Piers

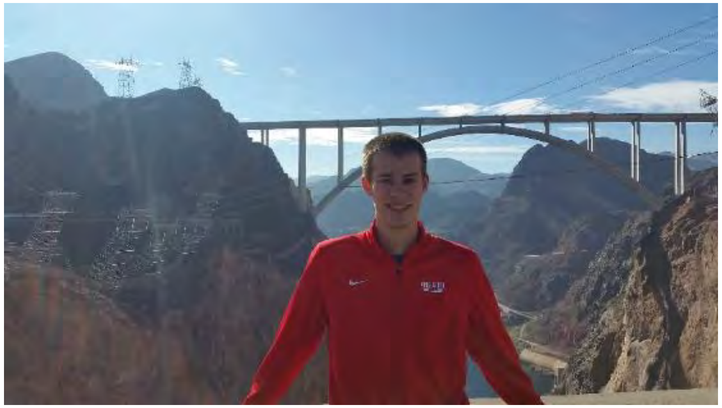
Daniel Freiburger | Graduate Engineer 2

June 3, 2021

DEPARTMENT OF TRANSPORTATION

Bridge Office | mndot.gov/bridge

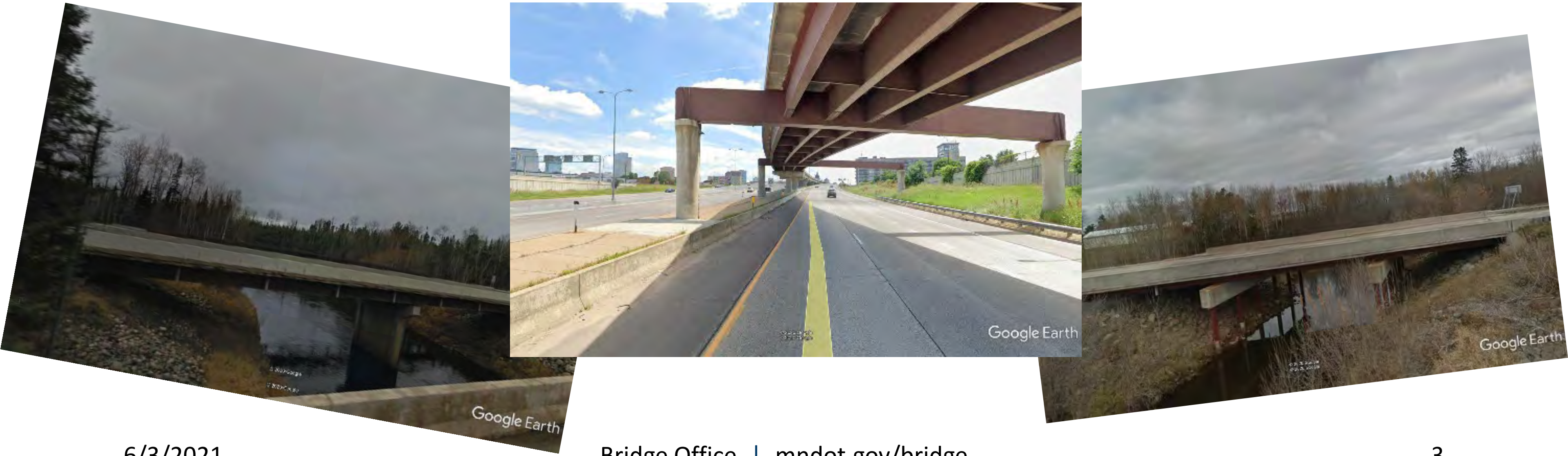
Introductions: Me



- Daniel Freiburger, EIT
- Graduate Engineer 2 in MnDOT Bridge Final Design Unit 2 (Karl Johnson Unit)
- Originally from Rochester, MN
- Graduated from University of Notre Dame in 2017 (Bachelor of Science in Civil Engineering)
- Graduate Engineer Program with MnDOT starting June 2017 (Rotations in Construction, Foundations, Bridge Design)
- Full time in Bridge Design since December 2018

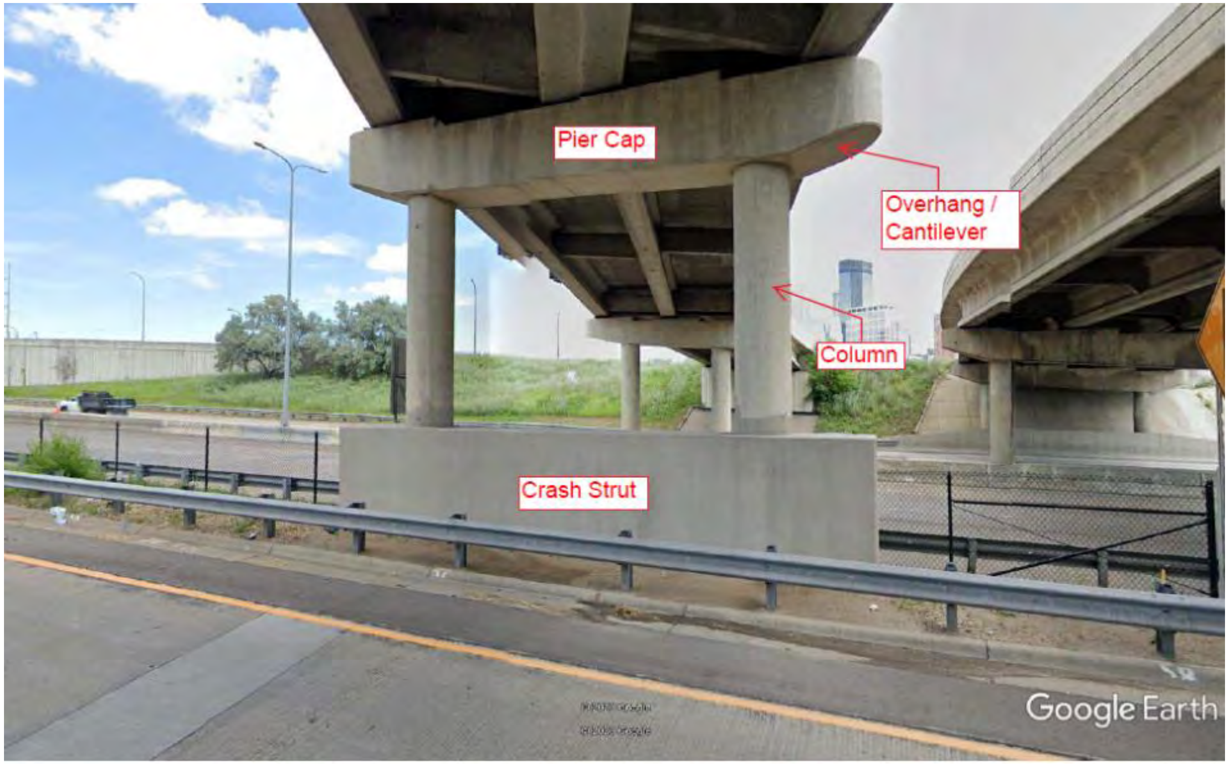
Introductions: Piers

- Pier: “an intermediate support for the adjacent ends of two bridge spans” (*Merriam-Webster*)
- Many different types
    - Wall, Pile Bent, Hammerhead, Cap and Column, Integral Steel Box Beam



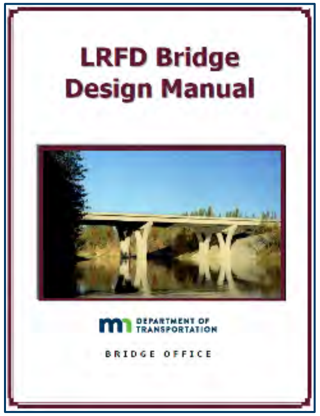
Introductions: Piers

- Most common type: Reinforced Concrete Cap and Column



Notation / References

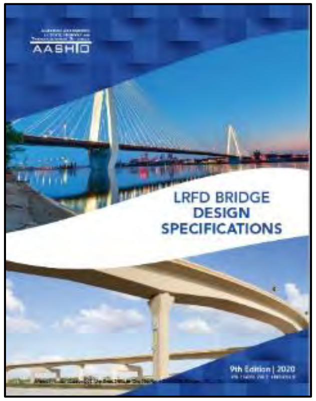
- AASHTO = *AASHTO LRFD Bridge Design Specifications*, 9th Edition (2020)
- MnDOT BDM = *MnDOT LRFD Bridge Design Manual* (April 2021)
- NCHRP = NCHRP Research Report 892: Project 12-90 *Guidelines for Shielding Bridge Piers* (2018)
- References provided in Red text boxes throughout the presentation



LRFD Bridge Design Manual

DEPARTMENT OF TRANSPORTATION

BRIDGE OFFICE



AASHTO

LRFD BRIDGE DESIGN SPECIFICATIONS

9th Edition | 2020

NCHRP RESEARCH REPORT 892

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Guidelines for Shielding Bridge Piers

- Photo credits
  - My own
  - Google Earth Screenshots
  - Figures from resources cited at left

Presentation Overview

- Design of Reinforced Concrete Pier Caps
  - Pier Cap Design Philosophies / Procedures
  - Strut-and-Tie Method
- Evaluation of Need for Pier Protection
  - AASHTO / MnDOT policies
  - AASHTO 9th Edition revisions (Risk-Based Assessment)

Reinforced Concrete Design Methods

- B-Regions
  - Conventional beam theory
  - Plane sections remain plane (Bernoulli's Theory)
  - Flexure: AASHTO 5.6
  - Shear: AASHTO 5.7

- D-Regions
  - Locations with abrupt changes in geometry or concentrated forces
  - Nonlinear strain distribution within member depth of discontinuity (St. Venant's Principle)
  - Strut-and-Tie Method (STM): AASHTO 5.8.2

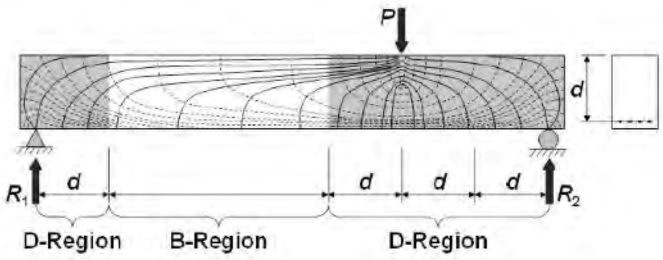


Figure 5.5.1.2.1-1— Stress Trajectories within B- and D-Regions of a Flexural Member (adapted from Birrcher et al., 2009)

AASHTO 5.5.1.2

Pier Cap Design Methodology

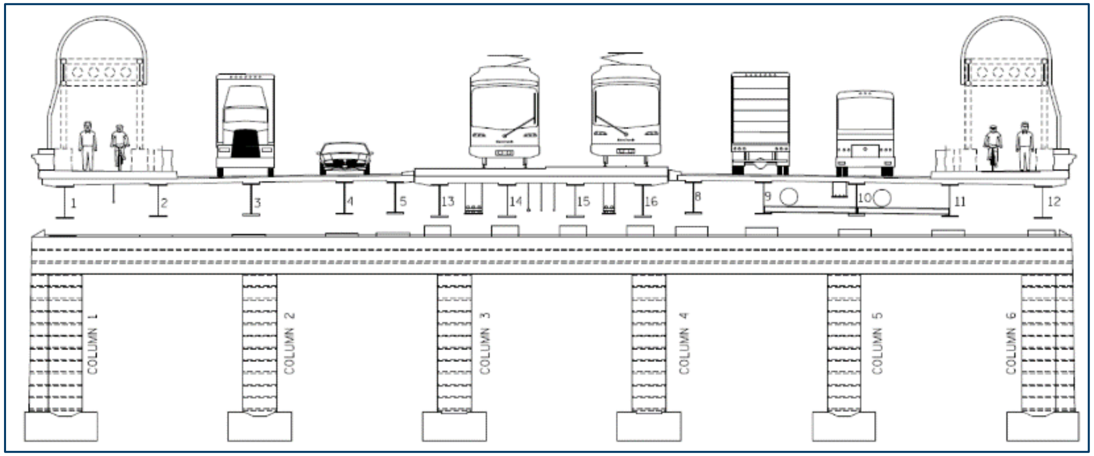
- Most pier caps are subject to concentrated forces at superstructure reactions → D Regions Present
  - Per AASHTO, design shall be done with STM
- MnDOT expects all new pier caps to be designed with STM

Pier Cap Design Methodology

- Suggested Design Procedure (New Piers)
  1. Size components / Design reinforcement using beam theory
  2. Analyze beam theory design using STM and detail rebar appropriately
- Suggested Evaluation Procedure (Existing Piers)
  - LRFD rating on case-by-case basis for increased loads / adverse conditions
  - MnDOT developing guidelines (contact Jessica Duncan for latest)
  1. Analyze pier cap using beam theory (likely how pier was originally designed)
  2. Perform STM analysis
  3. Review results with MnDOT Evaluation Unit
     - Compare with condition / cracking, include localized section loss as warranted
     - Consider permit / legal live loads as directed

Pier Cap Design: Loads

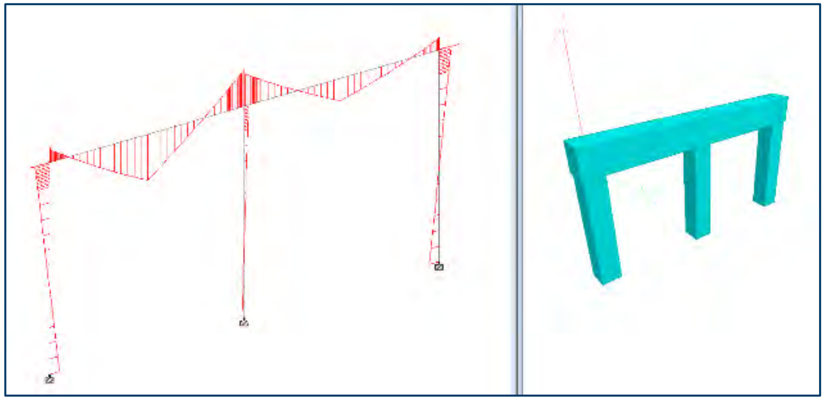
- Design pier caps for vertical loads only (MnDOT BDM 11.4.3.D)
- Dead Loads: Barriers, deck, stool, beams, bearings, pedestals, cap self-weight, utilities, sidewalks, etc.
- Live Loads: Pattern live loads longitudinally and transversely to generate worst case effects in pier cap
- Things to remember:
  - Worst case girder reactions are not necessarily worst-case pier reactions
  - Some load factors are different when evaluating existing piers
- Loads are the same for both Beam Theory and STM!

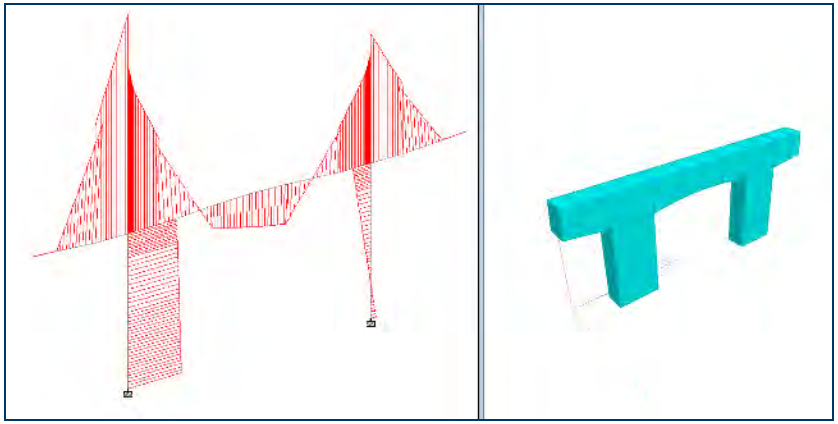


MnDOT BDM 11.2.2.2,11.4.3

Pier Cap Design: Beam Theory

- Model cap and columns with fixed support at top of footing
- Use gross section properties
- Apply vertical loads to obtain design moments and shears
- Can take negative moment at center of column (conservative) or quarter points of column
    - Use face of column for existing piers
- Design reinforcement for flexural strength, crack control, fatigue, and minimum reinforcement
- Design section for shear by sizing concrete and adding stirrups
    - Calculate β and θ per AASHTO 5.7.3.4 based on reinforcement





MnDOT BDM 11.4.3.D

Pier Cap Design: Strut-and-Tie

- Basic steps for STM given in AASHTO:

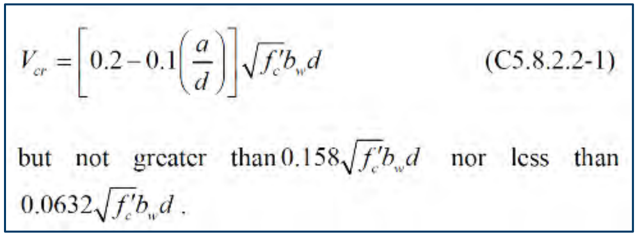
Beam Theory!

1. Determine the locations of the B- and D- Regions.
2. Define load cases.
3. Analyze structural components.
4. Size structural components using the shear serviceability check, given by Eq. C5.8.2.2-1.
5. Develop a strut-and-tie model. See Article 5.8.2.2.
6. Proportion ties.
7. Perform nodal strength checks. See Article 5.8.2.5.
8. Proportion crack control reinforcement. See Article 5.8.2.6.
9. Provide necessary anchorage for ties.

AASHTO C5.8.2.1

STM: Shear Serviceability Check

- Use service shear demand from beam theory analysis
- Calculate estimated resistance at which diagonal cracks begin to form:



$$V_{cr} = \left[0.2 - 0.1\left(\frac{a}{d}\right)\right]\sqrt{f'_c}b_w d \qquad \text{(C5.8.2.2-1)}$$

but not greater than $0.158\sqrt{f'_c}b_w d$ nor less than $0.0632\sqrt{f'_c}b_w d$.

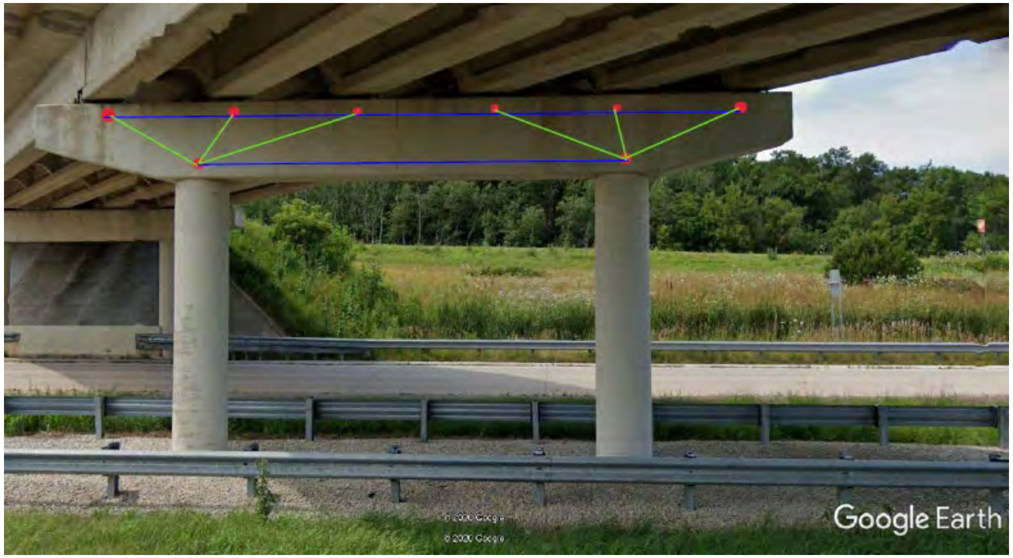
- Note: shear span “a” is the distance from the support to the applied load. It may be taken to the face of the column.
- New designs: size pier cap such that $V_{cr} > V_{service}$
- Evaluation: perform calculation to predict likelihood of diagonal shear cracking

AASHTO C5.8.2.2-1

STM: Develop the Model

- Truss assembly of steel ties and concrete struts that carry applied loads to supports
- Recommend drawing in CAD program for easy measurement and iteration

1. Place nodes at all applied load and support locations (Red)
2. Place top and bottom ties at centroid of flexural reinforcement (Blue)
3. Connect nodes with applied loads to support nodes with struts (Green)



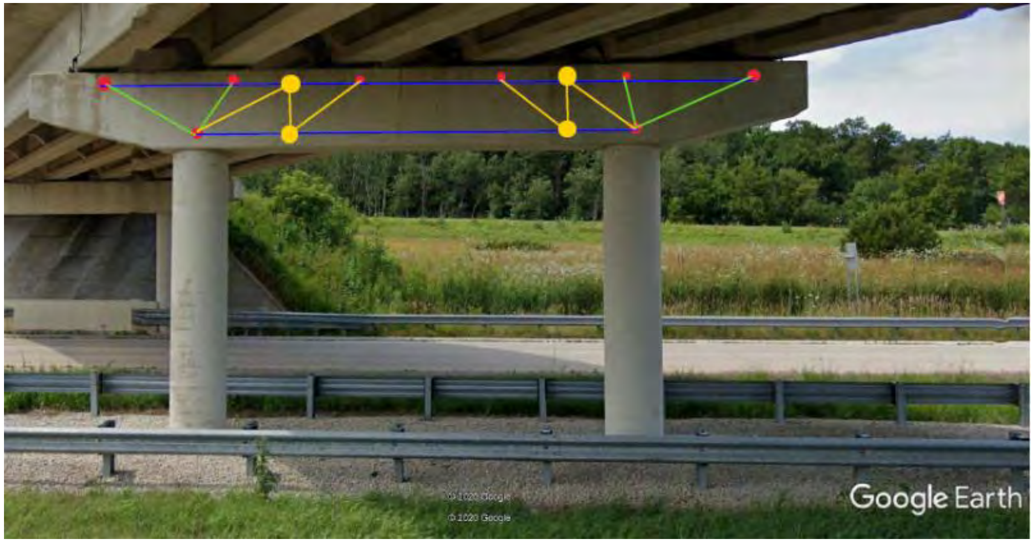
AASHTO 5.8.2.2

STM: Develop the Model

4. Check that angles between struts and ties are not less than 25°

5. Introduce additional nodes and struts with connecting vertical ties to carry load to supports without violating 25° limit (Gold)

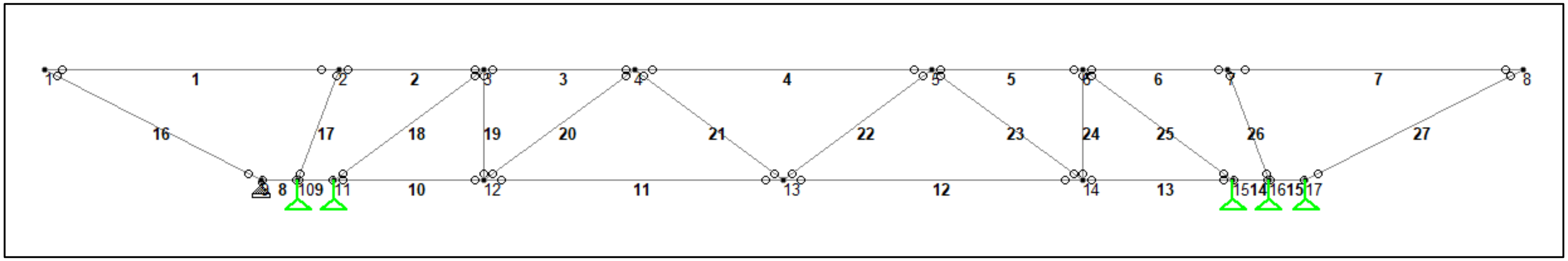
- This constitutes the most efficient load path
- Alternate load paths can be considered for evaluation of in-place reinforcement



AASHTO 5.8.2.2

STM: Develop the Model

- Most efficient strut-and-tie model may not be able to run in structural analysis software
  - Introduce additional members to create triangular panels
  - Note that any member in tension must have steel reinforcement in that direction
    - Example: most pier caps cannot carry tension in a diagonal tie
  - Consider using compression only members to simplify iteration of model due to asymmetric live load patterns



6/3/2021

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AASHTO C5.8.2.2

STM: Develop the Model

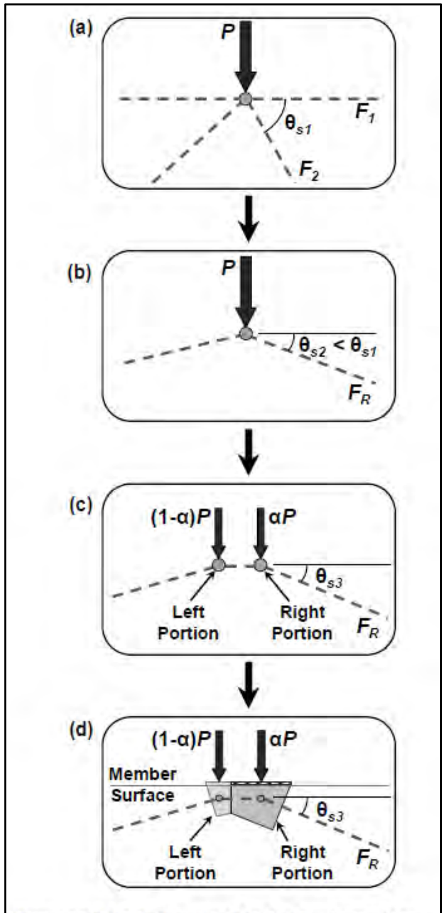


Figure C5.8.2.2-4—Division of Node when Struts Enter from Both Sides

- Support nodes may be split when developing the model
  - Split effective column area based on percentage of vertical load carried by struts
  - Proportion support nodes based on stiffness of columns
    - Required for evaluation
    - Add horizontal loads and moment couple loads for reactions based on beam theory model

AASHTO C5.8.2.2

STM: Proportion Ties

- Check factored tension force in ties against tie strength
- Nominal resistance of steel tie: $P_n = f_y A_{st} + A_{ps}\left[f_{pe} + f_y\right]$ (5.8.2.4.1-1)
- Prestressing unusual for pier caps, so typically $P_n = f_y A_s$
- A_s for flexural reinforcement = developed longitudinal steel
- A_s for vertical ties = stirrups available within shear span:
  - Cannot double count any steel

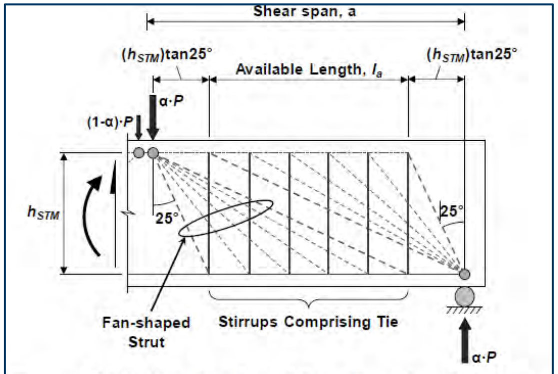
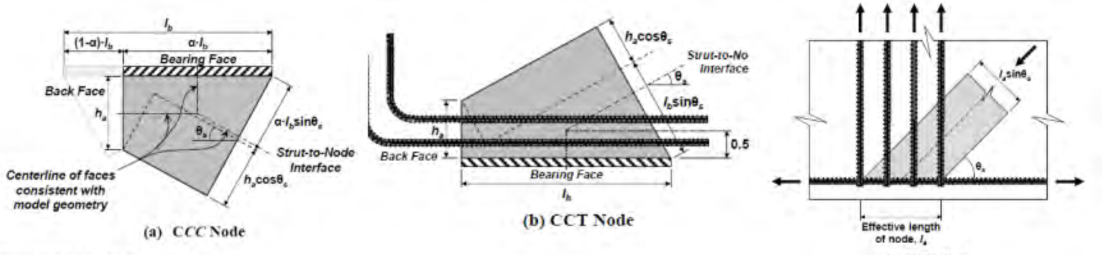


Figure C5.8.2.2-2—Fan-shaped Strut Engaging Transverse Reinforcement Forming a Tie

AASHTO 5.8.2.3, 5.8.2.4

STM: Nodal Strength Checks

- Check factored compression force against nodal face strength (coincides with the narrowest point of the strut)
- Nominal resistance of node face: $P_n = f_{cu} A_{cn}$ (5.8.2.5.1-1)
- Effective area A_{cn} dependent on geometry / node type
  - Suggest drawing critical nodes in CAD software to simplify calculations
  - Interior nodes (CTT) not located at an applied load or support are called “smeared nodes” and do not require nodal strength checks
  - Height of back face h_a is either:
    - The effective depth of compression stress block (“a” from beam theory flexural design) in CCC Nodes
    - Twice the distance from the concrete surface to the centroid of reinforcement in CCT Nodes



(a) CCC Node

(b) CCT Node

(c) CTT Node

Figure 5.8.2.2-1—Nodal Geometries

AASHTO 5.8.2.5

STM: Nodal Strength Checks

- Node face compressive strength limit:

$$f_{cu} = m\nu f'_c \qquad (5.8.2.5.3a\text{-}1)$$

- Confinement modification factor defined by bearing area:

$$m = \sqrt{\frac{A_2}{A_1}} \leq 2.0 \qquad (5.6.5\text{-}3)$$

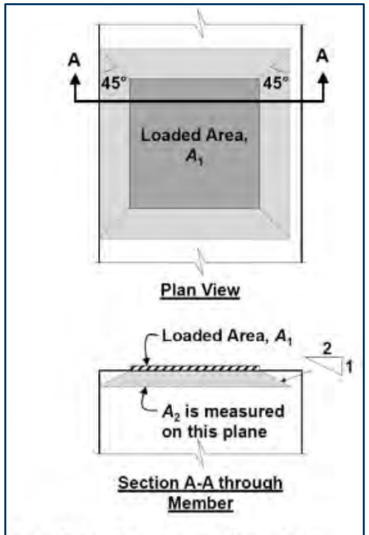
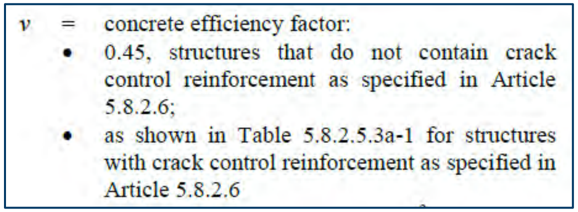


Figure 5.6.5-1—Determination of Notional Area

- Concrete efficiency factor:



ν = concrete efficiency factor:
- 0.45, structures that do not contain crack control reinforcement as specified in Article 5.8.2.6;
- as shown in Table 5.8.2.5.3a-1 for structures with crack control reinforcement as specified in Article 5.8.2.6

  - Always provide crack control reinforcement for new designs
  - For existing structures, check in-place reinforcement for crack control criteria
    - Often ν = 0.45

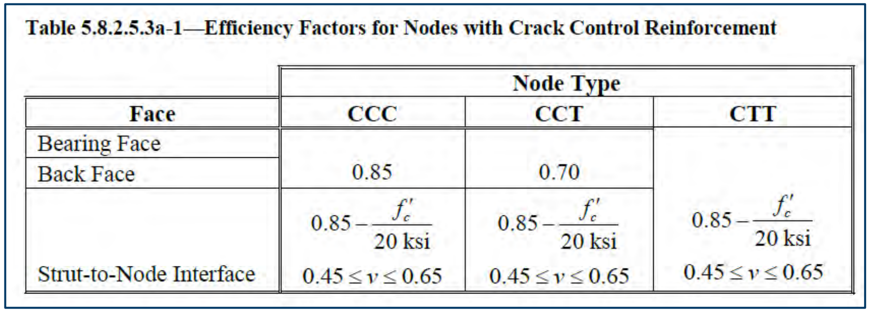
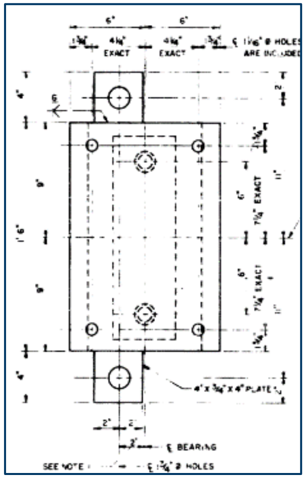


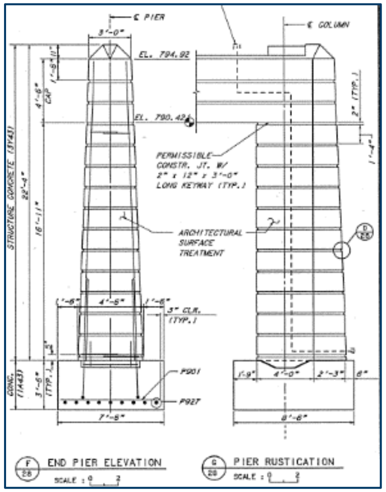
Table 5.8.2.5.3a-1—Efficiency Factors for Nodes with Crack Control Reinforcement

	Node Type		
Face	**CCC**	**CCT**	**CTT**
Bearing Face	0.85	0.70	
Back Face			
Strut-to-Node Interface	$0.85 - \frac{f'_c}{20\text{ ksi}}$ $0.45 \leq \nu \leq 0.65$	$0.85 - \frac{f'_c}{20\text{ ksi}}$ $0.45 \leq \nu \leq 0.65$	$0.85 - \frac{f'_c}{20\text{ ksi}}$ $0.45 \leq \nu \leq 0.65$

AASHTO 5.8.2.5

STM: Nodal Strength Checks





- Helpful hints
  - Conservatively assume m = 1 for initial strength checks and only revise if necessary
  - When computing bearing areas, convert unusual column or bearing shapes to equivalent rectangular or square areas
  - For existing pier caps, consider nonstandard crack control reinforcement (Example: column bars projecting into cap) when determining efficiency factor ν
  - Ignore architectural concrete when computing nodal areas (but include for dead load calculation)

STM: Crack Control Reinforcement

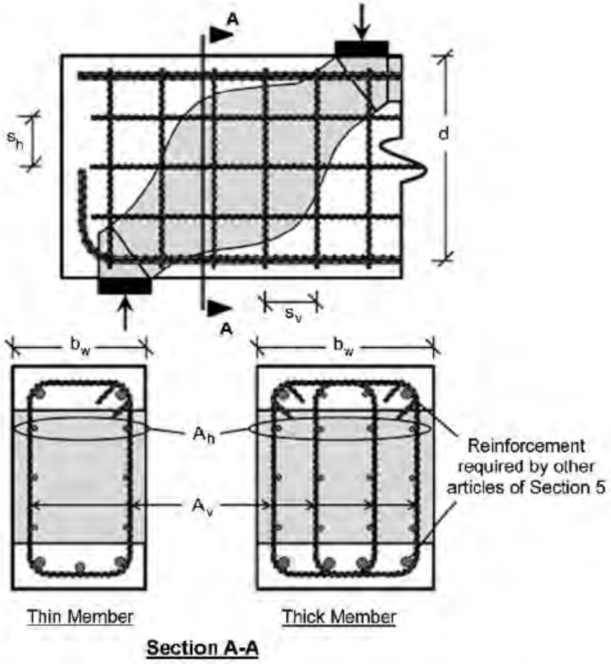


Figure C5.8.2.6-1—Distribution of Crack Control Reinforcement in Struts

- Provide crack control steel
  - Skin reinforcement

$$A_{sk} \geq 0.012\,(d_\ell - 30) \qquad (5.6.7\text{-}3)$$

  - STM crack control grid

$$\frac{A_v}{b_w s_v} \geq 0.003 \qquad (5.8.2.6\text{-}1)$$

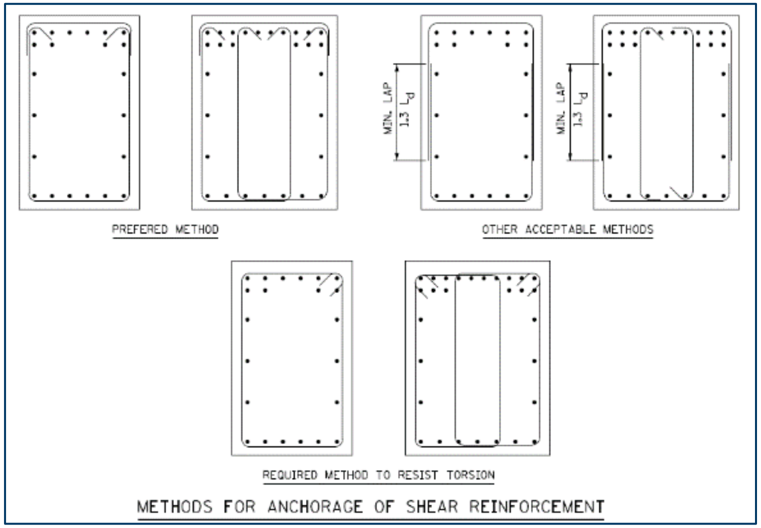
$$\frac{A_h}{b_w s_h} \geq 0.003 \qquad (5.8.2.6\text{-}2)$$

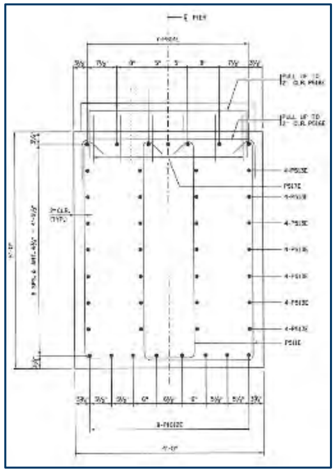
- Maximum spacing
  - Lesser of $d_\ell/6$ and 12.0” (5.6.7)
  - Smaller of d/4 and 12.0” (5.8.2.6)

AASHTO 5.6.7,5.8.2.6

STM: Crack Control Reinforcement

- See MnDOT BDM Figure 5.2.2.8 for stirrup layouts (Above right)
- Distribute reinforcement evenly near the side faces of the pier cap
  - Interior layers are permissible and sometimes necessary to meet all requirements
  - Provide a 6” minimum opening at the top and 2” clear to all anchor rods
  - Use reasonable spacing to facilitate concrete placement
- If crack control steel is not provided, concrete efficiency factor ν = 0.45
  - Common in evaluation of existing piers





AASHTO 5.6.7,5.8.2.6

STM: Tension Tie Anchorage

- Only steel that is developed can carry tension forces
- Available length determined by extending the nodal zone to the centroid of reinforcement
    - Helpful to draw in CAD software
    - Can consider partial development
- Development length calculation is the same for beam theory and STM

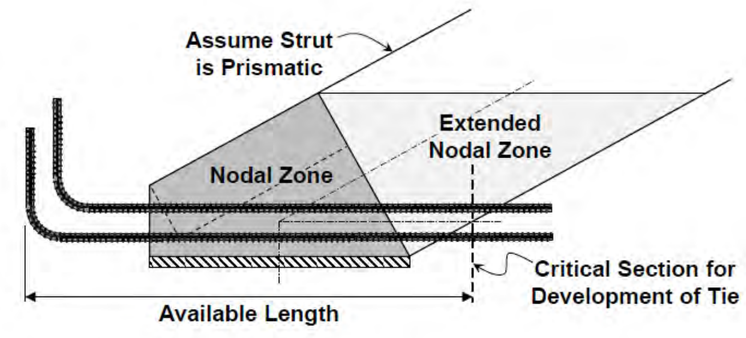


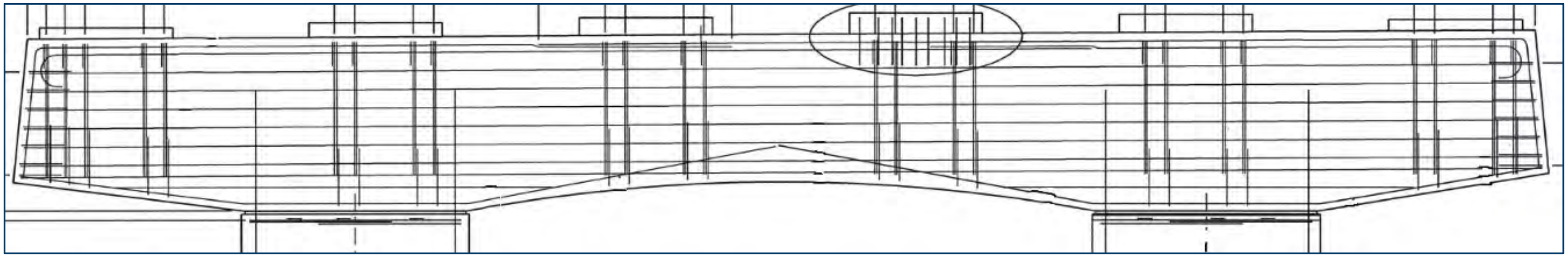
Figure C5.8.2.4.2-1—Available Development Length for Ties

$$\ell_d = \ell_{db} \times \left(\frac{\lambda_{rl} \times \lambda_{cf} \times \lambda_{rc} \times \lambda_{er}}{\lambda}\right) \qquad (5.10.8.2.1a\text{-}1)$$

AASHTO 5.8.2.4.2,5.10.8.2

STM: Tension Tie Anchorage

- Proper detailing is the key to reinforcement anchorage / development
- Always hook top longitudinal bars at pier cap ends (MnDOT BDM 11.2.2.2)
  - Use 90° hooks for top layer (do not use 180° hooks in top row)
  - Use 90° or 180° hooks for additional layers, considering bar length and radii to avoid bar conflicts
- Consider bar size / spacing effect on development length



Pier Protection

NCHRP Table 3

Pier Protection: AASHTO Requirements

- Substructures within the clear zone to be investigated for collision
  - “Unless the Owner determines that site conditions indicate otherwise”
- Provide structural resistance or redirect / absorb collision load
  - Structural resistance: must carry a 600 k static force at a distance of 2’ to 5’ above the ground at an angle of 0°-15° to produce the maximum effect
  - Redirection / absorption of collision load: MASH TL-5 rigid barrier with a minimum height of 42” and the top edge at least 3.25’ from face of pier
- Note that AREMA has separate guidelines for rail underpasses
  - MnDOT requires 600 k collision load and adherence to AREMA geometric guidance (MnDOT BDM 11.2.3.2.2)

AASHTO 3.6.5

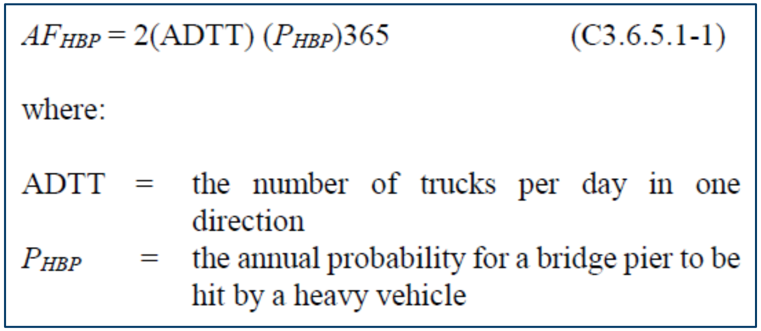
Pier Protection: MnDOT Interpretations

- Abutments are adequate for collision loads due to resistance provided by soil backfill
- Footings and piling can resist collision loads with passive soil pressure, friction, and pile structural capacity and need not be analyzed
- Piers for non-exempt roadway bridges must be protected by:
  - Providing a crash strut designed to resist the 600 k collision load,
  - Designing individual columns for the 600 k collision load,
  - Protecting the pier with a TL-5 barrier per AASHTO 3.6.5, or
  - Validating that the structure will not collapse due to the removal of any single column

MnDOT BDM 11.2.3.2

Pier Protection: When is it Needed?

- What does “Unless the Owner determines that site conditions indicate otherwise” mean?
- 8th Edition (2017) AASHTO commentary: design for vehicular collision force not required if annual frequency of heavy vehicle impact is below specified thresholds
  - $AF_{HBP} < 0.001$ for typical bridges
  - $AF_{HBP} < 0.0001$ for critical or essential bridges



$$AF_{HBP} = 2(\text{ADTT})\,(P_{HBP})365 \qquad \text{(C3.6.5.1-1)}$$

where:

ADTT = the number of trucks per day in one direction

P_{HBP} = the annual probability for a bridge pier to be hit by a heavy vehicle

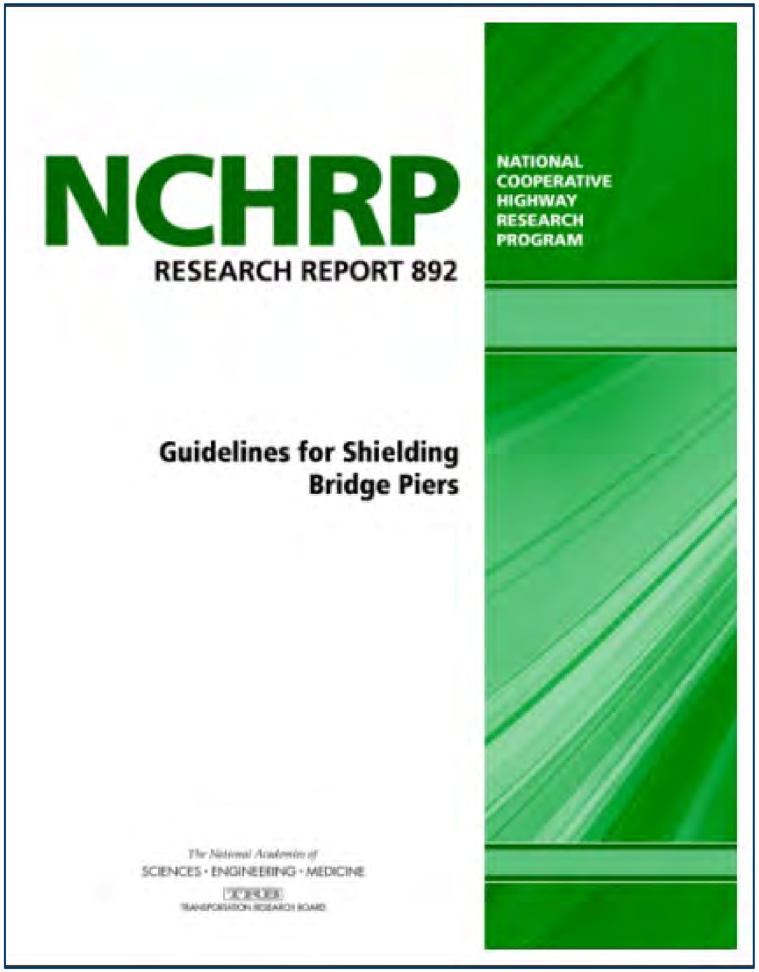
Pier Protection: When is it Needed?

- MnDOT: Bridges that meet either of the criteria below are exempt from pier protection requirements
  - All bridges with redundant piers and design speed of roadway underneath < 40 MPH
  - All non-critical bridges where the roadway underneath > 40 MPH and is:
    - Undivided with ADTT < 800
    - Divided, on tangent section, and ADTT < 2400
    - Divided, horizontally curved, and ADTT < 1200

- "Redundant" = pile bent piers or piers containing continuous pier caps with a minimum of 3 columns
- "Critical bridge"
  - Bridge carrying or spanning over a mainline Interstate
  - Bridge carrying or spanning over a roadway carrying more than 40,000 ADT

MnDOT BDM 11.2.3.2

Pier Protection: When is it Needed?



NCHRP
RESEARCH REPORT 892

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Guidelines for Shielding Bridge Piers

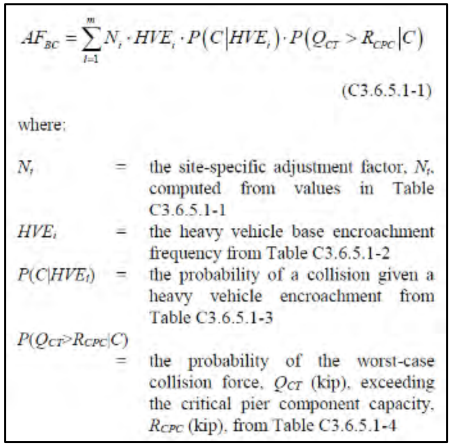
The National Academies of
SCIENCES · ENGINEERING · MEDICINE
TRANSPORTATION RESEARCH BOARD

- Proposed updates to AASHTO 3.6.5 to quantify need for pier protection with risk-based assessment based on:
    - Site conditions
    - Traffic
    - Bridge design configurations
    - Underneath roadway geometry
    - Operations characteristics
    - Benefit / cost
- Adopted in AASHTO 9th Edition Commentary

NCHRP 1.1

Pier Protection: Risk-Based Assessment (RBA)

- With approval of the owner, the expected annual frequency of bridge collapse, AF_{BC}, can be calculated as follows:
  1. Identify each approach direction, i, where a pier component is at risk of an impact from approaching traffic.
  2. Calculate the annual frequency of bridge collapse as follows:
- Protect from vehicle collision force if:
  - $AF_{BC} > 0.0001$ for critical / essential bridges
  - $AF_{BC} > 0.001$ for typical bridges



$$AF_{BC} = \sum_{i=1}^{m} N_i \cdot HVE_i \cdot P(C|HVE_i) \cdot P(Q_{CT} > R_{CPC}|C) \qquad \text{(C3.6.5.1-1)}$$

where:

N_i = the site-specific adjustment factor, N_i, computed from values in Table C3.6.5.1-1

HVE_i = the heavy vehicle base encroachment frequency from Table C3.6.5.1-2

$P(C|HVE_i)$ = the probability of a collision given a heavy vehicle encroachment from Table C3.6.5.1-3

$P(Q_{CT}>R_{CPC}|C)$ = the probability of the worst-case collision force, Q_{CT} (kip), exceeding the critical pier component capacity, R_{CPC} (kip), from Table C3.6.5.1-4

AASHTO C3.5.6.1

RBA: Site-Specific Adjustment Factor, N_i

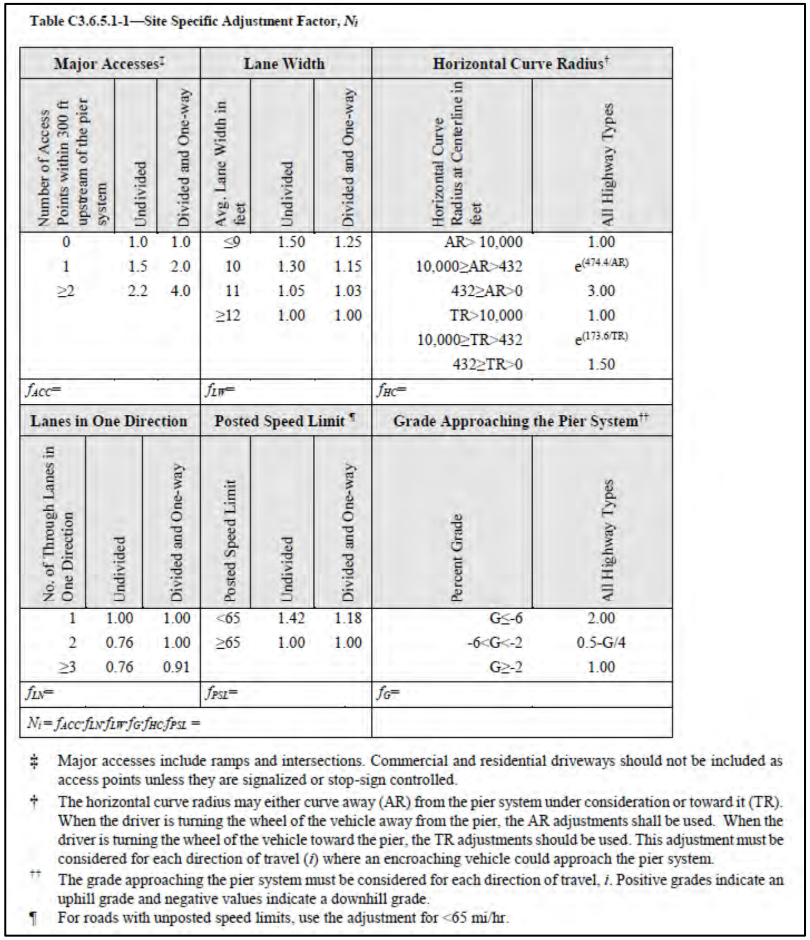


Table C3.6.5.1-1—Site Specific Adjustment Factor, N_i

Major Accesses[‡]			Lane Width			Horizontal Curve Radius[†]	
Number of Access Points within 300 ft upstream of the pier system	Undivided	Divided and One-way	Avg. Lane Width in feet	Undivided	Divided and One-way	Horizontal Curve Radius at Centerline in feet	All Highway Types
0	1.0	1.0	≤ 9	1.50	1.25	$AR > 10{,}000$	1.00
1	1.5	2.0	10	1.30	1.15	$10{,}000 \geq AR > 432$	$e^{(474.4/AR)}$
≥ 2	2.2	4.0	11	1.05	1.03	$432 \geq AR > 0$	3.00
			≥ 12	1.00	1.00	$TR > 10{,}000$	1.00
						$10{,}000 \geq TR > 432$	$e^{(173.6/TR)}$
						$432 \geq TR > 0$	1.50
$f_{ACC}=$			$f_{LW}=$			$f_{HC}=$	

Lanes in One Direction			Posted Speed Limit[¶]			Grade Approaching the Pier System[††]	
No. of Through Lanes in One Direction	Undivided	Divided and One-way	Posted Speed Limit	Undivided	Divided and One-way	Percent Grade	All Highway Types
1	1.00	1.00	<65	1.42	1.18	$G \leq -6$	2.00
2	0.76	1.00	≥ 65	1.00	1.00	$-6 < G < -2$	$0.5 - G/4$
≥ 3	0.76	0.91				$G \geq -2$	1.00
$f_{LN}=$			$f_{PSL}=$			$f_G=$	
$N_i = f_{ACC} \cdot f_{LN} \cdot f_{LW} \cdot f_G \cdot f_{HC} \cdot f_{PSL} =$							

[‡] Major accesses include ramps and intersections. Commercial and residential driveways should not be included as access points unless they are signalized or stop-sign controlled.

[†] The horizontal curve radius may either curve away (AR) from the pier system under consideration or toward it (TR). When the driver is turning the wheel of the vehicle away from the pier, the AR adjustments shall be used. When the driver is turning the wheel of the vehicle toward the pier, the TR adjustments should be used. This adjustment must be considered for each direction of travel (i) where an encroaching vehicle could approach the pier system.

[††] The grade approaching the pier system must be considered for each direction of travel, i. Positive grades indicate an uphill grade and negative values indicate a downhill grade.

[¶] For roads with unposted speed limits, use the adjustment for <65 mi/hr.

- Likelihood of vehicles leaving travel lanes is related to many factors
  - Major accesses (ramps & intersections)
  - Lane width
  - Horizontal curvature
  - Number of lanes
  - Posted speed limit
  - Approach grade
- Calculate N_i for each direction of possible encroachment (i) using Table C3.6.5.1-1

AASHTO C3.5.6.1

RBA: Heavy Vehicle Base Encroachment Frequency, HVE_i

- Establish estimated frequency of heavy vehicles that leave travel lanes under base conditions (Table C3.5.6.1-2)
    - Straight and flat roadway
    - 12' travel lanes
    - No major access points
    - Posted speed limit = 65 MPH
    - 2 lanes (divided), 1 lane (undivided)
- Statistical model for heavy vehicles leaving travel lanes within 300' of a bridge pier

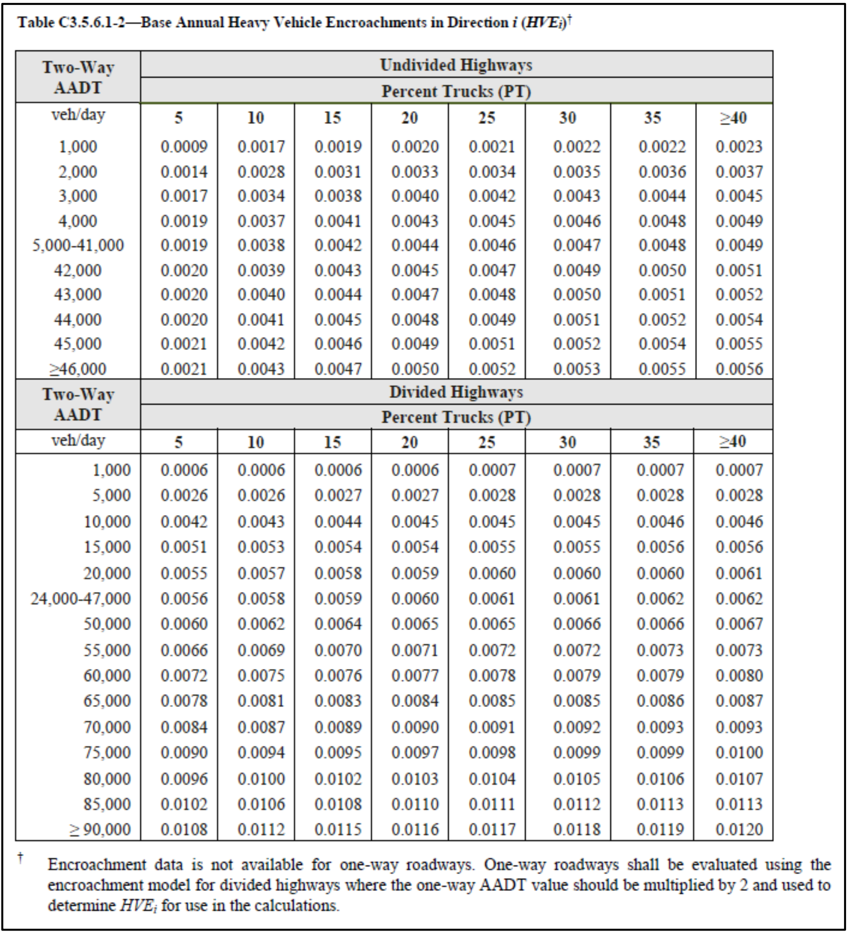


Table C3.5.6.1-2—Base Annual Heavy Vehicle Encroachments in Direction *i* (HVE_i)[†]

Two-Way AADT	**Undivided Highways**							
	Percent Trucks (PT)							
veh/day	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**≥40**
1,000	0.0009	0.0017	0.0019	0.0020	0.0021	0.0022	0.0022	0.0023
2,000	0.0014	0.0028	0.0031	0.0033	0.0034	0.0035	0.0036	0.0037
3,000	0.0017	0.0034	0.0038	0.0040	0.0042	0.0043	0.0044	0.0045
4,000	0.0019	0.0037	0.0041	0.0043	0.0045	0.0046	0.0048	0.0049
5,000-41,000	0.0019	0.0038	0.0042	0.0044	0.0046	0.0047	0.0048	0.0049
42,000	0.0020	0.0039	0.0043	0.0045	0.0047	0.0049	0.0050	0.0051
43,000	0.0020	0.0040	0.0044	0.0047	0.0048	0.0050	0.0051	0.0052
44,000	0.0020	0.0041	0.0045	0.0048	0.0049	0.0051	0.0052	0.0054
45,000	0.0021	0.0042	0.0046	0.0049	0.0051	0.0052	0.0054	0.0055
≥46,000	0.0021	0.0043	0.0047	0.0050	0.0052	0.0053	0.0055	0.0056
Two-Way AADT	**Divided Highways**							
	Percent Trucks (PT)							
veh/day	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**≥40**
1,000	0.0006	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007
5,000	0.0026	0.0026	0.0027	0.0027	0.0028	0.0028	0.0028	0.0028
10,000	0.0042	0.0043	0.0044	0.0045	0.0045	0.0045	0.0046	0.0046
15,000	0.0051	0.0053	0.0054	0.0054	0.0055	0.0055	0.0056	0.0056
20,000	0.0055	0.0057	0.0058	0.0059	0.0060	0.0060	0.0060	0.0061
24,000-47,000	0.0056	0.0058	0.0059	0.0060	0.0061	0.0061	0.0062	0.0062
50,000	0.0060	0.0062	0.0064	0.0065	0.0065	0.0066	0.0066	0.0067
55,000	0.0066	0.0069	0.0070	0.0071	0.0072	0.0072	0.0073	0.0073
60,000	0.0072	0.0075	0.0076	0.0077	0.0078	0.0079	0.0079	0.0080
65,000	0.0078	0.0081	0.0083	0.0084	0.0085	0.0085	0.0086	0.0087
70,000	0.0084	0.0087	0.0089	0.0090	0.0091	0.0092	0.0093	0.0093
75,000	0.0090	0.0094	0.0095	0.0097	0.0098	0.0099	0.0099	0.0100
80,000	0.0096	0.0100	0.0102	0.0103	0.0104	0.0105	0.0106	0.0107
85,000	0.0102	0.0106	0.0108	0.0110	0.0111	0.0112	0.0113	0.0113
≥ 90,000	0.0108	0.0112	0.0115	0.0116	0.0117	0.0118	0.0119	0.0120

[†] Encroachment data is not available for one-way roadways. One-way roadways shall be evaluated using the encroachment model for divided highways where the one-way AADT value should be multiplied by 2 and used to determine HVE_i for use in the calculations.

AASHTO C3.5.6.1

RBA: Probability of Collision Given Heavy Vehicle Encroachment, $P(C|HVE_i)$

- Not all vehicles that leave the travel lanes will hit the bridge pier
- Use a probability based on statistics of modeled heavy-vehicle trajectories for a variety (Table C3.6.5.1-3)
  - Larger pier sizes
  - Smaller roadway offsets

More likely to be struck by errant vehicles

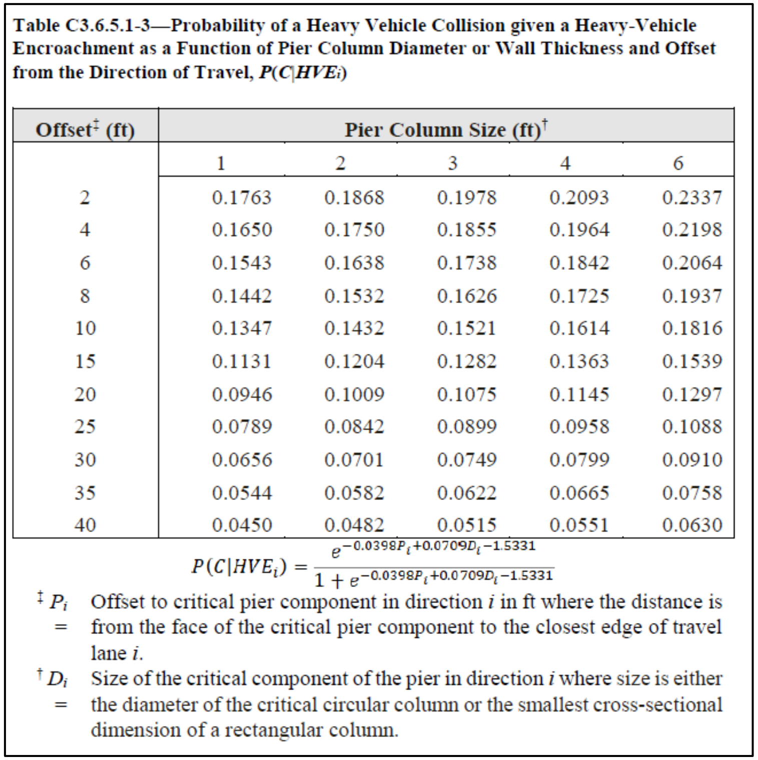


Table C3.6.5.1-3—Probability of a Heavy Vehicle Collision given a Heavy-Vehicle Encroachment as a Function of Pier Column Diameter or Wall Thickness and Offset from the Direction of Travel, *P(C|HVEi)*

Offset‡ (ft)	Pier Column Size (ft)†				
	1	2	3	4	6
2	0.1763	0.1868	0.1978	0.2093	0.2337
4	0.1650	0.1750	0.1855	0.1964	0.2198
6	0.1543	0.1638	0.1738	0.1842	0.2064
8	0.1442	0.1532	0.1626	0.1725	0.1937
10	0.1347	0.1432	0.1521	0.1614	0.1816
15	0.1131	0.1204	0.1282	0.1363	0.1539
20	0.0946	0.1009	0.1075	0.1145	0.1297
25	0.0789	0.0842	0.0899	0.0958	0.1088
30	0.0656	0.0701	0.0749	0.0799	0.0910
35	0.0544	0.0582	0.0622	0.0665	0.0758
40	0.0450	0.0482	0.0515	0.0551	0.0630

$$P(C|HVE_i) = \frac{e^{-0.0398P_i+0.0709D_i-1.5331}}{1+e^{-0.0398P_i+0.0709D_i-1.5331}}$$

‡ P_i = Offset to critical pier component in direction i in ft where the distance is from the face of the critical pier component to the closest edge of travel lane i.

† D_i = Size of the critical component of the pier in direction i where size is either the diameter of the critical circular column or the smallest cross-sectional dimension of a rectangular column.

AASHTO C3.5.6.1

RBA: Probability of Impact Force Exceeding Critical Pier Lateral Resistance, $P(Q_{CT}>R_{CPC}|C)$

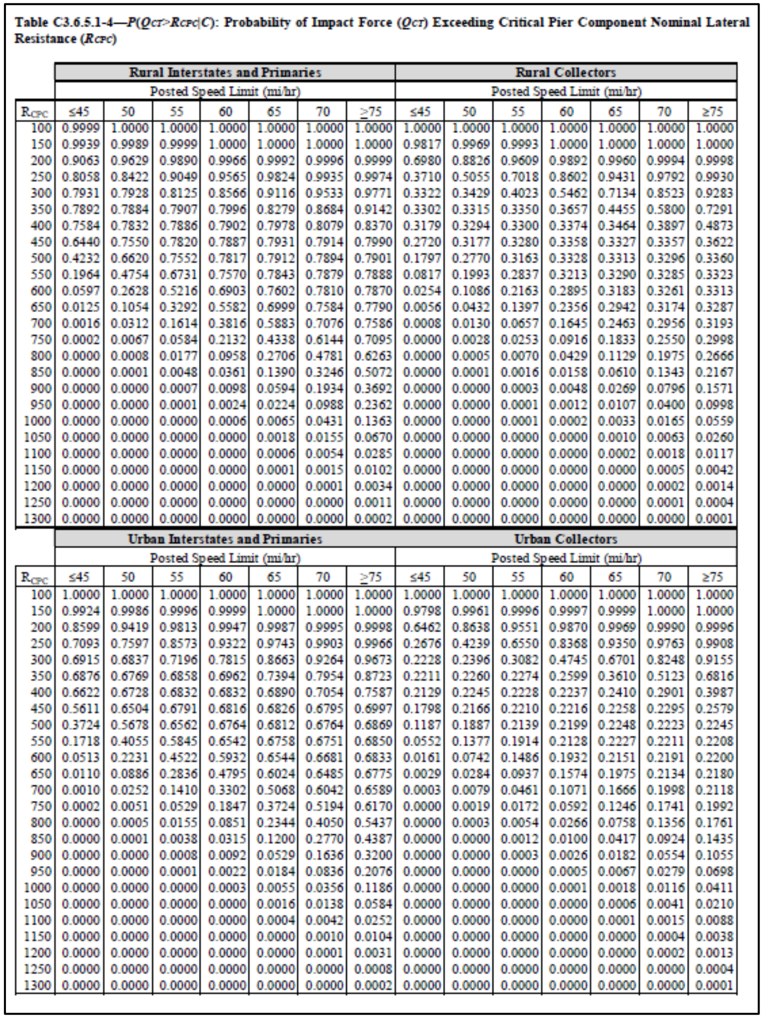


Table C3.6.5.1-4—$P(Q_{CT}>R_{CPC}|C)$: Probability of Impact Force (Q_{CT}) Exceeding Critical Pier Component Nominal Lateral Resistance (R_{CPC})

	Rural Interstates and Primaries							Rural Collectors						
	Posted Speed Limit (mi/hr)							Posted Speed Limit (mi/hr)						
R_{CPC}	≤45	50	55	60	65	70	≥75	≤45	50	55	60	65	70	≥75
100	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
150	0.9939	0.9989	0.9999	1.0000	1.0000	1.0000	1.0000	0.9817	0.9969	0.9993	1.0000	1.0000	1.0000	1.0000
200	0.9063	0.9629	0.9890	0.9966	0.9992	0.9996	0.9999	0.6980	0.8826	0.9609	0.9892	0.9960	0.9994	0.9998
250	0.8058	0.8422	0.9049	0.9565	0.9824	0.9935	0.9974	0.3710	0.5055	0.7018	0.8602	0.9431	0.9792	0.9930
300	0.7931	0.7928	0.8125	0.8566	0.9116	0.9533	0.9771	0.3322	0.3429	0.4023	0.5462	0.7134	0.8523	0.9283
350	0.7892	0.7884	0.7907	0.7996	0.8279	0.8684	0.9142	0.3302	0.3315	0.3350	0.3657	0.4455	0.5800	0.7291
400	0.7584	0.7832	0.7886	0.7902	0.7978	0.8079	0.8370	0.3179	0.3294	0.3300	0.3374	0.3464	0.3897	0.4873
450	0.6440	0.7550	0.7820	0.7887	0.7931	0.7914	0.7990	0.2720	0.3177	0.3280	0.3358	0.3327	0.3357	0.3622
500	0.4232	0.6620	0.7552	0.7817	0.7912	0.7894	0.7901	0.1797	0.2770	0.3163	0.3328	0.3313	0.3296	0.3360
550	0.1964	0.4754	0.6731	0.7570	0.7843	0.7879	0.7888	0.0817	0.1993	0.2837	0.3213	0.3290	0.3285	0.3323
600	0.0597	0.2628	0.5216	0.6903	0.7602	0.7810	0.7870	0.0254	0.1086	0.2163	0.2895	0.3183	0.3261	0.3313
650	0.0125	0.1054	0.3292	0.5582	0.6999	0.7584	0.7790	0.0056	0.0432	0.1397	0.2356	0.2942	0.3174	0.3287
700	0.0016	0.0312	0.1614	0.3816	0.5883	0.7076	0.7586	0.0008	0.0130	0.0657	0.1645	0.2463	0.2956	0.3193
750	0.0002	0.0067	0.0584	0.2132	0.4338	0.6144	0.7095	0.0000	0.0028	0.0253	0.0916	0.1833	0.2550	0.2998
800	0.0000	0.0008	0.0177	0.0958	0.2706	0.4781	0.6263	0.0000	0.0005	0.0070	0.0429	0.1129	0.1975	0.2666
850	0.0000	0.0001	0.0048	0.0361	0.1390	0.3246	0.5072	0.0000	0.0001	0.0016	0.0158	0.0610	0.1343	0.2167
900	0.0000	0.0000	0.0007	0.0098	0.0594	0.1934	0.3692	0.0000	0.0000	0.0003	0.0048	0.0269	0.0796	0.1571
950	0.0000	0.0000	0.0001	0.0024	0.0224	0.0988	0.2362	0.0000	0.0000	0.0001	0.0012	0.0107	0.0400	0.0998
1000	0.0000	0.0000	0.0000	0.0006	0.0065	0.0431	0.1363	0.0000	0.0000	0.0001	0.0002	0.0033	0.0165	0.0559
1050	0.0000	0.0000	0.0000	0.0000	0.0018	0.0155	0.0670	0.0000	0.0000	0.0000	0.0000	0.0010	0.0063	0.0260
1100	0.0000	0.0000	0.0000	0.0000	0.0006	0.0054	0.0285	0.0000	0.0000	0.0000	0.0000	0.0002	0.0018	0.0117
1150	0.0000	0.0000	0.0000	0.0000	0.0001	0.0015	0.0102	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0042
1200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0034	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0014
1250	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0011	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0004
1300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001

	Urban Interstates and Primaries							Urban Collectors						
	Posted Speed Limit (mi/hr)							Posted Speed Limit (mi/hr)						
R_{CPC}	≤45	50	55	60	65	70	≥75	≤45	50	55	60	65	70	≥75
100	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
150	0.9924	0.9986	0.9996	0.9999	1.0000	1.0000	1.0000	0.9798	0.9961	0.9996	0.9997	0.9999	1.0000	1.0000
200	0.8599	0.9419	0.9813	0.9947	0.9987	0.9995	0.9998	0.6462	0.8638	0.9551	0.9870	0.9969	0.9990	0.9996
250	0.7093	0.7597	0.8573	0.9322	0.9743	0.9903	0.9966	0.2676	0.4239	0.6550	0.8368	0.9350	0.9763	0.9908
300	0.6915	0.6837	0.7196	0.7815	0.8663	0.9264	0.9673	0.2228	0.2396	0.3082	0.4745	0.6701	0.8248	0.9155
350	0.6876	0.6769	0.6858	0.6962	0.7394	0.7954	0.8723	0.2211	0.2260	0.2274	0.2599	0.3610	0.5123	0.6816
400	0.6622	0.6728	0.6832	0.6832	0.6890	0.7054	0.7587	0.2129	0.2245	0.2228	0.2237	0.2410	0.2901	0.3987
450	0.5611	0.6504	0.6791	0.6816	0.6826	0.6795	0.6997	0.1798	0.2166	0.2210	0.2216	0.2258	0.2295	0.2579
500	0.3724	0.5678	0.6562	0.6764	0.6812	0.6764	0.6869	0.1187	0.1887	0.2139	0.2199	0.2248	0.2223	0.2245
550	0.1718	0.4055	0.5845	0.6542	0.6758	0.6751	0.6850	0.0552	0.1377	0.1914	0.2128	0.2227	0.2211	0.2208
600	0.0513	0.2231	0.4522	0.5932	0.6544	0.6681	0.6833	0.0161	0.0742	0.1486	0.1932	0.2151	0.2191	0.2200
650	0.0110	0.0886	0.2836	0.4795	0.6024	0.6485	0.6775	0.0029	0.0284	0.0937	0.1574	0.1975	0.2134	0.2180
700	0.0010	0.0252	0.1410	0.3302	0.5068	0.6042	0.6589	0.0003	0.0079	0.0461	0.1071	0.1666	0.1998	0.2118
750	0.0002	0.0051	0.0529	0.1847	0.3724	0.5194	0.6170	0.0000	0.0019	0.0172	0.0592	0.1246	0.1741	0.1992
800	0.0000	0.0005	0.0155	0.0851	0.2344	0.4050	0.5437	0.0000	0.0003	0.0054	0.0266	0.0758	0.1356	0.1761
850	0.0000	0.0001	0.0038	0.0315	0.1200	0.2770	0.4387	0.0000	0.0000	0.0012	0.0100	0.0417	0.0924	0.1435
900	0.0000	0.0000	0.0008	0.0092	0.0529	0.1636	0.3200	0.0000	0.0000	0.0003	0.0026	0.0182	0.0554	0.1055
950	0.0000	0.0000	0.0001	0.0022	0.0184	0.0836	0.2076	0.0000	0.0000	0.0000	0.0005	0.0067	0.0279	0.0698
1000	0.0000	0.0000	0.0000	0.0003	0.0055	0.0356	0.1186	0.0000	0.0000	0.0000	0.0001	0.0018	0.0116	0.0411
1050	0.0000	0.0000	0.0000	0.0000	0.0016	0.0138	0.0584	0.0000	0.0000	0.0000	0.0000	0.0006	0.0041	0.0210
1100	0.0000	0.0000	0.0000	0.0000	0.0004	0.0042	0.0252	0.0000	0.0000	0.0000	0.0000	0.0001	0.0015	0.0088
1150	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0104	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0038
1200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0031	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0013
1250	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004
1300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001

- Establish nominal lateral resistance of critical pier component (R_{CPC})
  - Can be governed by shear, flexure, or column connection strength
  - See further discussion in NCHRP Appendix E
- Select probability based on roadway type and posted speed limit (Table C3.6.5.1-4)

AASHTO C3.5.6.1

RBA: Probability of Impact Force Exceeding Critical Pier Lateral Resistance, $P(Q_{CT}>R_{CPC}|C)$

- Worst case collision force (Q_{CT}) determined by crash tests and finite element modeling
- Table probabilities, as well as the 600 k design load, are based on these tests
  - Note that the peak load in tests was briefly above 600 k

Figure 62. [CONTINUED] Sequential Views of Test 429730-2 and the FEA Results

NCHRP 3.3.2, Appendix D

RBA: Annual Frequency of Bridge Collapse

- Annual frequency of bridge collapse, AF_{BC}
  - Multiply the four factors together for each direction
  - Sum all directions to obtain the estimated annual frequency of bridge collapse for an unprotected pier
- AASHTO 3.14.5 uses a similar approach for vessel collision
  - Annual frequency of bridge component collapse, AF ($\neq AF_{BC}$)
  - Cutoffs of 0.001 (typical) and 0.0001 (critical / essential)

AASHTO C3.5.6.1

RBA: Annual Frequency of Bridge Collapse

- Design AF_{BC} limit depends on operational importance
- AASHTO commentary provides guidelines for classifying critical or essential bridges:

  1. Usable by emergency vehicles and for security, defense, economic, or secondary life safety purposes immediately after the design event
  2. Be open to all traffic once inspected after the design event

  - Operational priority may differ from Owner to Owner and network to network

AASHTO C1.3.5

Pier Protection: MnDOT Policy

- Current MnDOT BDM guidance for design speeds over 40 mph is based on the AASHTO 8th Edition AF_{HBP} (See slides 29-30)
  - Allows exemption from pier protection for certain typical bridges
  - Does not allow any exemptions for critical bridges
- Using the improved AASHTO 9th Edition AF_{BC} method may result in different exemptions than current MnDOT guidelines
  - Most bridges should follow published MnDOT BDM rules
  - On case-by-case basis, investigation using the 9th Edition method may allow for a bridge to be exempted from pier protection requirements
    - Discuss with preliminary plans staff, RBCE, and/or Dave Dahlberg

MnDOT BDM 11.2.3.2

Presentation Overview

- Design of Reinforced Concrete Pier Caps
  - Pier Cap Design Philosophies / Procedures
  - Strut-and-Tie Method
- Evaluation of Need for Pier Protection
  - AASHTO / MnDOT policies
  - AASHTO 9th Edition revisions (Risk-Based Assessment)

DEPARTMENT OF TRANSPORTATION

Daniel Freiburger