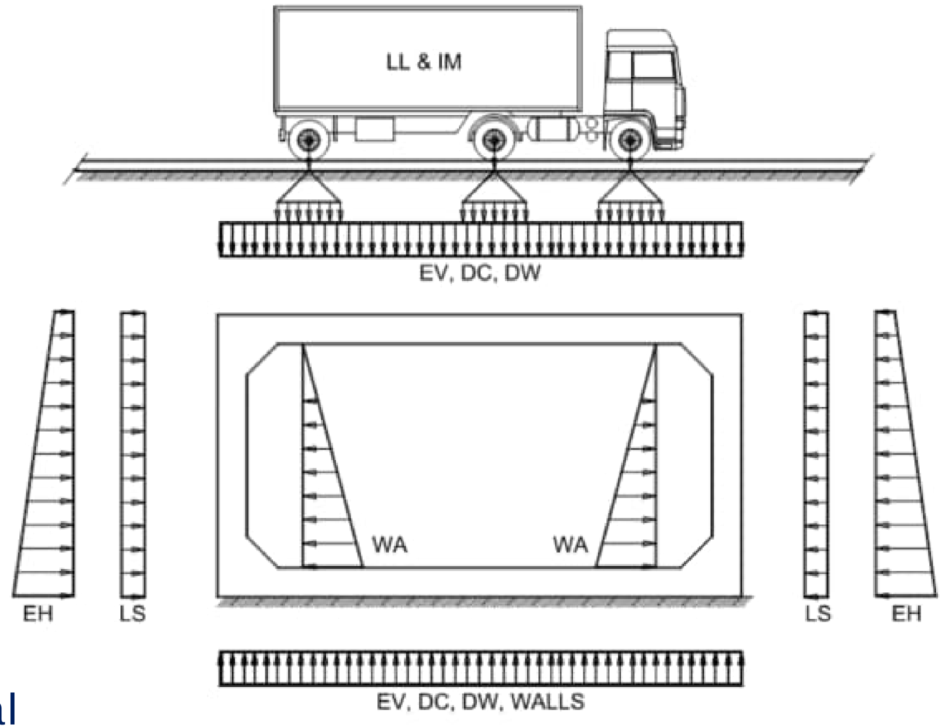
$$IM = 33(1.0 - 0.125D_E) \geq 0\% \qquad (3.6.2.2\text{-}1)$$

where:

D_E = the minimum depth of earth cover above the structure (ft)

Demand Side

- Load Combinations



C12.11.2.1

1. Maximum vertical + maximum horizontal
2. Maximum vertical + minimum horizontal
3. Minimum vertical + maximum horizontal
4. Minimum vertical + minimum horizontal (not checked)

ACPA

Demand Side

- Load Combinations

12.5.3—Strength Limit State

Buried structures and tunnel liners shall be investigated for construction loads and at Strength Load Combinations I and II, as specified in Table 3.4.1-1, as follows:

12.5.2—Service Limit State

Buried structures shall be investigated at Service Load Combination I, as specified in Table 3.4.1-1.

Demand Side

- Load Combinations
  - Achieved through use of AASHTO max/min load factors

Table 3.4.1-2—Load Factors for Permanent Loads, γ_p

Type of Load, Foundation Type, and Method Used to Calculate Downdrag		Load Factor	
		Maximum	Minimum
DC: Component and Attachments		1.25	0.90
DC: Strength IV only		1.50	0.90
DD: Downdrag	Piles, α Tomlinson Method	1.40	0.25
	Piles, λ Method	1.05	0.30
	Drilled shafts, O'Neill and Reese (2010) Method	1.25	0.35
DW: Wearing Surfaces and Utilities		1.50	0.65
EH: Horizontal Earth Pressure			
• Active		1.50	0.90
• At-Rest		1.35	0.90
• *AEP* for anchored walls		1.35	N/A
EL: Locked-in Construction Stresses		1.00	1.00
EV: Vertical Earth Pressure			
• Overall and Compound Stability		1.00	N/A
• Retaining Walls and Abutments		1.35	1.00
• MSE wall internal stability soil reinforcement loads			
○ Stiffness Method			
▪ Reinforcement and connection rupture		1.35	N/A
▪ Soil failure – geosynthetics (Service I)		1.20	N/A
○ Coherent Gravity Method		1.35	N/A
• Rigid Buried Structure		1.30	0.90
• Rigid Frames		1.35	0.90
• Flexible Buried Structures			
○ Metal Box Culverts, Structural Plate Culverts with Deep Corrugations, and Fiberglass Culverts		1.50	0.90
○ Thermoplastic Culverts		1.30	0.90
○ All others		1.95	0.90
• Internal and Compound Stability for Soil Failure in Soil Nail Walls		1.00	N/A
ES: Earth Surcharge		1.50	0.75

ACPA

Demand Side

- Load Combinations
  - Special case for lateral earth loads on culverts

3.11.7—Reduction Due to Earth Pressure

For culverts and bridges and their components where earth pressure may reduce effects caused by other loads and forces, such reduction shall be limited to the extent earth pressure can be expected to be permanently present. In lieu of more precise information, a 50 percent reduction may be used, but need not be combined with the minimum load factor specified in Table 3.4.1-2.

ACPA

Demand Side

- Load Combinations
  - Fatigue

5.5.3—Fatigue Limit State

5.5.3.1—General

Fatigue need not be investigated for concrete deck slabs in multigirder applications or reinforced-concrete box culverts.

Demand Side

- Load Modifiers

1.3.2.1—General

For loads for which a maximum value of γ_i is appropriate:

$$\eta_i = \eta_D \eta_R \eta_I \geq 0.95 \qquad (1.3.2.1\text{-}2)$$

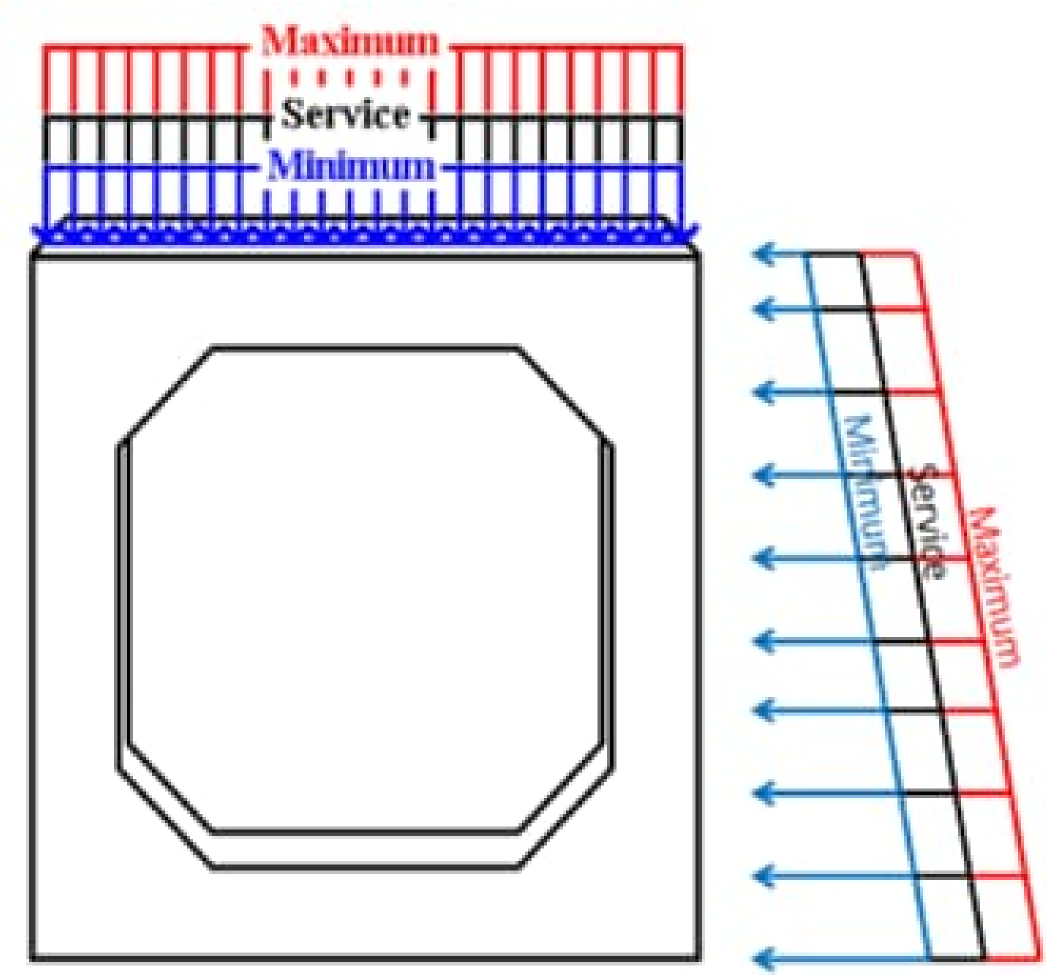
For loads for which a minimum value of γ_i is appropriate:

$$\eta_i = \frac{1}{\eta_D \eta_R \eta_I} \leq 1.0 \qquad (1.3.2.1\text{-}3)$$

ACPA

Demand Side

- Final Demand



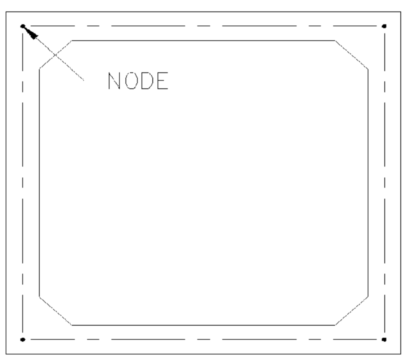
Capacity Side

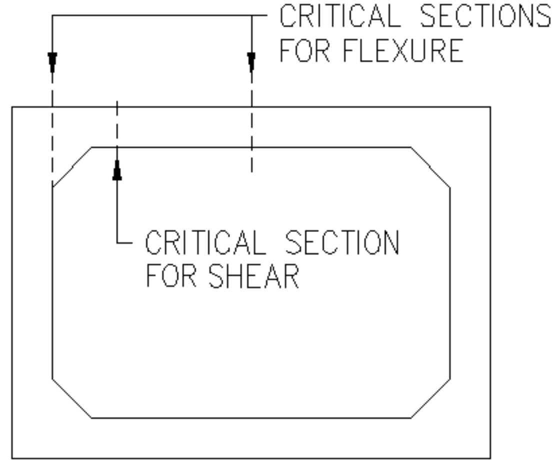
$$\sum \eta_i \gamma_i Q_i \leq \phi R_n = R_r$$

Demand **≤** Capacity

Capacity Side

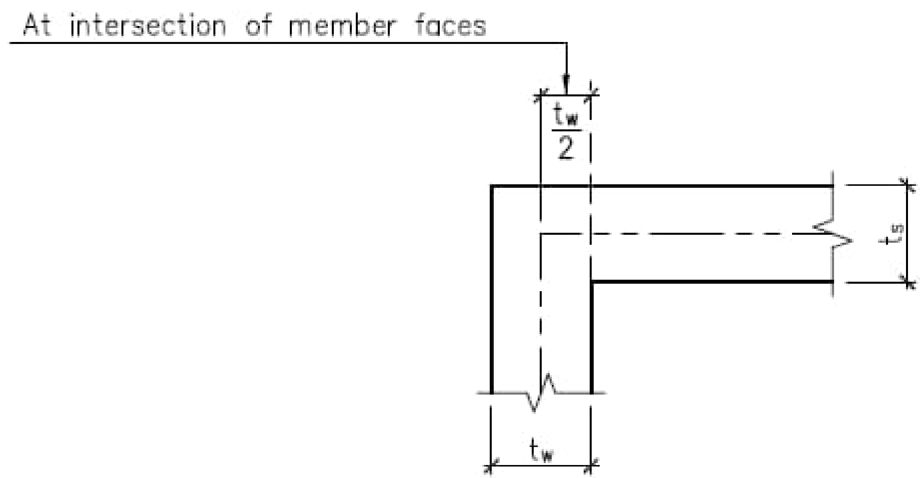
- Critical Sections
  - Flexure
    - Typically checked at three places per member
    - Determines amount of reinforcement
  - Shear
    - Typically checked at two places per member
    - Determines member thickness





Capacity Side

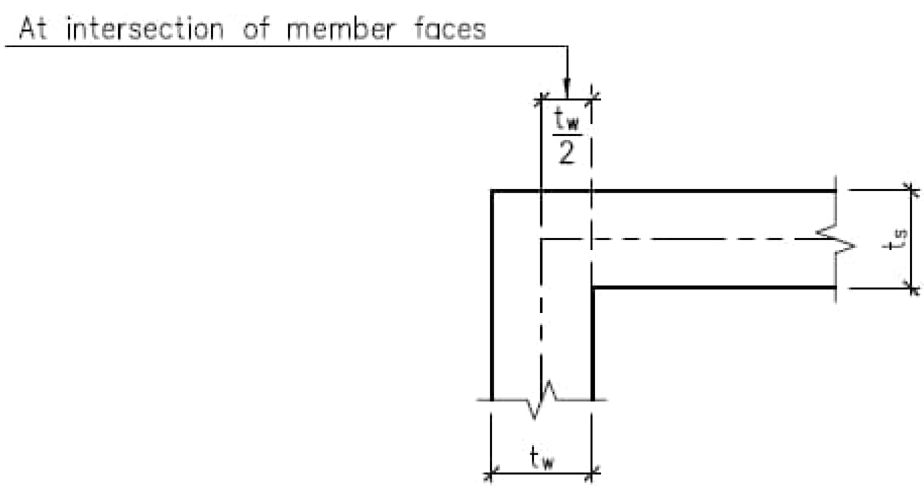
- Critical Sections for Flexure (3 Locations)



Haunches not included

Capacity Side

- Critical Sections for Flexure (3 Locations)



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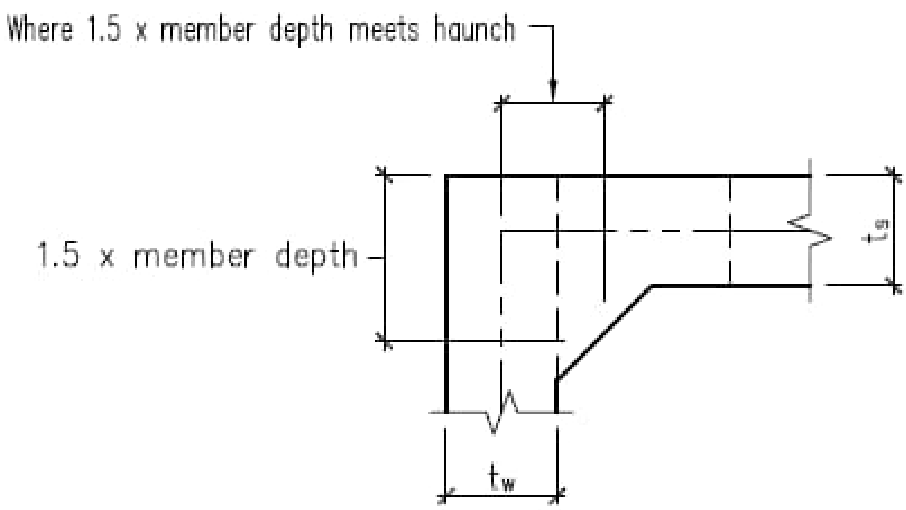
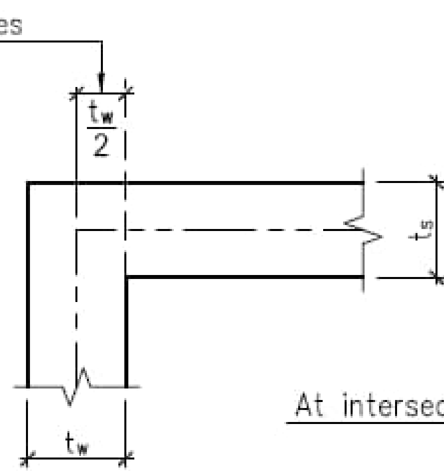


Haunches included

Capacity Side

- Critical Sections for Flexure (3 Locations)



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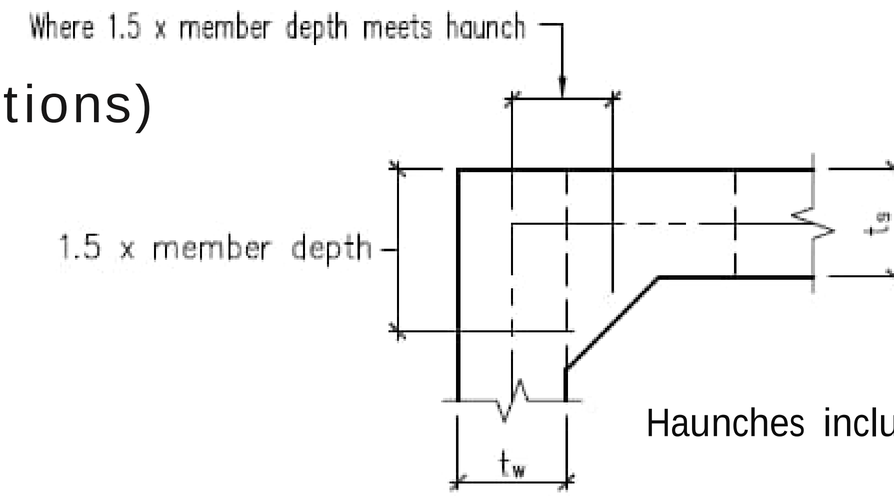

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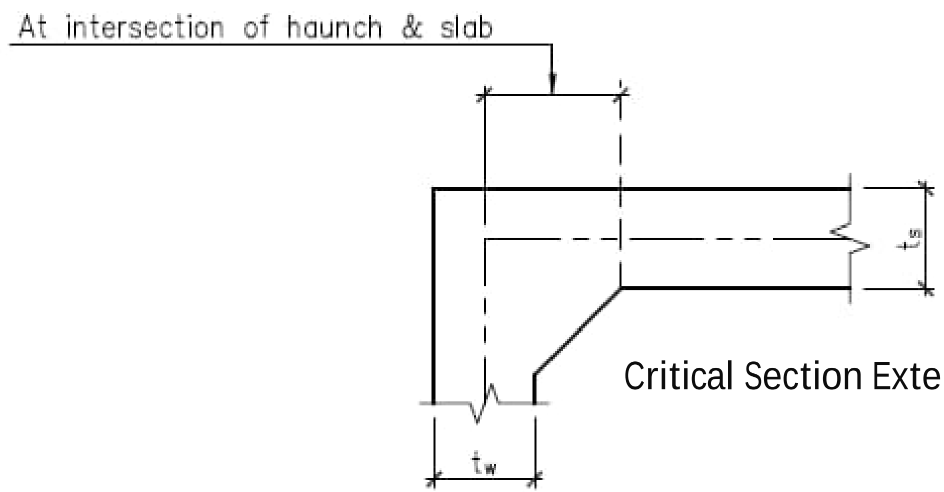
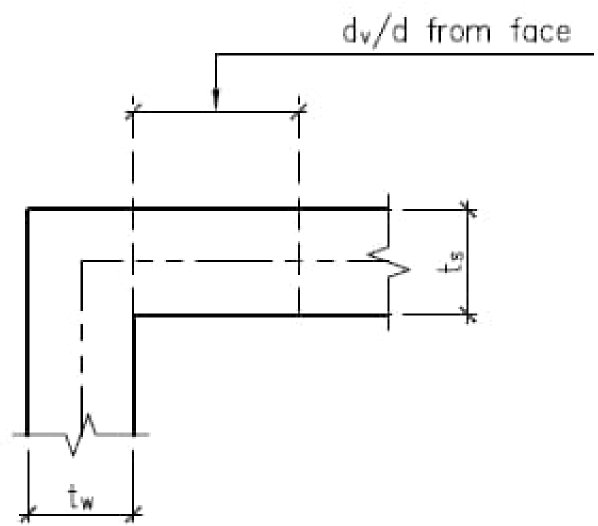


Critical Section Extended

Capacity Side

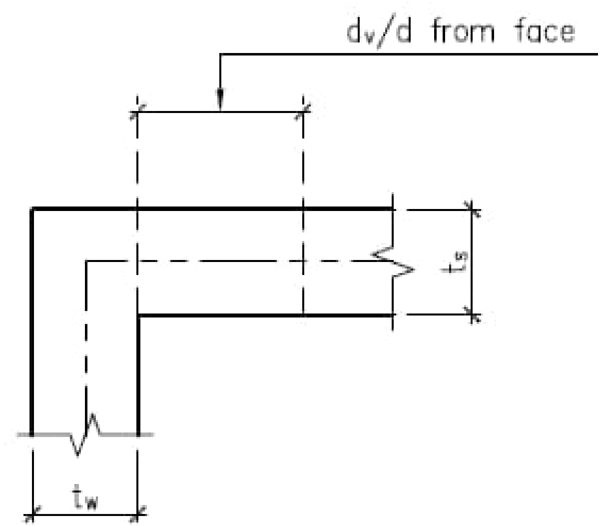
- Critical Sections for Shear (2 Locations)



Haunches not included

Capacity Side

- Critical Sections for Shear (2 Locations)



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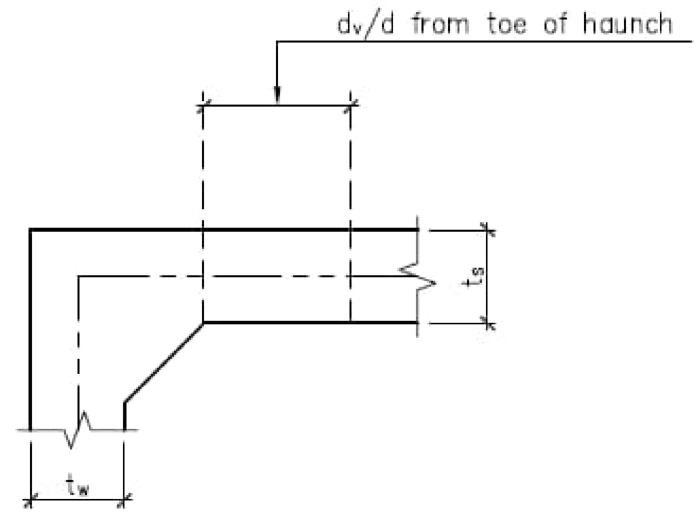


Haunches Included and Critical Section Extended

Capacity Side

- Calculation of d_v

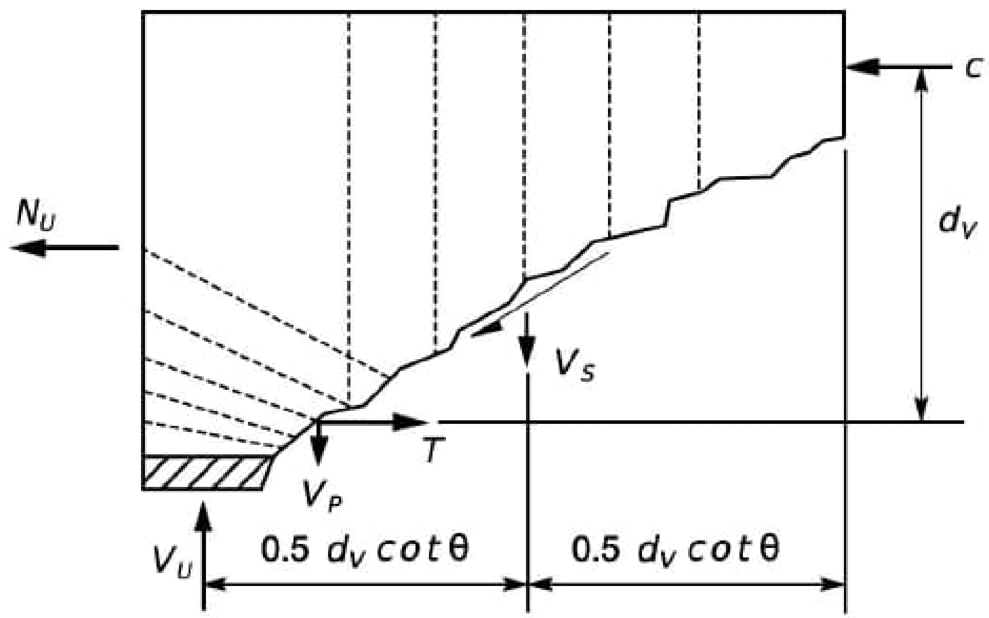


Figure C5.7.3.5-1—Forces Assumed in Resistance Model Caused by Moment and Shear

Capacity Side

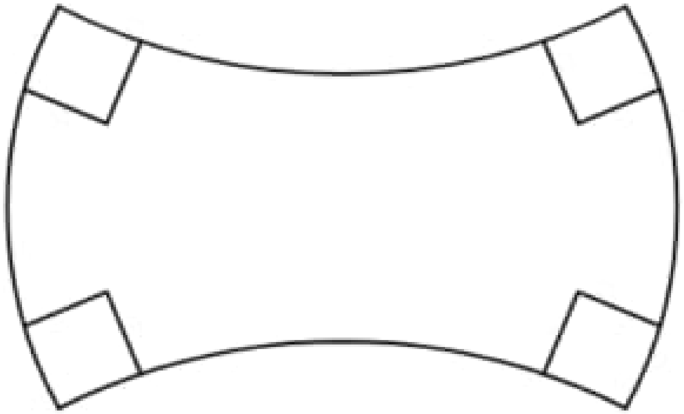
- Resistance Factors

1.3.2.1—General

ϕ = resistance factor: a statistically based multiplier applied to nominal resistance, as specified in Sections 5, 6, 7, 8, 10, 11, and 12

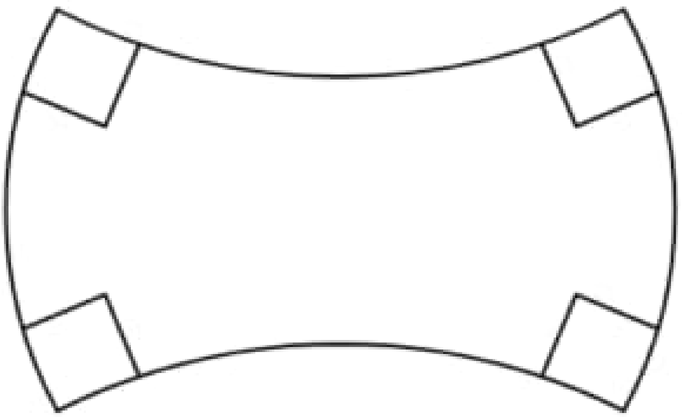
Capacity Side

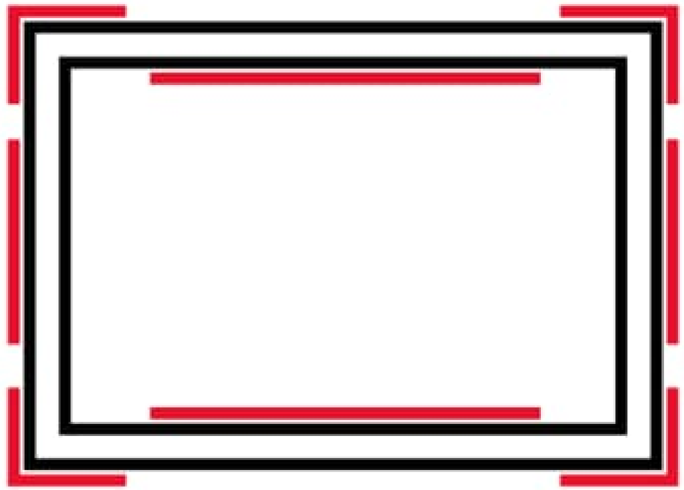
- Tension Zones



Capacity Side

- Tension Zones



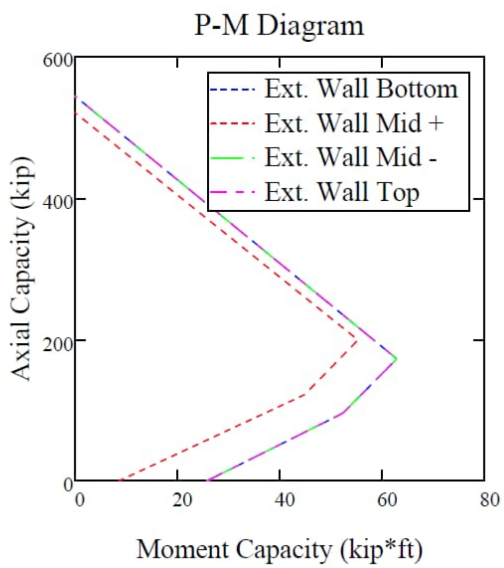


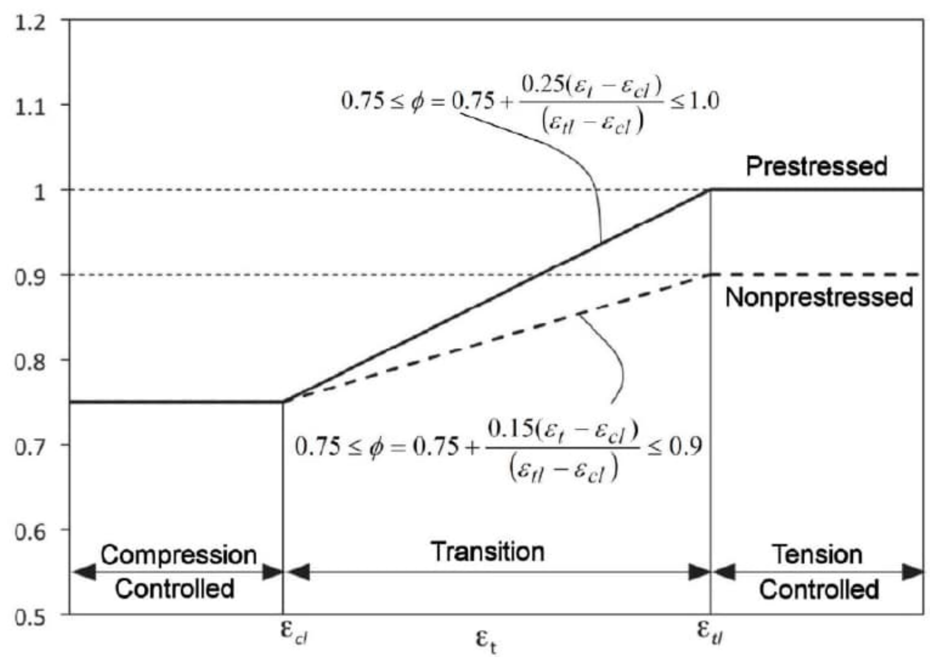
Capacity Side

- Flexural Capacity Methods
  - Two methods available

Capacity Side

- Flexural Capacity Methods
  - P-M Diagrams
  - Include axial loads in capacity





Capacity Side

- Flexural Capacity Methods
  - Also allowed to use Section 12.10.4.2.4a

12.11.3—Strength Limit State

The provisions of Article 12.10.4.2.4a may be applied to the flexural strength design of slabs and walls of reinforced concrete cast-in-place and precast box culverts and reinforced cast-in-place arches.

ACPA

Capacity Side

- Flexural Capacity Methods
  - Also allowed to use Section 12.10.4.2.4a
  - Which send us to this equation (commonly referred to as the Pipe Equation)

12.10.4.2.4—Flexural Resistance at the Strength Limit State

12.10.4.2.4a—Circumferential Reinforcement

Reinforcement for flexural resistance provided in a length, b, usually taken as 12.0 in., shall satisfy:

$$A_s \geq \frac{g\phi d - N_u - \sqrt{g\left[g(\phi d)^2 - N_u(2\phi d - h) - 2M_u\right]}}{f_y}$$

(12.10.4.2.4a-1)

Table 12.5.5-1—Resistance Factors for Buried Structures

Reinforced Concrete Precast Box Structures	
• Flexure	1.00
• Shear	0.90

ACPA

Capacity Side

- Flexural Capacity Methods
  - Maximum reinforcement ratio

- For reinforcing steel in compression:

$$A_{smax} \leq \frac{\left[\left(\frac{55g'\phi d}{87+f_y}\right) - 0.75N_u\right]}{f_y}$$

(12.10.4.2.4c-2)

Capacity Side

- Shear Capacity Methods
  - Several methods available

Capacity Side

- Shear Capacity Methods
  - Basic Shear Equation

$$V_c = 0.0316\beta\lambda\sqrt{f'_c}\ b_v d_v \qquad (5.7.3.3\text{-}3)$$

Capacity Side

- Shear Capacity Methods
  - Constant Beta (b)   b = 2.0

5.7.3.4.1—Simplified Procedure for Nonprestressed Sections

For concrete footings in which the distance from point of zero shear to the face of the column, pier, or wall is less than $3d_v$ with or without transverse reinforcement, and for other nonprestressed concrete sections not subjected to axial tension and containing at least the minimum amount of transverse reinforcement specified in Article 5.7.2.5, or having an overall depth of less than 16.0 in., the following values may be used:

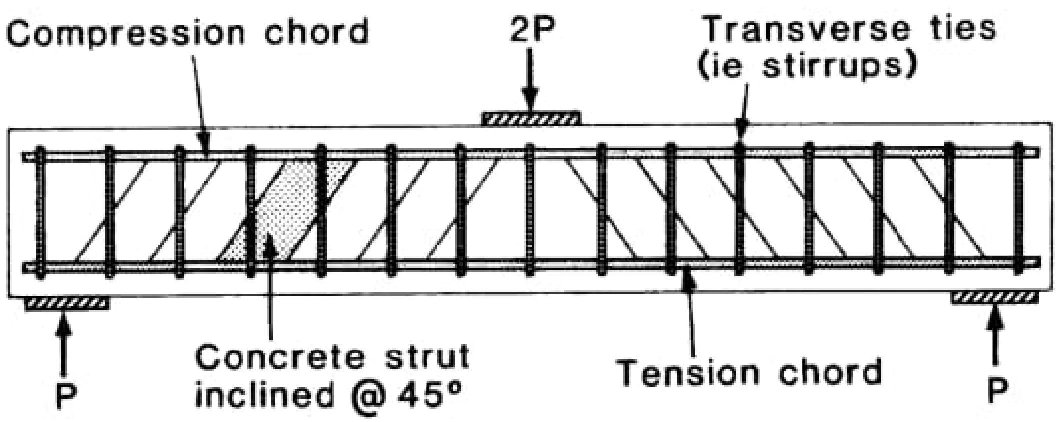
$$\beta = 2.0$$

Capacity Side

- Shear Capacity Methods
  - Interactive Beta (Modified Compression Field Theory)
  - Direct Beta (Modified Compression Field Theory)

Capacity Side

- Shear Capacity Methods
  - Interactive Beta (Modified Compression Field Theory)
  - Direct Beta (Modified Compression Field Theory)



Capacity Side

- Shear Capacity Methods
  - Interactive Beta (Modified Compression Field Theory)
  - Direct Beta (Modified Compression Field Theory)

$$\beta = \frac{4.8}{(1+750\varepsilon_s)}\frac{51}{(39+s_{xe})} \qquad (5.7.3.4.2\text{-}2)$$

Capacity Side

- Shear Capacity Methods
  - Interactive Beta (Modified Compression Field Theory)
  - Direct Beta (Modified Compression Field Theory)

$$\beta = \frac{4.8}{(1+750\varepsilon_s)} \frac{51}{(39+s_{xe})} \quad (5.7.3.4.2\text{-}2)$$

$$s_{xe} = s_x \frac{1.38}{a_g + 0.63} \quad (5.7.3.4.2\text{-}7)$$

s_x = crack spacing parameter, taken as the lesser of either d_v or the maximum distance between layers of longitudinal crack control reinforcement, where the area of the reinforcement in each layer is not less than $0.003 b_v s_x$, as shown in Figure 5.7.3.4.2-3 (in.)

Capacity Side

- Shear Capacity Methods
  - Interactive Beta (Modified Compression Field Theory)
  - Direct Beta (Modified Compression Field Theory)

$$\varepsilon_s = \frac{\left(\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps} f_{po}\right)}{E_s A_s + E_p A_{ps}} \qquad (5.7.3.4.2\text{-}4)$$

$$\beta = \frac{4.8}{(1 + 750\varepsilon_s)} \frac{51}{(39 + s_{xe})} \qquad (5.7.3.4.2\text{-}2)$$

$$s_{xe} = s_x \frac{1.38}{a_g + 0.63} \qquad (5.7.3.4.2\text{-}7)$$

s_x = crack spacing parameter, taken as the lesser of either d_v or the maximum distance between layers of longitudinal crack control reinforcement, where the area of the reinforcement in each layer is not less than $0.003 b_v s_x$, as shown in Figure 5.7.3.4.2-3 (in.)

Capacity Side

- Shear Capacity Methods
  - Special Provision for Box Culverts (Beta = 3.0)

5.12.7.3—Design for Shear in Slabs of Box Culverts

The provisions of Article 5.7 apply unless modified herein. For slabs of box culverts under 2.0 ft or more fill, nominal shear resistance V_c may be determined as the lesser of the following:

$$V_c = \left(0.0676\lambda\sqrt{f'_c} + 4.6\frac{A_s}{bd_e}\frac{V_u d_e}{M_u}\right)bd_e \qquad (5.12.7.3\text{-}1)$$

$$V_c \leq 0.126\lambda\sqrt{f'_c}\,bd_e \qquad (5.12.7.3\text{-}2)$$

For single-cell box culverts only, V_c for slabs monolithic with walls need not be taken to be less than $0.0948\lambda\sqrt{f'_c}bd_e$, and V_c for slabs simply supported need

Capacity Side

- Shear Reinforcement

$$V_n = V_c + V_s \qquad (5.7.3.3\text{-}1)$$

$$V_s = \frac{A_v f_y d_v (\cot\theta + \cot\alpha)\sin\alpha}{s}\lambda_{duct} \qquad (5.7.3.3\text{-}4)$$

Where α = 90 degrees, Eq. 5.7.3.3-4 reduces to:

$$V_s = \frac{A_v f_y d_v \cot\theta}{s}\lambda_{duct} \qquad (C5.7.3.3\text{-}1)$$

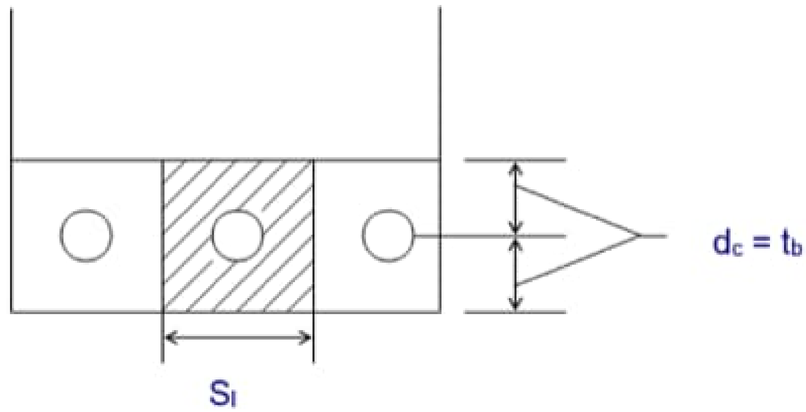
ACPA

Capacity Side

- Shear Reinforcement
  - Stirrup spacing is important

Capacity Side

- Serviceability
  - Crack Control



Capacity Side

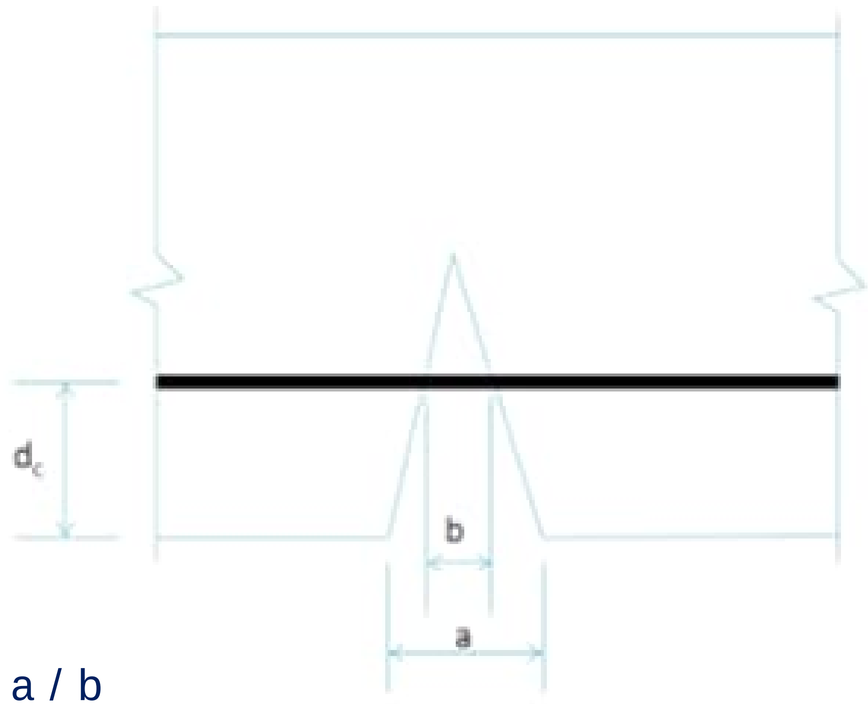
- Serviceability
  - Crack Control – Basic Equation

5.6.7—Control of Cracking by Distribution of Reinforcement

$$s \leq \frac{700\gamma_e}{\beta_s f_{ss}} - 2d_c \qquad (5.6.7\text{-}1)$$

Capacity Side

- Serviceability
  - Crack Control – $\mathbf{b}_s$ Term



$\beta_s = a / b$

Capacity Side

- Serviceability
  - Crack Control – Stress Limits in Reinforcement

$$f_s = \frac{M_s + N_s\left(d - \frac{h}{2}\right)}{(A_s jid)} \qquad \text{(C12.11.4-1)}$$

f_{ss} = calculated tensile stress in nonprestressed reinforcement at the service limit state not to exceed 0.60 f_y (ksi)

Capacity Side

- Serviceability
  - Crack Control – Exposure Factor

5.6.7—Control of Cracking by Distribution of Reinforcement

γ_e = exposure factor
= 1.00 for Class 1 exposure condition
= 0.75 for Class 2 exposure condition

Capacity Side

- Serviceability
  - Top Slab Deflection

12.14—PRECAST REINFORCED CONCRETE THREE-SIDED STRUCTURES

12.14.5.9—Deflection Control at the Service Limit State

The deflection limits for concrete structures specified in Article 2.5.2.6.2 shall be taken as mandatory and pedestrian usage as limited to urban areas.

Capacity Side

- Minimum Reinforcement

Capacity Side

- Minimum Reinforcement
  - Temperature and Shrinkage Steel

12.11.5.3.2—Precast Box Structures

Where the fabricated length exceeds 16.0 ft, the minimum reinforcement shall also meet the requirements of Article 5.10.6.

Capacity Side

- Minimum Reinforcement
  - Temperature and Shrinkage Steel
  - Circumferential Reinforcement

12.11.5.3.2—Precast Box Structures

At all box culvert cross-sections subjected to flexural tension, the minimum reinforcement area shall be not less than 0.002 times the gross concrete area.

ACPA

Capacity Side

- Minimum Reinforcement
  - Temperature and Shrinkage Steel
  - Circumferential Reinforcement
  - Distribution Reinforcement

12.11.5.3.2—Precast Box Structures

For top slabs of box culverts having less than 2.0 ft of cover, the bottom longitudinal reinforcement area shall be the greater of the distribution reinforcement required per Article 9.7.3.2 or 0.002 times the gross concrete area.

Capacity Side

- Minimum Reinforcement
  - Temperature and Shrinkage Steel
  - Circumferential Reinforcement
  - Distribution Reinforcement
  - Longitudinal Reinforcement

12.11.5.3.2—Precast Box Structures

For all other longitudinal reinforcement, the minimum longitudinal reinforcement area shall not be less than 0.03 $in.^2/ft$ at each face.

ACPA

Capacity Side

- Maximums
  - Steel yields
  - Concrete Strengths

12.4.2.7—Steel Reinforcement

The nominal yield strength shall be the minimum as specified for the grade of steel selected, but shall not exceed 80 ksi.

5.4.2.1—Compressive Strength

Design concrete compressive strengths above 10.0 ksi for normal weight concrete shall be used only when allowed by specific articles or when physical tests are made to establish the relationships between the concrete strength and other properties. Concrete with

Load Ratings

- What is a Load Rating?

Load Ratings

- What is a Load Rating?
  - “Units of live load that can be supported by a bridge or structure before that structure reaches a defined limit state”

Load Ratings

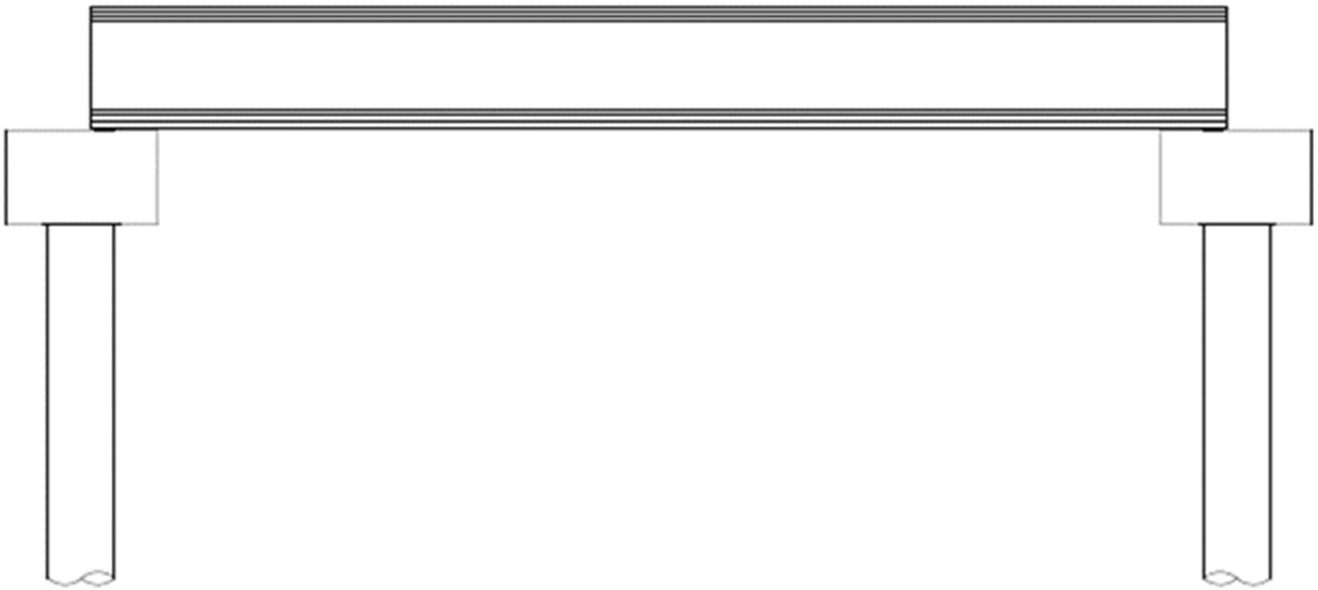
- What is a Limit State?

Load Ratings

- What is a Limit State?
  - (from LRFD) - "A condition beyond which the bridge or component ceases to satisfy the provisions for which it was designed."

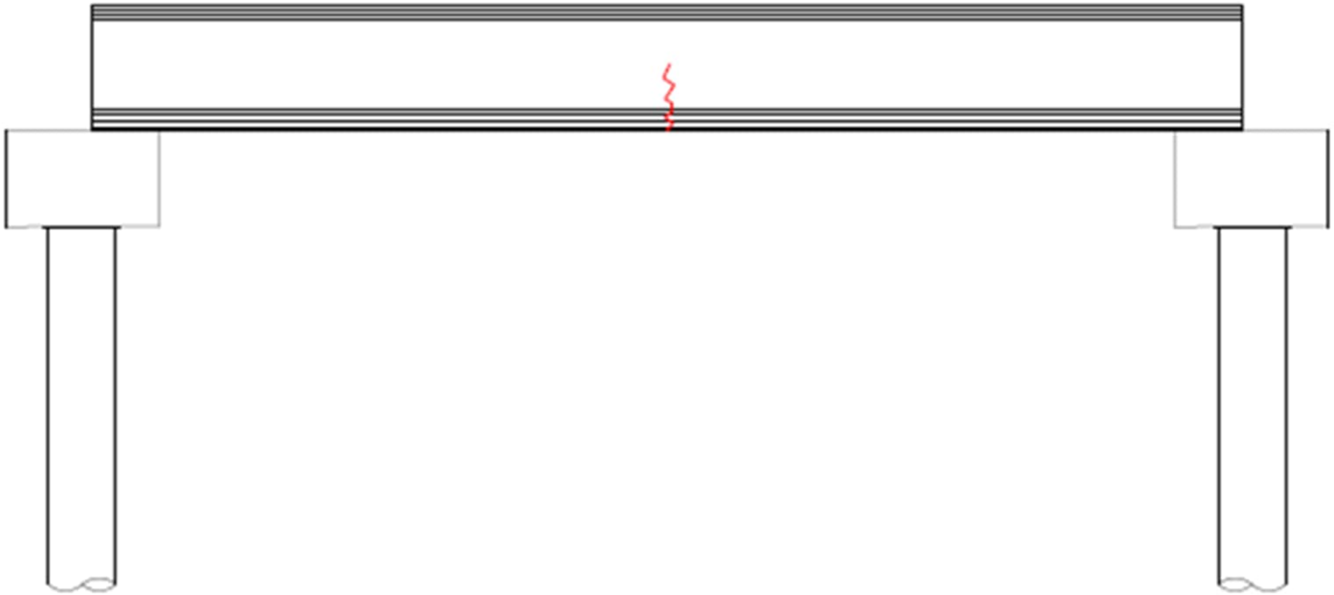
Load Ratings

- Simple Example



Load Ratings

- Simple Example

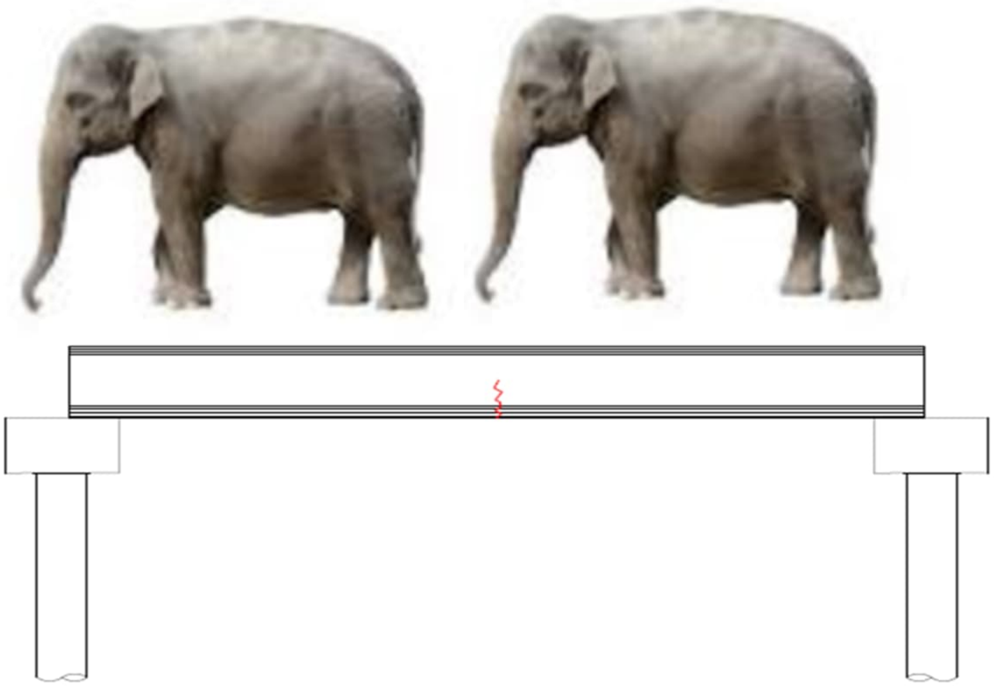


Load Ratings

- Simple Example

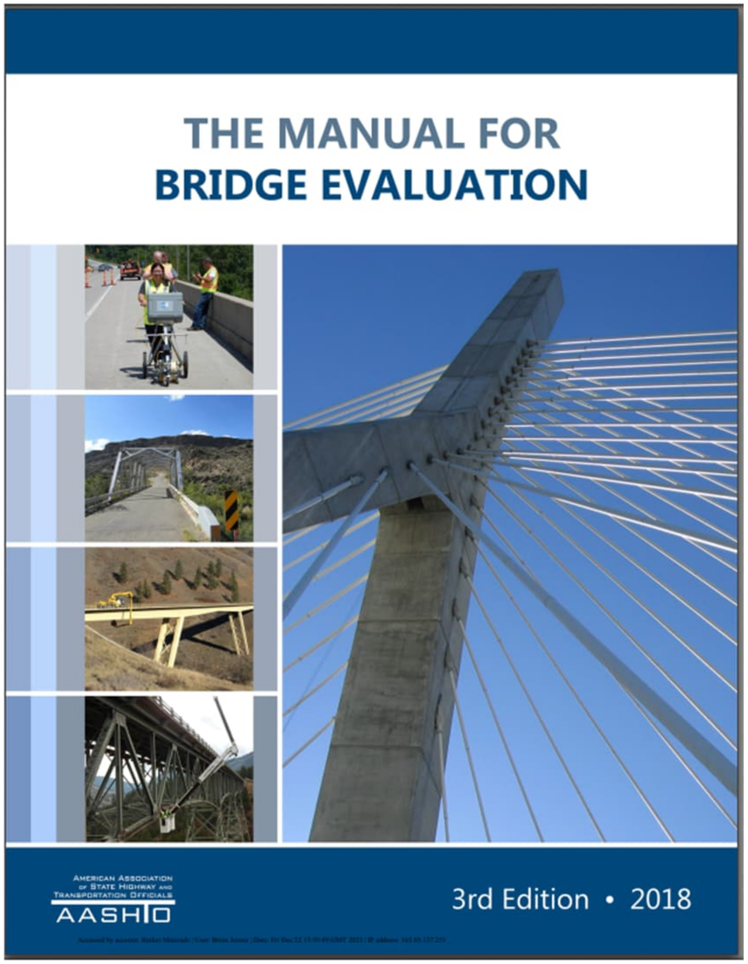
Load Ratings

- Simple Example



Load Ratings

- Where are Load Ratings defined?



Load Ratings

- In simple terms, the rating equation is:
  - RF = (C-DL) / LL
  - C = Capacity of the bridge element
  - DL = Dead Load Effects (all non-live load)
  - LL = Live Load Effects (based on 1’ unit of LL)

Load Ratings

- In actuality, the rating equation is:
  - RF = (C-DL) / LL

$$RF = \frac{C \pm \gamma_{DC} DC \pm \gamma_{DW} DW \pm \gamma_{EV} EV \pm \gamma_{EH} EH \pm \gamma_{ES} ES}{(\gamma_{LL})(LL + IM) \pm (\gamma_{LS})(LS)} \qquad (6A.5.12.4\text{-}1)$$

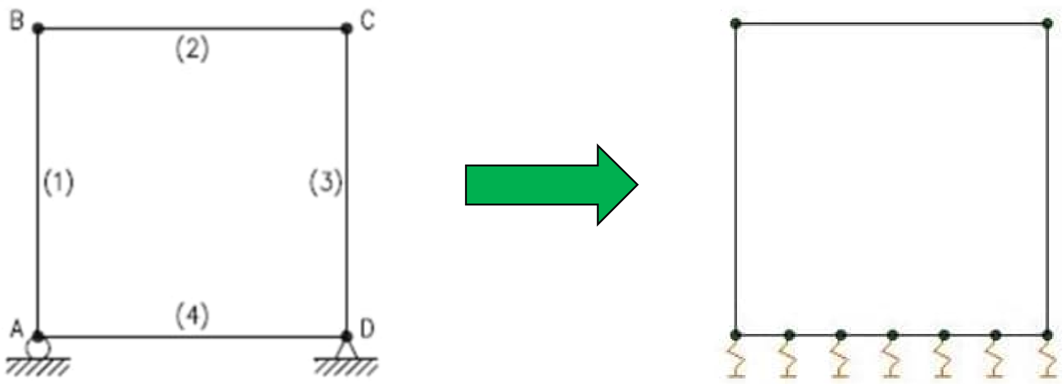
ACPA

Load Ratings

- What control do you have?
  - Flexure and shear critical sections (C)
  - Flexure and Shear capacities (C)
  - Rating Factors (applied to LL force effects)
  - Load Factors (applied to DL force effects)

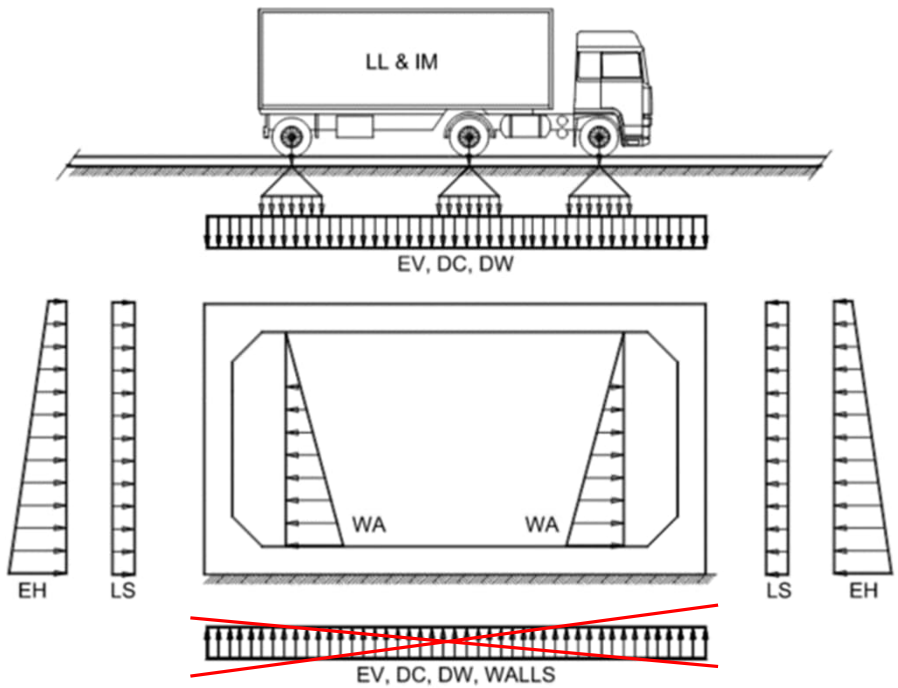
Advanced Topics

- Flexible Foundation
  - Replace pin-roller with springs



Advanced Topics

➢ Flexible Foundation
  - Loads on the bottom slab are removed



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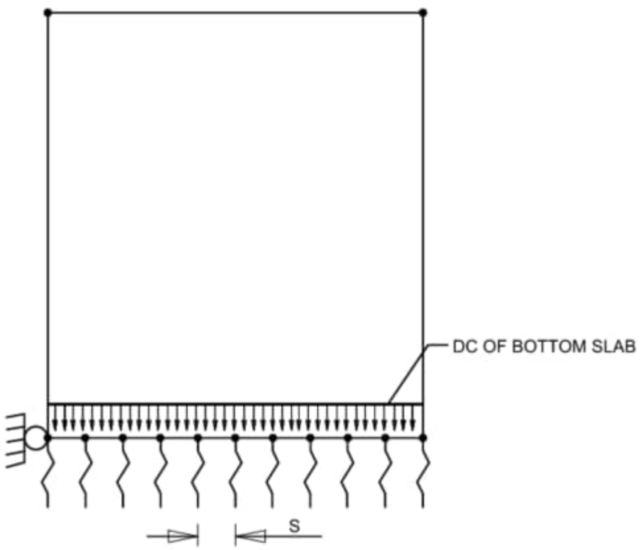
Advanced Topics

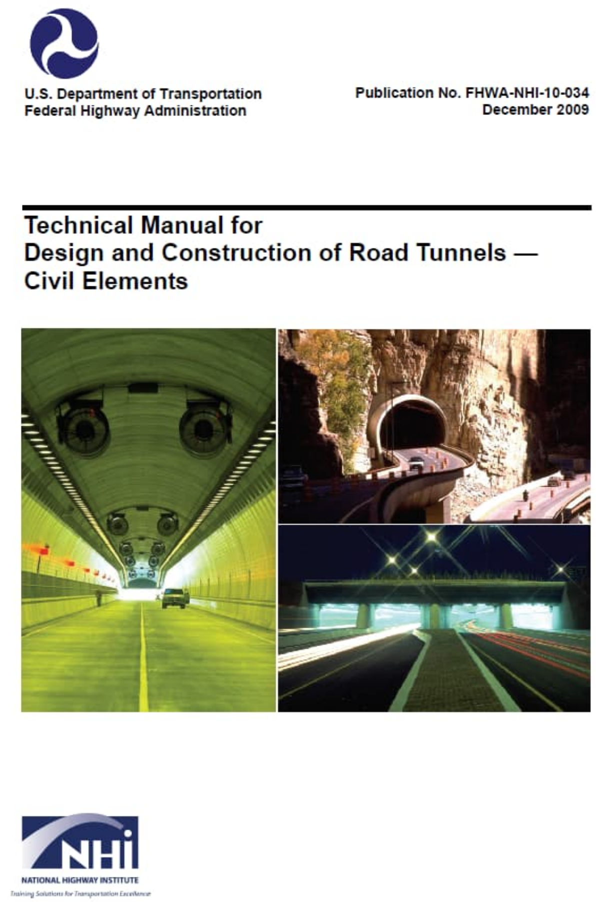
- Flexible Foundation
  - Spring stiffness based on soil subgrade modulus
  - Must account for the weight of the bottom slab



Spring Stiffness = k * s * b

Advanced Topics

- Seismic Analysis
  - Base document from FHWA


U.S. Department of Transportation
Federal Highway Administration

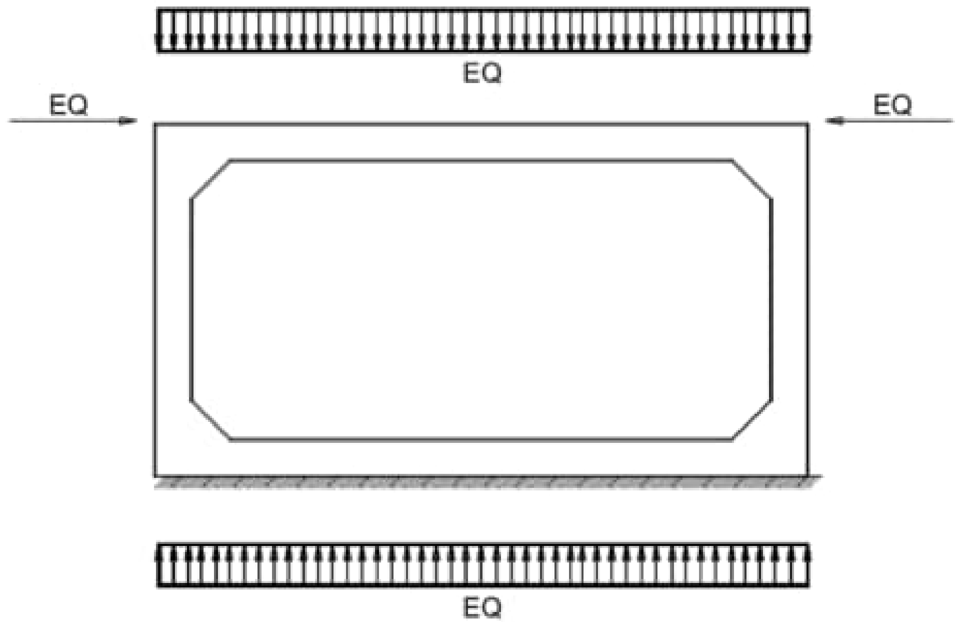
Publication No. FHWA-NHI-10-034
December 2009

Technical Manual for
Design and Construction of Road Tunnels —
Civil Elements

NATIONAL HIGHWAY INSTITUTE

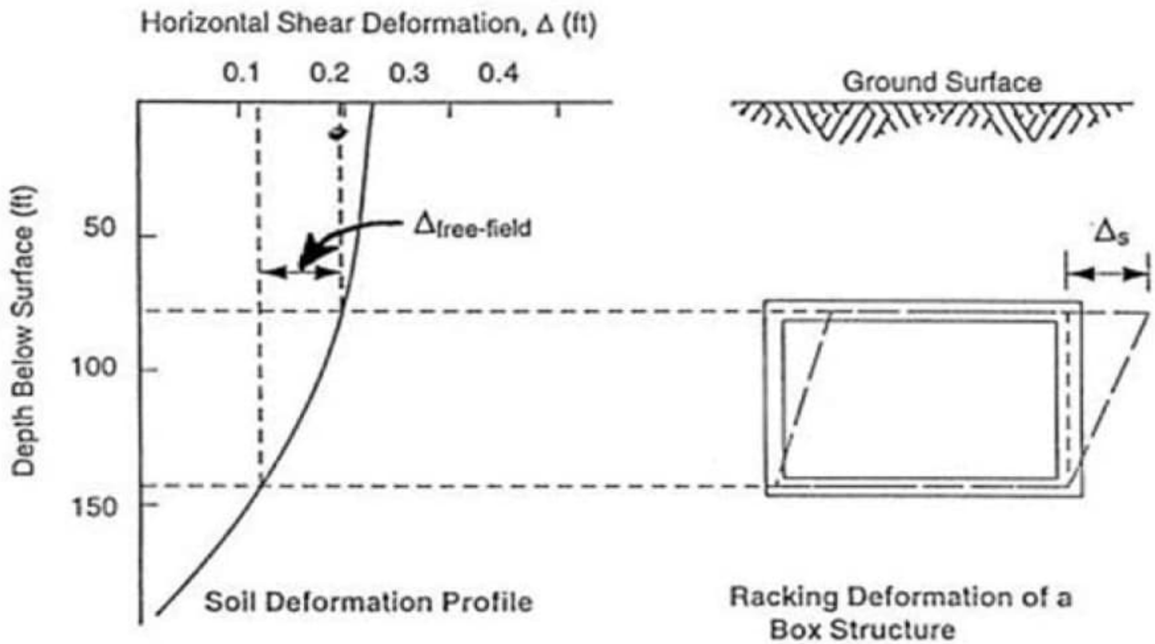
Advanced Topics

- Seismic Analysis
  - Base document from FHWA
  - Horizontal and Vertical Components



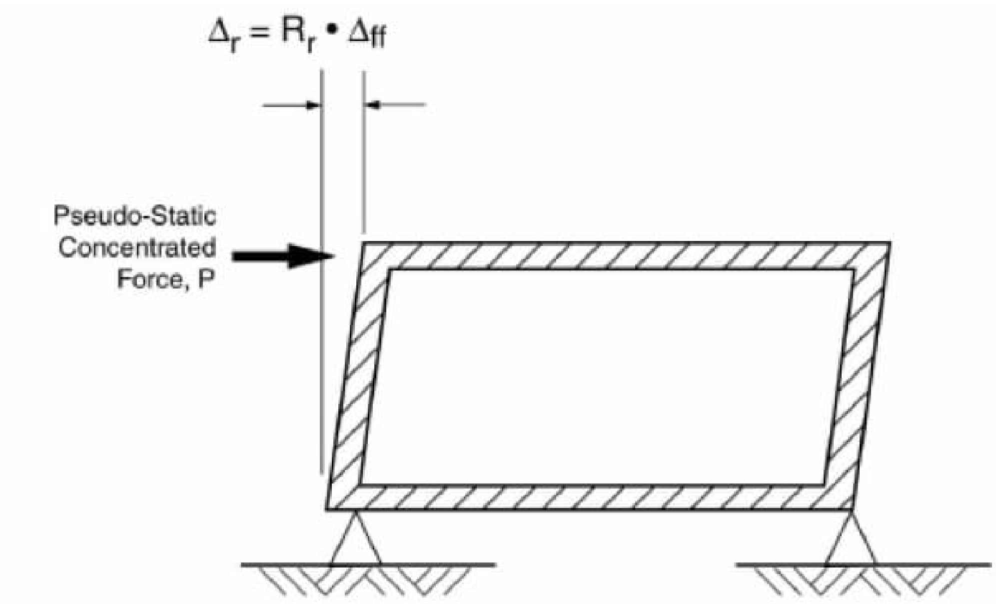
Advanced Topics

- Seismic Analysis
  - Horizontal component is a racking analysis



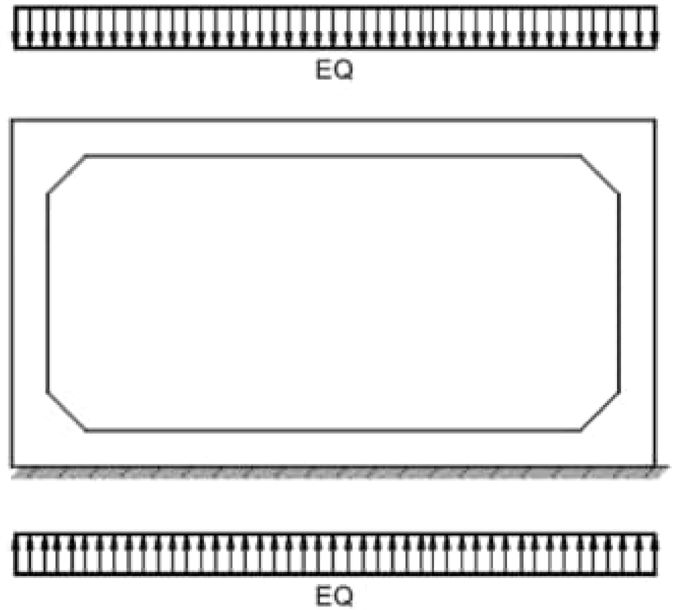
Advanced Topics

- Seismic Analysis
    - Horizontal component is a racking analysis



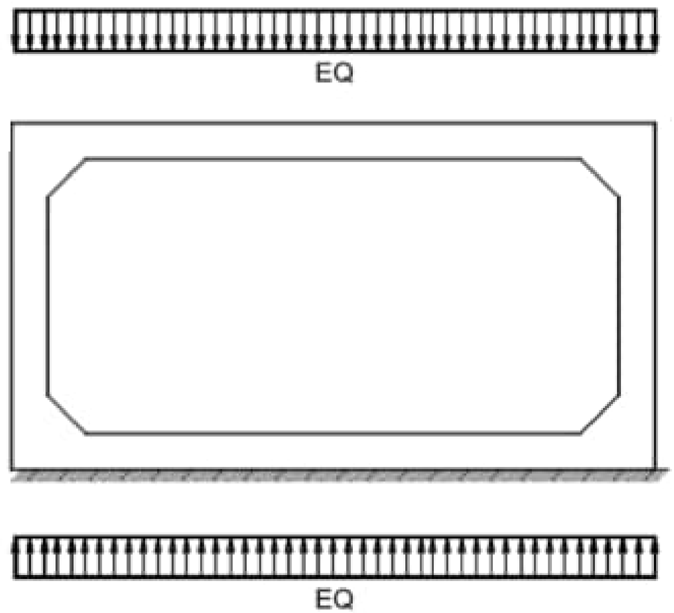
Advanced Topics

- Seismic Analysis
  - Vertical Component is much simpler



Advanced Topics

- Seismic Analysis
  - Vertical Component is much simpler
  - EQ = (EV + DC) * 2/3 * PGA



Advanced Topics

- Seismic Analysis
  - Both horizontal and vertical components are reduced based on the depth of the structure

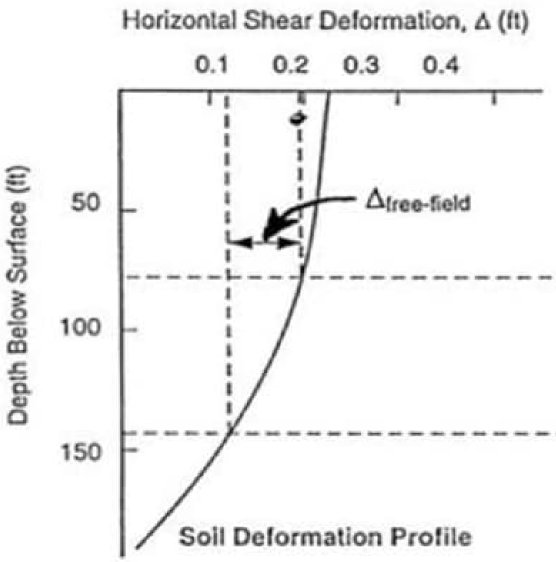


Table 13-1 Ground Motion Attenuation with Depth

Tunnel Depth (m)	Ratio Of Ground Motion At Tunnel Depth To Motion At Ground Surface
≤ 6	1.0
6 -15	0.9
15 -30	0.8
≥ 30	0.7

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Eriksson Culvert Design Example

- Box Culvert Design Requirements
  - Single Cell Box Culvert
  - 10’ Span x 10’ Rise
  - 2’ – 5’ fill over box culvert
  - HL93 Live Load

Thank you for the opportunity to present to you today!

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ACPA
American Concrete Pipe Association