Texas A&M Transportation Institute
3135 TAMU, College Station,
TX 77843-3135
Tel.: 979-317-2707
Fax: 979-845-6107
http://tti.tamu.edu/crashtesting

PROFESSIONAL RECOMMENDATION MEMORANDUM

Project Name: Engineering Support Services and Recommendations for Roadside Safety Issues/Problems for Member States

Sponsor: Roadside Safety Pooled Fund

Task 22-14: Utah Single Slope Barrier Anchored to 12 Inches Thick Moment Slab (End Section) and 6 Inches Thick Sidewalk (Mid-Span) for MASH Test Level 2

DATE: September 15, 2022

FROM: William Williams, P.E., Associate Research Engineer
Jilong Cui, Postdoctoral Research Associate

FOR MORE INFORMATION:
Name: William Williams
Phone: 979-317-2707
Email: w-williams@tti.tamu.edu

Overview/Problem Statement

Texas A&M Transportation Institute has received details from Shawn Debenham entitled BA 3K MSE Wall 2.pdf. These details show a 42 inches high single slope barrier anchored to a 12'-0" long by 6'-0" wide by 12 inches thick moment slab. For this project the strength of the barrier end section and moment slab were analyzed for global sliding and overturning of the section (1). In addition, the strength of the end section was evaluated for MASH Test Level 2 (TL-2) impact loading conditions. As part of this project, the details of the barrier and moment slab were evaluated and designed as necessary to meet the strength requirements of MASH Test Level 2 impact conditions. In addition, the strength of the barrier out at mid-span as shown in Figure 2 was also evaluated with respect to MASH TL-2. Based on these analyses, recommendations were made in the reinforcement and anchorage of the barrier to improve the strength and performance with respect to MASH TL-2.

·Strength Evaluation

As shown in Figure 1, the structural capacity of the barrier and the global sliding and overturning was evaluated at the end-section in accordance with the AASHTO LRFD Bridge Design Specifications and the design guidelines provided in the NCHRP 22-20(02) Section 10, respectively. Note that, the design guidelines in NCHRP 22-20(02) are only applicable to test levels TL-3 through TL-5 criteria. The equivalent static load for the test level TL-2 was calculated using the cubic interpolation based on the load requirements for TL-3 through TL-5 specified in the design guidelines. Table 1 presents the equivalent static loads for the various test levels including the calculated load requirement for TL-2.

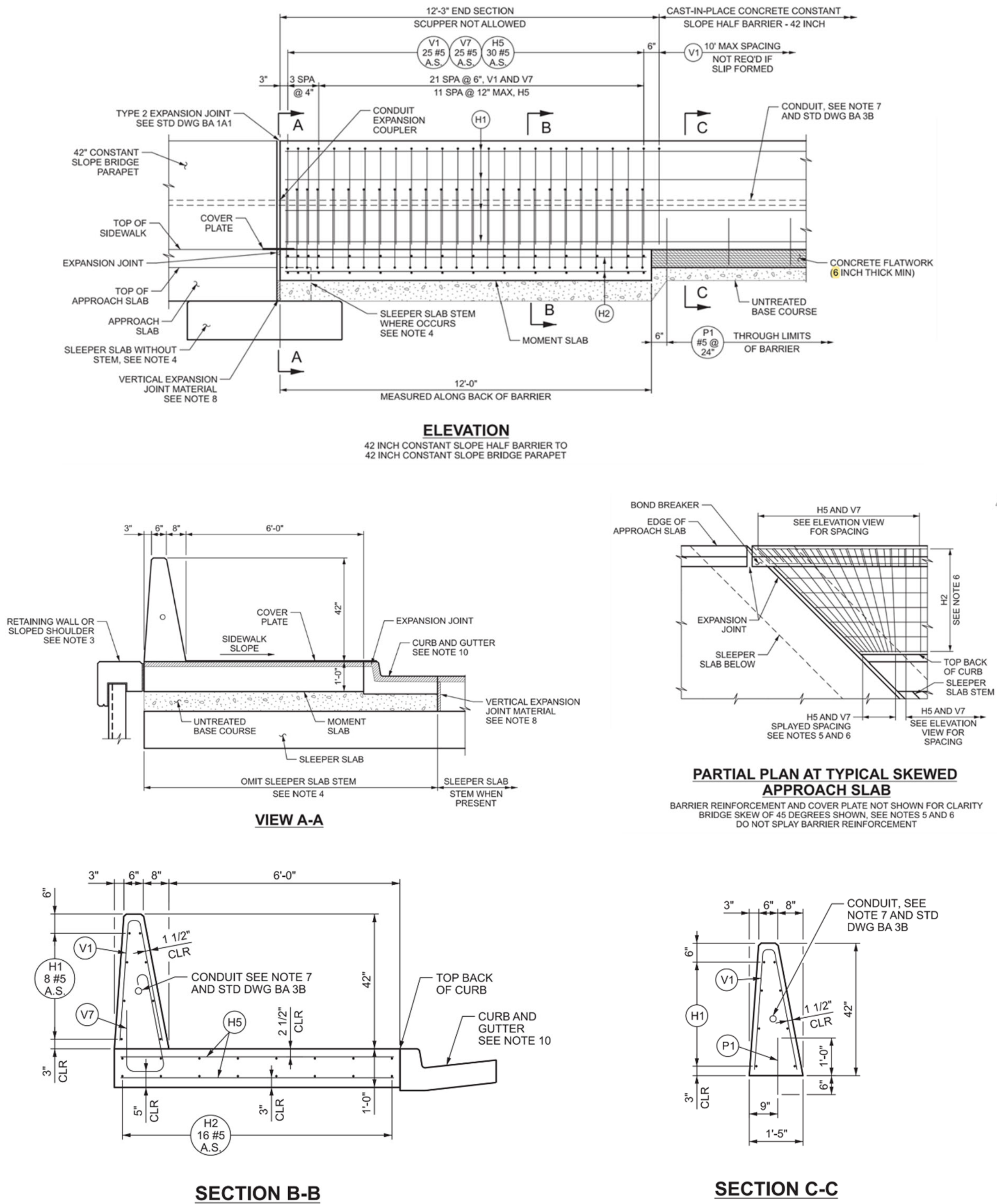


Figure 1. Design Details of CIP Barrier

Table 1. Equivalent Static Loads for Moment Slab Design (adapted from NCHRP 22-20(02) Table 1.4.2-1)

Test Designation	TL-2	TL-3	TL-4 (1)	TL-4 (2)	TL-5 (1)	TL-5 (2)
Rail Height, H (in)	18	32	36	>36	42	>42
L_s (kips)	9 (interpolation)	23	28	28	80	132
H_e (in)	20	24	25	30	34	43
W_{min} (ft)	4	4	4.5	4.5	7	12

The strength of the mid-section (mid-span case) was also evaluated for this project. Additional reinforcement was recommended for the barrier and the concrete flat work (sidewalk) to gain adequate resistance for MASH TL-2 impact conditions. Based on our analyses, it is recommended that the vertical "V1" (#5 stirrups) Bars in the mid-section of the barrier, be spaced on 4'-0" centers to meet the strength requirements of MASH TL-2 impact conditions. It is recommended that the "P1" Bars anchor into the 6 inches thick concrete sidewalk a minimum depth of 4.0 inches (top cover) with a bottom cover of 1 3/8" (minimum) and spaced on 24 inches on centers. The "P1" Bars should be fabricated using an 8.0 inches long hook. This hook should anchor into the sidewalk concrete a minimum depth of 4.0 inches (top cover). This P1 bar should extend up into the barrier a minimum of 20 inches. It is recommended that the #5 transverse reinforcement in the sidewalk be spaced on 10 inches on centers and located 2 ¼" from the top of the sidewalk. The detailed calculations developed for this project are provided in appendix. Table 2 summarizes the overall analysis results for both the End-Section and Mid-Span Section.

Table 2. Evaluation of Barrier for MASH TL-2 Conditions

Item	Demand	Calculated/Provided	Check
End-Section Case			
Minimum height (in.)	18	42	O.K.
Ultimate resistance at midspan (kip)	27	382	O.K.
Ultimate resistance at end/joint (kip)	27	293	O.K.
Punching Shear capacity of interior segment (kip)	27	112	O.K.
Punching Shear capacity of end segment (kip)	27	74	O.K.
Sliding (kip)	9	11	O.K.
Overturning (kip-ft)	24	53	O.K.
Shear capacity (kip)	27	84	O.K.
Torsional capacity (kip-ft)	45	85	O.K.
Mid-Span Case			
Item	**Demand**	**Calculated/Provided**	**Check**
Minimum height (in.)	18	42	O.K.
Ultimate resistance (kip)	27	115	O.K.
Punching Shear capacity (kip)	27	112	O.K.
Shear capacity (kip)	27	60	O.K.
Torsional capacity (kip-ft)	45	67	O.K.

Summary

The barrier as shown in Figure 1 was evaluated in accordance with AASHTO LRFD 2022 and NCHRP 22-20(02) design guidelines for test level TL-2 impact load condition. Based on the information provided in Table 2, the 42 inches high single slope barrier anchored to the moment slab and sidewalk as analyzed/designed herein, meets the strength and performance requirements of MASH Test Level 2.

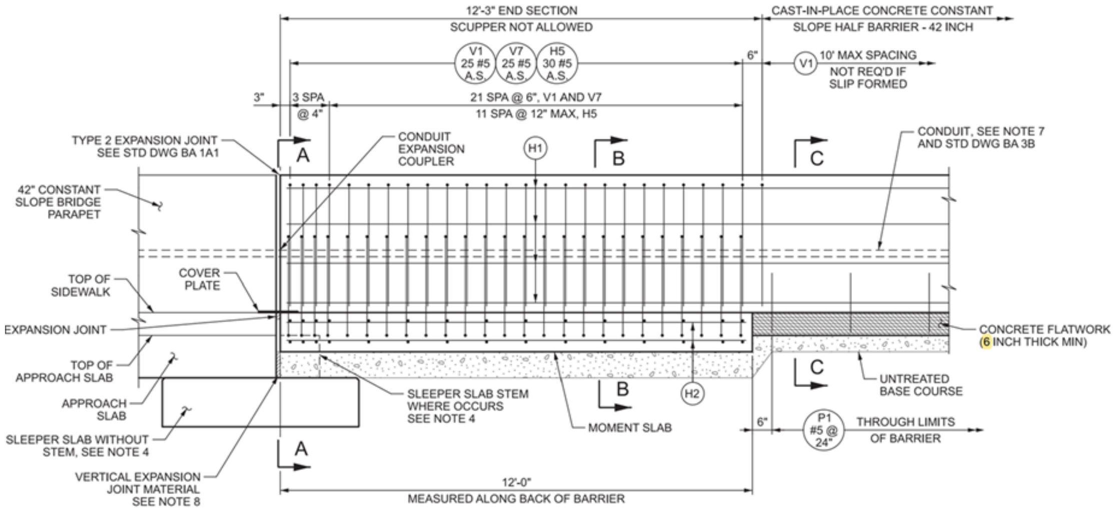
Reference

1.) National Academies of Sciences, Engineering, and Medicine 2022. (NCHRP Project 22-20(02)). "Design Guidelines for Test Level 3 through Test Level 5 Roadside Barrier Systems Placed on Mechanically Stabilized Earth Retaining Walls" Washington DC. (https://doi.org/10.17226/26580.)

2.) AASHTO (2020). "LRFD Bridge Design Specifications" Seventh edition, American Association of State Highway and Transportation Officials, Washington DC.

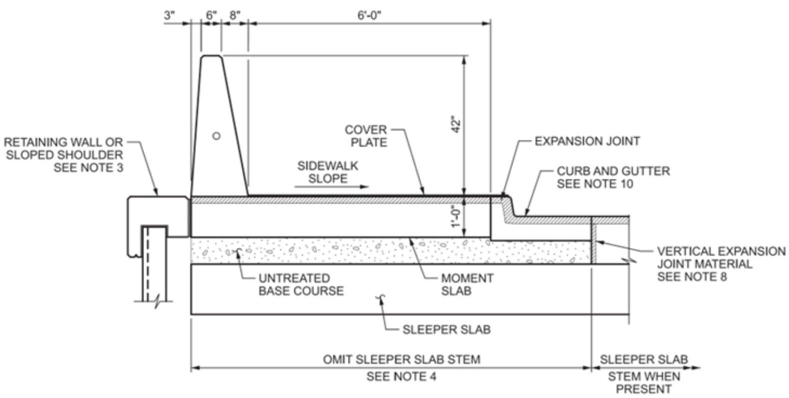
Appendix A.
Calculation Worksheet – Region A

Given the Design Details:

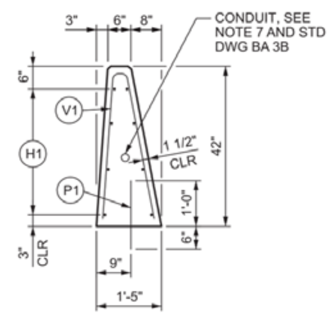


ELEVATION

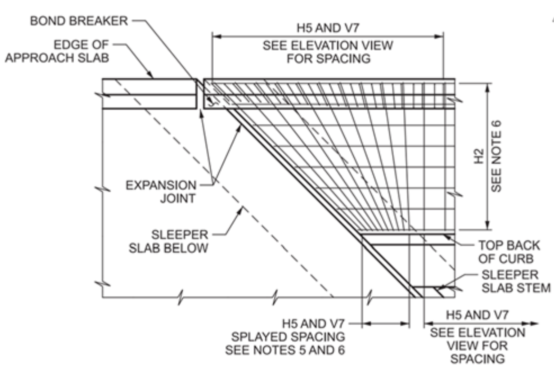
42 INCH CONSTANT SLOPE HALF BARRIER TO
42 INCH CONSTANT SLOPE BRIDGE PARAPET



VIEW A-A

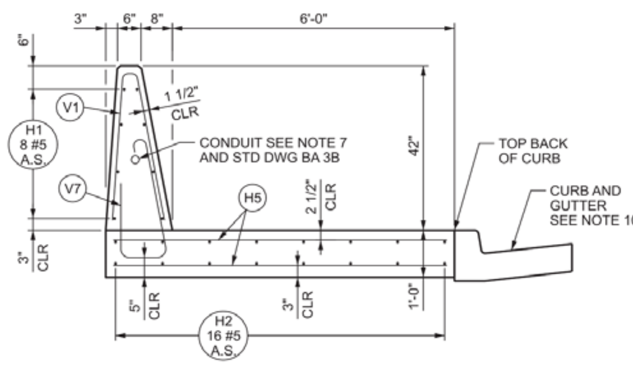


SECTION C-C



PARTIAL PLAN AT TYPICAL SKEWED APPROACH SLAB

BARRIER REINFORCEMENT AND COVER PLATE NOT SHOWN FOR CLARITY
BRIDGE SKEW OF 45 DEGREES SHOWN, SEE NOTES 5 AND 6
DO NOT SPLAY BARRIER REINFORCEMENT



SECTION B-B

(1) General Information and Inputs:

This calcualtion was presetned to evaluate the strength, sliding, and stability of the given barreier design to meet MASH TL-2 impact load condtions.

(1a) General Inputs:

$f'_c := 4000\ psi$ — *Compressive strength of concrete*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$E_s := 29000\ ksi$ — *Modulus of elasticity of steel*

$H_w := 42\ in$ — *Height of concrete barrier measured from top of the roadway*

$t_o := 0\ in$ — *Asphalt thickness*

$h_w := H_w + t_o = 42\ in$ — *Total height of barrier*

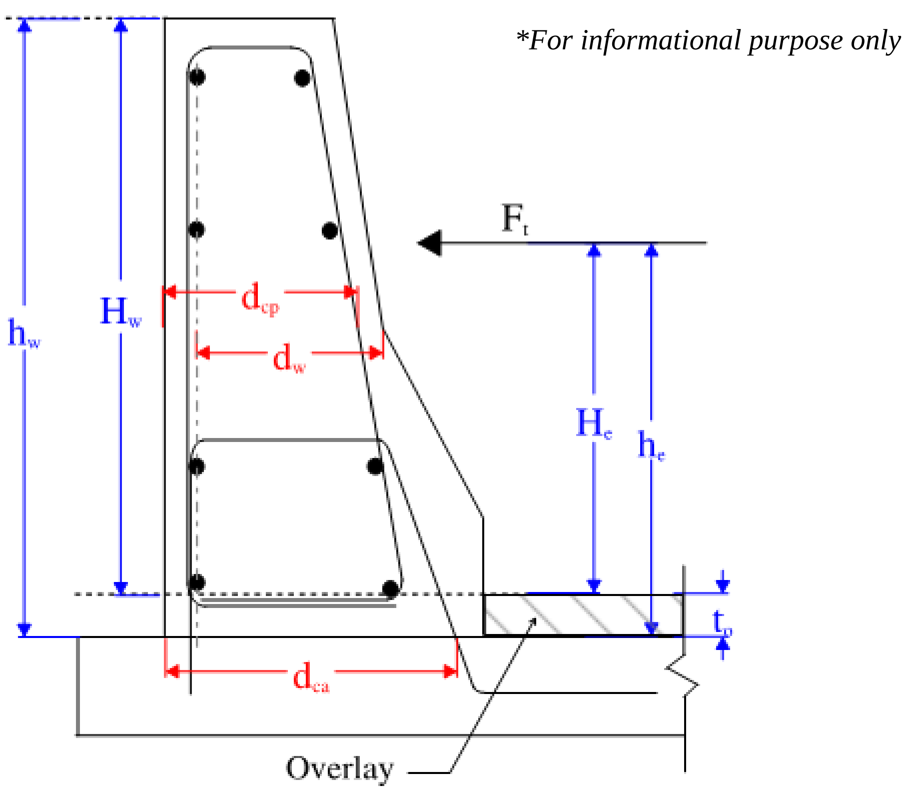


Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable

(1b) Concrete Parapet Inputs:

Parapet vertical reinforcement inputs:

$A_{vpl.mid} := 0.31\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} := 6\ in$ *Spacing of parapet vertical reinforcement at midspan*

$d_{cp.mid} := 11.5\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$A_{vpl.end} := 0.31\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} := 4\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$d_{cp.end} := 11.5\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ ends*

Deck anchorage vertical reinforcement inputs:

$A_{val.mid} := 0.31\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 15\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$A_{val.end} := 0.31\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} := 4\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$d_{ca.end} := 15\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

Longitudinal reinforcement inputs:

$A_w := 0.31 \cdot 4\ in^2 = 1.24\ in^2$ *Area of longitudinal reinforcement bars in tension*

$d_w := 10\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

(1c) Design Force Inputs:

Design Forces for Traffic Railings

Test Level	Rail Height (in.)	F_t (kip)	F_L (kip)	F_v (kip)	L_t/L_L (ft)	L_v (ft)	H_e (in)	H_{min} (in)
TL-1	18 or above	13.5	4.5	4.5	4.0	18.0	18.0	18.0
TL-2	18 or above	27.0	9.0	4.5	4.0	18.0	20.0	18.0
TL-3	29 or above	71.0	18.0	4.5	4.0	18.0	19.0	29.0
TL-4 (a)	36	68.0	22.0	38.0	4.0	18.0	25.0	36.0
TL-4 (b)	between 36 and 42	80.0	27.0	22.0	5.0	18.0	30.0	36.0
TL-5 (a)	42	160.0	41.0	80.0	10.0	40.0	35.0	42.0
TL-5 (b)	greater than 42	262.0	75.0	160.0	10.0	40.0	43.0	42.0
TL 6		175.0	58.0	80.0	8.0	40.0	56.0	90.0

References:

- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

$TL := 2$ — *Test level*

$F_t := 27\ kip$ — *Transverse impact force*

$L_t := 4\ ft$ — *Longitudinal length of distribution of impact force*

$H_e := 20\ in$ — *Height of equivalent transverses load*

$H_{min} := 18\ in$ — *Minimum height of a MASH TL-2 barrier*

$H_w := 42\ in$ — *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

(2) Stability Criteria:

$H_{min} = 18\ in$ — *Minimum height of a MASH TL-2 barrier*

$H_w = 42\ in$ — *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

```
Minimum_Height_of_Barrier_Check := if H_w > H_min
                                       "OK"
                                   else
                                       "Not OK"
```

Minimum_Height_of_Barrier_Check = "OK"

(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:

(3a) Bending Capacity of the Wall about the Longitudinal Axis at Midspan: M_{cmid} (k-ft/ft)

For parapet vertical reinforcement:

$b_c := 12\ in$ — *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.31\ in^2$ — *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 6\ in$ — *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.62\ in^2$$

Total area of parapet vertical reinforcement per unit length at midspan

$d_{cp.mid} = 11.5\ in$ — *Average extreme distance of parapet vertical reinforcement at midspan*

$$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.912\ in$$

Depth of Whitney stress block

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 34.237\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)

For deck anchorage reinforcement:

$A_{val.mid} = 0.31\ in^2$ — *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 6\ in$ — *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.62\ in^2$$

Total area of deck anchorage vertical reinforcement per unit length at midspan

$d_{ca.mid} = 15\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.912\ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 45.087\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)

$$M_{cmid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 34.237\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement

(3b) Bending Capacity of the Wall about the Longitudinal Axis at Joints/Ends: M_{cend} (k-ft/ft)

For parapet vertical reinforcement:

$A_{vpl.end} = 0.31\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} = 4\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$$A_{vp.end} := \left(\frac{b_c}{S_{vp.end}}\right) \cdot A_{vpl.end} = 0.93\ in^2$$ *Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{cp.end} = 11.5\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ends*

$$a_{cp.end} := \frac{A_{vp.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 1.368\ in$$ *Depth of Whitney stress block*

$$M_{cp.end} := \frac{\left(A_{vp.end} \cdot f_y \cdot \left(d_{cp.end} - \frac{a_{cp.end}}{2}\right)\right)}{b_c} = 50.295\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)

For deck anchorage reinforcement:

$A_{val.end} = 0.31\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} = 4\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$A_{va.end} := \left(\frac{b_c}{S_{va.end}}\right) \cdot A_{val.end} = 0.93\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at joints/ends*

$d_{ca.end} = 15\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

$a_{ca.end} := \frac{A_{va.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 1.368\ in$ *Depth of Whitney stress block*

$$M_{ca.end} := \frac{\left(A_{va.end} \cdot f_y \cdot \left(d_{ca.end} - \frac{a_{ca.end}}{2}\right)\right)}{b_c} = 66.57\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)

$$M_{cend} := min\left(M_{cp.end}, M_{ca.end}\right) = 50.295\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at joints/ends when considering the critical reinforcement

(3c) Bending Capacity of the Wall about the Vertical Axis: M_w

$d_w = 10\ in$ *Total height of barrier*

$A_w = 1.24\ in^2$ *Area of longitudinal reinforcement bars in tension*

$h_w = 42\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot h_w} = 0.521\ in$ *Depth of Whitney stress block*

$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 60.385\ kip \cdot ft$ *Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

(3d) Ultimate Resistance of the Wall at Midspan: R_{wmid}

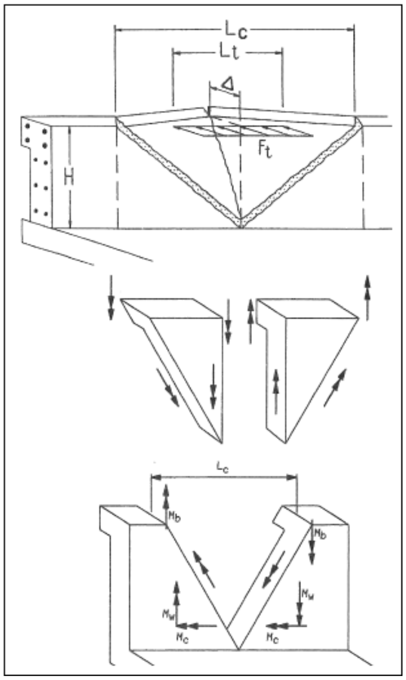


Figure 3d. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment.

$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{cmid} = 34.237\ \dfrac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 60.385\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

$$L_{cmid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{cmid}}} = 9.306\ ft$$

AASHTO Equation A13.3.1-2

$$R_{wmid} := \left(\frac{2}{2 \cdot L_{cmid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{cmid} \cdot (L_{cmid})^2}{H_w}\right) = 182.071\ kip$$

AASHTO Equation A13.3.1-1

(3e) Ultimate Resistance of the Wall at Joints/Ends: R_{wend}

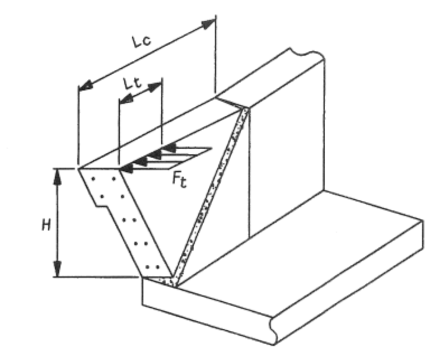


Figure 3e. Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment

$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{cend} = 50.295\ \dfrac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at joints/ends*

$M_w = 60.385\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

$$L_{cend} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{H_w \cdot (M_B + M_w)}{M_{cend}}} = 4.864\ ft$$

AASHTO Equation A13.3.1-4

$$R_{wend} := \left(\frac{2}{2 \cdot L_{cend} - L_t}\right) \cdot \left(M_B + M_w + \frac{M_{cend} \cdot (L_{cend})^2}{H_w}\right) = 139.79\ kip$$

AASHTO Equation A13.3.1-3

(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:

$H_w = 42\ in$ — *Height of the concrete barrier measured from the top of the roadway surface*

$R_{wmid} = 182.071\ kip$ — *Ultimate resistance of the wall at midspan*

$R_{wend} = 139.79\ kip$ — *Ultimate resistance of the wall at joints/ends*

$H_e = 20\ in$ — *Height of the transverse impact force, F_t*

$R_{R.mid} := R_{wmid} \cdot \left(\frac{H_w}{H_e}\right) = 382.349\ kip$ — *Structural capacity of the barrier at midspan located at H_e*

$R_{R.end} := R_{wend} \cdot \left(\frac{H_w}{H_e}\right) = 293.559\ kip$ — *Structural capacity of the barrier at joints/ends located at H_e*

$F_t = 27\ kip$ — *Transverses impact force located at H_e*

```
Structural_Capacity_of_Barrier_at_Midspan_Check := if R_R.mid > F_t
                                                      "OK"
                                                   else
                                                      "Not OK"
```

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

$$\text{Structural\_Capacity\_of\_Barrier\_at\_Ends\_Check} := \begin{array}{l} \text{if } R_{R.mid} > F_t \\ \quad \| \text{“OK”} \\ \text{else} \\ \quad \| \text{“Not OK”} \end{array}$$

$$\text{Structural\_Capacity\_of\_Barrier\_at\_Ends\_Check} = \text{“OK”}$$

(4) Punching Shear Capacity of the Barrier:

$\lambda := 1.0$	*Concrete modification factor*
$T_w := 6\ in$	*Top width of the parapet*
$h_c := 40\ in$	*Depth of the shear zone at the critical segment of the barrier*
$d_c := 10\ in$	*Distance from compression face to the tension reinforcement (average widht of the section)*
$L_t = 4\ ft$	*Length of the distribution of the impact force*
$f'_c = 4\ ksi$	*Concrete parapet compressive strength*

(4a) Punching Shear Capacity of an Interior Segment (3 sides) of the Barrier: V_{cint}

$$A_{c.int} := (L_t + d_c) \cdot T_w + 2 \cdot \left(h_c + \frac{d_c}{2}\right) \cdot T_w = 888\ in^2$$

Concrete parapet shear zone area of an interior segment of the barrier

$$V_{c.int} := 2 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{psi}} \cdot psi\right) \cdot A_{c.int} = 112.324\ kip$$

Shear capacity of an interior segment of the barrier

(4b) Punching Shear Capacity of an End Segment (2 sides) of the Barrier: V_{cend}

$$A_{c.end} := \left(L_t + \frac{d_c}{2}\right) \cdot T_w + \left(h_c + \frac{d_c}{2}\right) \cdot T_w = 588\ in^2$$

Concrete parapet shear zone area of an end segment of the barrier

$$V_{c.end} := 2 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{psi}} \cdot psi\right) \cdot A_{c.end} = 74.377\ kip$$

Shear capacity of an end segment of the barrier

$V_c := min\left(V_{c.int}, V_{c.end}\right) = 74.377\ kip$ — *Critical shear capacity of the barrier*

$F_t = 27\ kip$ — *Transverse impact force*

$$\text{Punching\_Shear\_Capacity\_of\_Barrier\_Check} := \begin{cases} \text{"OK"} & \text{if } V_c > F_t \\ \text{"Not OK"} & \text{else} \end{cases}$$

Punching_Shear_Capacity_of_Barrier_Check = "OK"

(5) Sliding and Overturning of the Barrier based on NCHRP Project 22-20(02) Design Guideline:

(5a) Sliding of the Barrier:

$b_{top} := 6\ in$ — *Top width/ of barrier*

$b_{base} := 17\ in$ — *Base width of barrier*

$H_w := 42\ in$ — *Height of concrete barrier measured from top of the roadway*

$t_{slab} := 12\ in$ — *Thickness of moment slab*

$L_{slab} := 89\ in$ — *Length of moment slab*

$L_b := 12\ ft$ — *Width of barrier/moment slab*

$w_{conc} := 0.15\ \frac{kip}{ft^3}$ — *Unit weight of reinforced concrete*

$A_g := \frac{\left(b_{top} + b_{base}\right)}{2} \cdot H_w + t_{slab} \cdot L_{slab} = 10.771\ ft^2$ — *Sectional area*

$W_{total} := A_g \cdot L_b \cdot w_{conc} = 19.388\ kip$ — *Total weight of barrier and moment slab*

$\phi_r := 30\ deg$ — *Friction angle of soil-moment slab interface*
**equal to friction angle of soil for rough interface (e.g., cast in place)*

$P := W_{total} \cdot \tan\left(\phi_r\right) = 11.193\ kip$ — *Static resistance of barrier*
(NCHRP 22-20(02) Eq. 1.4.2-1)

Table 1.4.2-1 Equivalent static loads for moment slab design

Test Designation	TL-3	TL-4 -1-	TL-4 -2-	TL-5 -1-	TL-5 -2-
Rail Height, H (in)	32	36	>36	42	>42
L_s (kips)	23	28	28	80	132
H_e (in)	24	25	30	34	43
W_{min} (ft)	4	4.5	4.5	7	12

* Given the equivalent static loads for moment slab design provided in NCHRP 22-20(02) Section 10-1.4.2, find the equivalent static load L_s for TL-2 using **cubic interpolation**.

Equivalent static load for TL-2 based on the cubic interpolation:

$L_{d\_TL2} := 27\ kip$ *Transverses impact load for TL-2*

$$L_{d\_TL3\_5} := \begin{bmatrix} 70 \\ 80 \\ 160 \\ 260 \end{bmatrix} kip$$ *Transverses impact load for TL-3 through TL-5*

$$L_{s\_TL3\_5} := \begin{bmatrix} 23 \\ 28 \\ 80 \\ 132 \end{bmatrix} kip$$ *Equivalent static load for TL-3 through TL-5*

$c := \text{cspline}\left(L_{d\_TL3\_5}, L_{s\_TL3\_5}\right)$

$L_{s\_TL2} := \text{interp}\left(c, L_{d\_TL3\_5}, L_{s\_TL3\_5}, L_{d\_TL2}\right) = 9.109\ kip$ *Equivalent static load for TL-2*

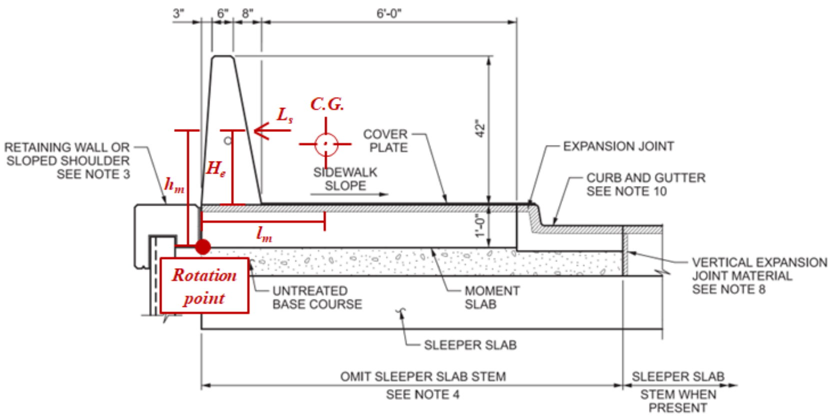
$\phi := 1.0$ *Resistance factor (AASHTO LRFD 10.5.5.3.3)*

$\gamma := 1.0$ *Load factor (NCHRP 22-20(02) Section 10-1.4.2)*

```
Sliding_of_Barrier_Check := if φ·P > γ·L_s_TL2
                               ‖ "OK"
                            else
                               ‖ "Not OK"
```

Sliding_of_Barrier_Check = "OK"

(5b) Overturning of the Barrier:



VIEW A-A

* The rotation point and the application of the static equivalent on the barrier is shown in the diagram.

$L_{s\_TL2} = 9.109\ kip$ — *Equivalent static load for TL-2*

$h_m := 32\ in$ — *Vertical moment arm to the point of rotation*

$$l_m := \frac{3 \cdot 42 \cdot \frac{1}{2} \cdot \frac{2}{3} \cdot 3 + 6 \cdot 42 \cdot \left(\frac{6}{2} + 3\right) + 8 \cdot 42 \cdot \frac{1}{2} \cdot \left(\frac{8}{3} + 3 + 6\right) + 12 \cdot 89 \cdot \frac{89}{2}}{3 \cdot 42 \cdot \frac{1}{2} + 6 \cdot 42 + 8 \cdot 42 \cdot \frac{1}{2} + 12 \cdot 89} \cdot in = 32.962\ in$$

Horizontal distance from the C.G. of the weight W to the point of rotation (please refer to the design drawings for the section dimensions)

$W_{total} = 19.388\ kip$ — *Total weight of barrier and moment slab*

$M := W_{total} \cdot l_m = 53.254\ kip \cdot ft$ — *Static moment resistance (NCHRP 22-20(02) Eq. 1.4.3-2)*

$L_{s\_TL2} \cdot h_m = 24.292\ kip \cdot ft$ — *Demand*

$\phi := 1.0$ — *Resistance factor (AASHTO LRFD 10.5.5.3.3)*

$\gamma := 1.0$ — *Load factor (NCHRP 22-20(02) Section 10-1.4.3)*

$$\text{Overturning\_of\_Barrier\_Check} := \text{if } \phi \cdot M > \gamma \cdot L_{s\_TL2} \cdot h_m \;\; \|\; \text{“OK”} \;\; \text{else} \;\; \|\; \text{“Not OK”}$$

$$\text{Overturning\_of\_Barrier\_Check} = \text{“OK”}$$

(6) Shear and Torsional Capacity of the Barrier at the Transition Part (Section C-C):

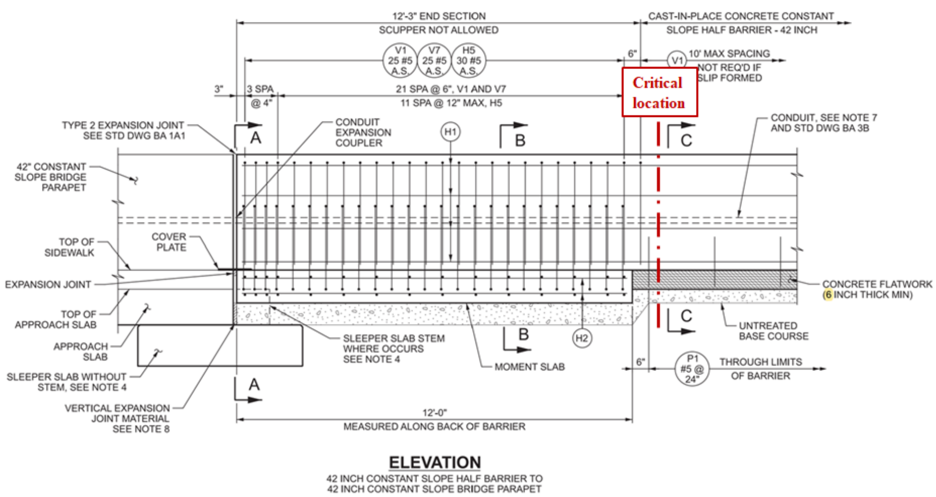


Figure 5. Critical section to check the shear and torsional capacity

(6a) Shear Capacity of the Barrier at Section C-C:

$F_t := 27 \; kip$ — *Transverse impact force*

$b_{v\_b} := 42 \; in$ — *Effecitve width of shear section*

$d_{v\_b} := 10 \; in$ — *Effecitve depth of shear section (avearege width of the section)*

$f'_c := 4000 \; psi$ — *Compressive strength of concrete*

$$V_{nb\_conc} := 0.0316 \cdot 2 \cdot \left(\sqrt{\frac{f'_c}{1000 \cdot psi}} \cdot ksi \right) \cdot b_{v\_b} \cdot d_{v\_b} = 53.088 \; kip$$

Shear resistance from concrete part (AASHTO LRFD Eq. 5.7.3.3-3)

$A_v := 0.31 \cdot 2\ in^2 = 0.62\ in^2$ — *Area of transverses reinforcement*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$s := 12\ in$ — *Spacing of transverses reinforcement*

$\theta := 45\ deg$ — *Angle of inclination of diagonal compresseive stresses (take as 45 degree for simplicity)*

$$V_{nb\_reinf} := \frac{A_v \cdot f_y \cdot d_{v\_b} \cdot \cot(\theta)}{s} = 31\ kip$$

Shear resistance from transverse reinforcement (AASHTO LRFD Eq. 5.7.3.3-4)

$$V_{nb\_total} := V_{nb\_conc} + V_{nb\_reinf} = 84.088\ kip$$

Nominal shear resistance of the barrier (AASHTO LRFD Eq. 5.7.3.3-1)

```
Shear_Capacity_of_Barrier_Check := if V_nb_total > F_t
                                       "OK"
                                   else
                                       "Not OK"
```

Shear_Capacity_of_Barrier_Check = "OK"

(6b) Torsional Capacity of the Barrier at Section C-C:

$H_e := 20\ in$ — *Effective barrier height*

$T_{ub} := F_t \cdot H_e = 45\ kip \cdot ft$ — *Maximum torque applied on the barrier section*

$A_o := 331.5\ in^2$ — *Area enclosed by the shear flow path (enclosed area of transverse reinforcement)*

$A_t := 0.31\ in^2$ — *Area of one leg of closed transverses torsion reinforcement*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$s := 12\ in$ — *Spacing of transverses reinforcement*

$\theta := 45\ deg$ — *Angle of inclination of diagonal compresseive stresses (take as 45 degree for simplicity)*

$T_{nb} := \frac{2 \cdot A_o \cdot A_t \cdot f_y \cdot \cot(\theta)}{s} = 85.638 \ kip \cdot ft$

Torsional resistance of the barrier (AASHTO LRFD Eq. 5.7.3.6.2-1)

Torsional_Capacity_of_Barrier_Check := if $T_{nb} > T_{ub}$
    "OK"
else
    "Not OK"

Torsional_Capacity_of_Barrier_Check = "OK"

(7) Conclusions:

Minimum_Height_of_Barrier_Check = "OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

Sliding_of_Barrier_Check = "OK"

Overturning_of_Barrier_Check = "OK"

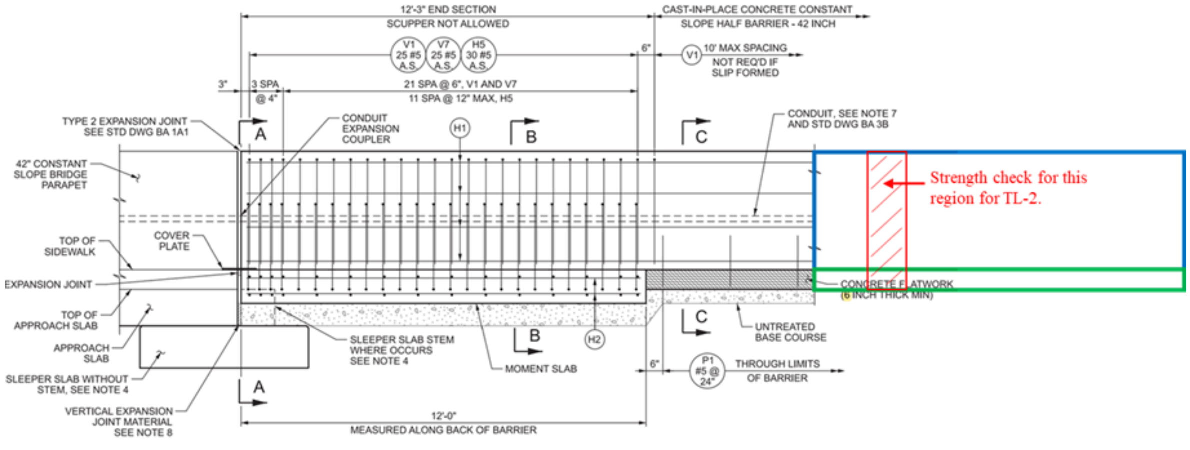
Shear_Capacity_of_Barrier_Check = "OK"

Torsional_Capacity_of_Barrier_Check = "OK"

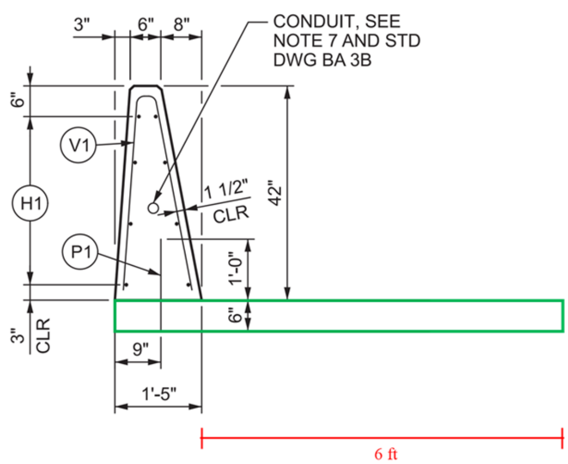
This barrier does satisfy MASH TL-2 criteria.

Appendix B.
Calculation Worksheet – Region B

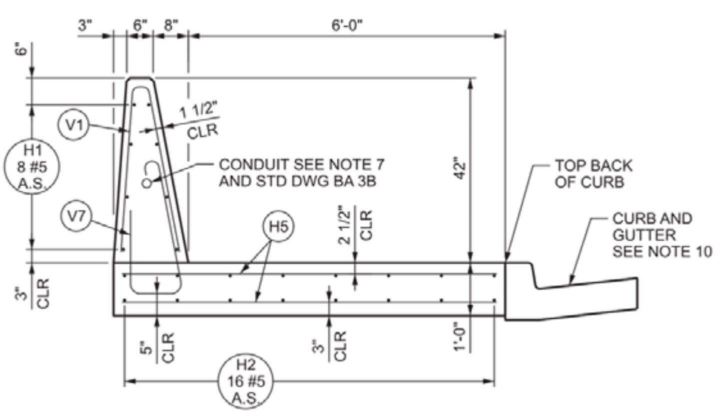
<u>Continued to check the strength at the region indicated below:</u>



ELEVATION
42 INCH CONSTANT SLOPE HALF BARRIER TO 42 INCH CONSTANT SLOPE BRIDGE PARAPET



SECTION C-C



SECTION B-B

(1) General Information and Inputs:

This calcualtion was presetned to evaluate the strength, sliding, and stability of the given barreier design to meet MASH TL-2 impact load condtions.

(1a) General Inputs:

$f'_c := 4000\ psi$	*Compressive strength of concrete*
$f_y := 60\ ksi$	*Yield strength reinforcing steel*
$E_s := 29000\ ksi$	*Modulus of elasticity of steel*
$H_w := 42\ in$	*Height of concrete barrier measured from top of the roadway*
$t_o := 0\ in$	*Asphalt thickness*
$h_w := H_w + t_o = 42\ in$	*Total height of barrier*

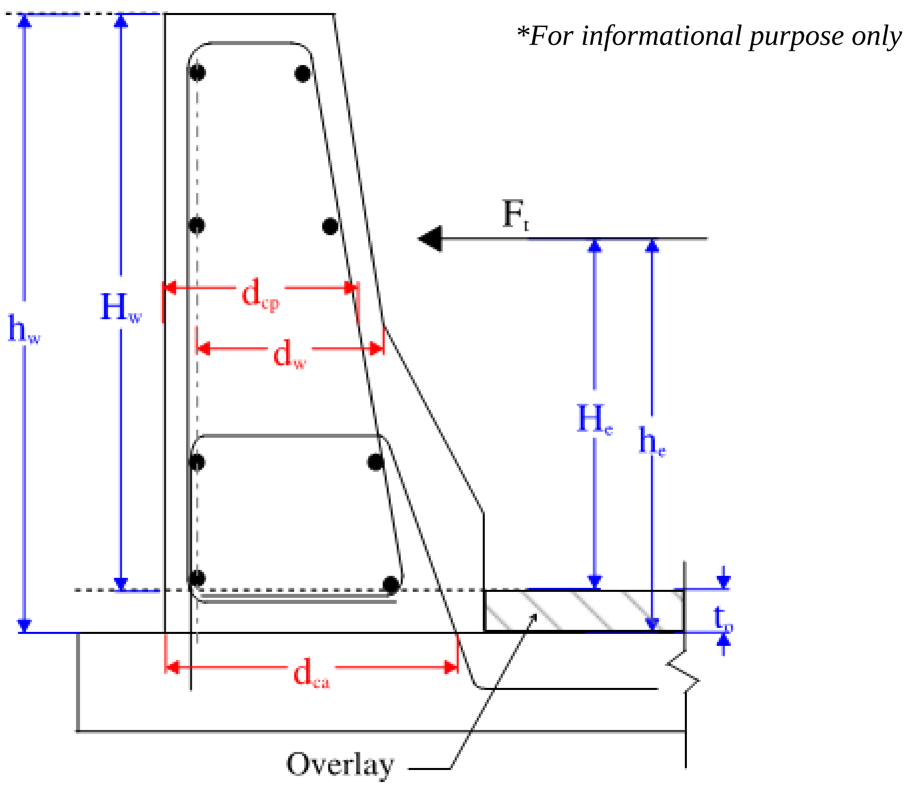


Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable

(1b) Concrete Parapet Inputs:

Parapet vertical reinforcement inputs:

Note that, the **vertical reinforcement (V1 bars)** were not provided at this region in the proposed design. It is recommended to provide the vertical reinforcement to the barrier to achieved the adequate strength.

$A_{vpl.mid} := 0.31\ in^2$ — *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} := 48\ in$ — *Spacing of parapet vertical reinforcement at midspan*

$d_{cp.mid} := 11.5\ in$ — *Average extreme distance of parapet vertical reinforcement at midspan*

Deck anchorage vertical reinforcement inputs:

$A_{val.mid} := 0.31\ in^2$ — *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 24\ in$ — *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 9\ in$ — *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$d_{dowel} := \frac{5}{8}\ in$ — *Diameter of deck anchorage bars*

$h_{ef} := 6\ in$ — *Embedment depth of deck anchorage bars*

Longitudinal reinforcement inputs:

$A_w := 0.31 \cdot 4\ in^2 = 1.24\ in^2$ — *Area of longitudinal reinforcement bars in tension*

$d_w := 10\ in$ — *Extreme distance of tension longitudinal reinforcement of barrier*

(1c) Design Force Inputs:

Design Forces for Traffic Railings

Test Level	Rail Height (in.)	F_t (kip)	F_L (kip)	F_v (kip)	L_t/L_L (ft)	L_v (ft)	H_e (in)	H_{min} (in)
TL-1	18 or above	13.5	4.5	4.5	4.0	18.0	18.0	18.0
TL-2	18 or above	27.0	9.0	4.5	4.0	18.0	20.0	18.0
TL-3	29 or above	71.0	18.0	4.5	4.0	18.0	19.0	29.0
TL-4 (a)	36	68.0	22.0	38.0	4.0	18.0	25.0	36.0
TL-4 (b)	between 36 and 42	80.0	27.0	22.0	5.0	18.0	30.0	36.0
TL-5 (a)	42	160.0	41.0	80.0	10.0	40.0	35.0	42.0
TL-5 (b)	greater than 42	262.0	75.0	160.0	10.0	40.0	43.0	42.0
TL 6		175.0	58.0	80.0	8.0	40.0	56.0	90.0

References:

- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

$TL := 2$ — *Test level*

$F_t := 27\ kip$ — *Transverse impact force*

$L_t := 4\ ft$ — *Longitudinal length of distribution of impact force*

$H_e := 20\ in$ — *Height of equivalent transverses load*

$H_{min} := 18\ in$ — *Minimum height of a MASH TL-2 barrier*

$H_w := 42\ in$ — *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

(2) Stability Criteria:

$H_{min} = 18\ in$ — *Minimum height of a MASH TL-2 barrier*

$H_w = 42\ in$ — *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

```
Minimum_Height_of_Barrier_Check := if H_w > H_min
                                       ‖ "OK"
                                   else
                                       ‖ "Not OK"
```

Minimum_Height_of_Barrier_Check = "OK"

(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:

(3a) Bending Capacity of the Wall about the Longitudinal Axis: **M_{cmid} (k-ft/ft)**

For parapet vertical reinforcement:

$b_c := 12\ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.31\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 48\ in$ *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.078\ in^2$$

Total area of parapet vertical reinforcement per unit length at midspan

$d_{cp.mid} = 11.5\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.114\ in$$ *Depth of Whitney stress block*

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 4.434\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)

For deck anchorage reinforcement:

$A_{val.mid} = 0.31\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 24\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.155\ in^2$$

Total area of deck anchorage vertical reinforcement per unit length at midspan

$d_{ca.mid} = 9\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.228\ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 6.887\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)

$$M_{cmid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 4.434\ \frac{kip \cdot ft}{ft}$$

Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement

<u>(3b) Bending Capacity of the Wall about the Vertical Axis:</u> M_w

$d_w = 10\ in$ *Total height of barrier*

$A_w = 1.24\ in^2$ *Area of longitudinal reinforcement bars in tension*

$h_w = 42\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

$$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot h_w} = 0.521\ in$$ *Depth of Whitney stress block*

$$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 60.385\ kip \cdot ft$$ *Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

(3d) Ultimate Resistance of the Wall at Midspan: R_{wmid}

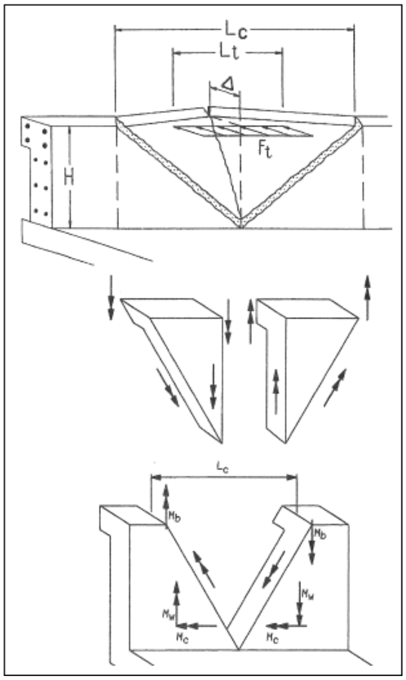


Figure 3d. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment.

$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{cmid} = 4.434\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 60.385\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

$$L_{cmid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{cmid}}} = 21.629\ ft$$

AASHTO Equation A13.3.1-2

$$R_{wmid} := \left(\frac{2}{2 \cdot L_{cmid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{cmid} \cdot (L_{cmid})^2}{H_w}\right) = 54.804\ kip$$

AASHTO Equation A13.3.1-1

(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:

$H_w = 42\ in$ — *Height of the concrete barrier measured from the top of the roadway surface*

$R_{wmid} = 54.804\ kip$ — *Ultimate resistance of the wall at midspan*

$H_e = 20\ in$ — *Height of the transverse impact force, F_t*

$R_{R.mid} := R_{wmid} \cdot \left(\frac{H_w}{H_e}\right) = 115.089\ kip$ — *Structural capacity of the barrier at midspan located at He*

$F_t = 27\ kip$ — *Transverses impact force located at He*

```
Structural_Capacity_of_Barrier_at_Midspan_Check := if R_R.mid > F_t
                                                       ‖ "OK"
                                                    else
                                                       ‖ "Not OK"
```

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

(4) Punching Shear Capacity of the Barrier - Interior Segment (3 sides): V_{cint}

$\lambda := 1.0$ — *Concrete weight modification factor*

$T_w := 6\ in$ — *Top width of the parapet*

$h_c := 40\ in$ — *Depth of the shear zone at the critical segment of the barrier*

$d_c := 10\ in$ — *Distance from compression face to the tension reinforcement (average widht of the section)*

$L_t = 4\ ft$ — *Length of the distribution of the impact force*

$f'_c = 4\ ksi$ — *Concrete parapet compressive strength*

$A_{c.int} := (L_t + d_c) \cdot T_w + 2 \cdot \left(h_c + \frac{d_c}{2}\right) \cdot T_w = 888\ in^2$ — *Concrete parapet shear zone area of an interior segment of the barrier*

$V_{c.int} := 2 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{psi}} \cdot psi\right) \cdot A_{c.int} = 112.324\ kip$ — *Shear capacity of an interior segment of the barrier*

$F_t = 27\ kip$ — *Transverse impact force*

$$\text{Punching\_Shear\_Capacity\_of\_Barrier\_Check} := \text{if } V_{c.int} > F_t \;\; \| \text{ "OK" } \;\; \text{else} \;\; \| \text{ "Not OK"}$$

$$\text{Punching\_Shear\_Capacity\_of\_Barrier\_Check} = \text{"OK"}$$

<u>(5) Shear Capacity of the Barrier:</u> V_{nb}

$F_t = 27\ kip$ — *Transverse impact force*

$b_{v\_b} := 42\ in$ — *Effecitve width of shear section*

$d_{v\_b} := 10\ in$ — *Effecitve depth of shear section (avearege width of the section)*

$f'_c = 4000\ psi$ — *Compressive strength of concrete*

$$V_{nb\_conc} := 0.0316 \cdot 2 \cdot \left(\sqrt{\frac{f'_c}{1000 \cdot psi}} \cdot ksi\right) \cdot b_{v\_b} \cdot d_{v\_b} = 53.088\ kip$$

Shear resistance from concrete part (AASHTO LRFD Eq. 5.7.3.3-3)

$A_v := 0.31 \cdot 2\ in^2 = 0.62\ in^2$ — *Area of transverses reinforcement*

$f_y = 60\ ksi$ — *Yield strength reinforcing steel*

$S_{vp.mid} = 48\ in$ — *Spacing of transverses reinforcement*

$\theta := 45\ deg$ — *Angle of inclination of diagonal compresseive stresses (take as 45 degree for simplicity)*

$$V_{nb\_reinf} := \frac{A_v \cdot f_y \cdot d_{v\_b} \cdot \cot(\theta)}{S_{vp.mid}} = 7.75\ kip$$

Shear resistance from transverse reinforcement (AASHTO LRFD Eq. 5.7.3.3-4)

$$V_{nb} := V_{nb\_conc} + V_{nb\_reinf} = 60.838\ kip$$

Nominal shear resistance of the barrier (AASHTO LRFD Eq. 5.7.3.3-1)

Shear_Capacity_of_Barrier_Check := if $V_{nb} > F_t$
  "OK"
else
  "Not OK"

Shear_Capacity_of_Barrier_Check = "OK"

(6) Torsional Capacity of the Barrier: T_{nb}

$H_e = 20\ in$ — *Height of equivalent transverses load*

$T_{ub} := F_t \cdot H_e = 45\ kip \cdot ft$ — *Maximum torque applied on the barrier section*

(6a) Cracking torque of the concrete section:

$A_{cp} := 483\ in^2$ — *Gross area of the barrier section*

$p_c := 107\ in$ — *Perimeter of the barrier section*

$$T_{cr} := 0.126 \cdot \left(\sqrt{\frac{f'_c}{1000 \cdot psi}} \cdot ksi\right) \cdot \left(\frac{A_{cp}^{\ 2}}{p_c}\right) = 45.786\ kip \cdot ft$$

Cracking torque of the section

*(*torsional effects shall be investigated if the torque T_u applied on the section is larger than 0.25 T_{cr} as per AASHTO LRFD Eq. 5.7.2.1-3)*

(6b) Torsional resistance from the reinforcement:

$A_o := 331.5\ in^2$ — *Area enclosed by the shear flow path (enclosed area of transverse reinforcement)*

$A_t := 0.31\ in^2$ — *Area of one leg of closed transverses torsion reinforcement*

$f_y = 60\ ksi$ — *Yield strength reinforcing steel*

$S_{vp.mid} = 48\ in$ — *Spacing of transverses reinforcement*

$\theta := 45\ deg$ — *Angle of inclination of diagonal compresseive stresses (take as 45 degree for simplicity)*

$$T_{nr} := \frac{2 \cdot A_o \cdot A_t \cdot f_y \cdot \cot(\theta)}{S_{vp.mid}} = 21.409\ kip \cdot ft$$

Torsional resistance of the reinforcement (AASHTO LRFD Eq. 5.7.3.6.2-1)

$T_{nb} := T_{cr} + T_{nr} = 67.195\ kip \cdot ft$ — *Total Torsional resistance of the barrier*

```
Torsional_Capacity_of_Barrier_Check := if T_nb > T_ub
                                           ‖ "OK"
                                       else
                                           ‖ "Not OK"
```

Torsional_Capacity_of_Barrier_Check = "OK"

(7) Slab (Flat Work) Reinforcement:

The moment resistance of the slab need to be stronger than the moment capacity of the deck anchorage reinforcement - the dowel bars spaced at 24 in.

Check strength of the deck anchorage bars for potential failure modes:

(i) Steel strength of anchor:

$A_{val.mid} = 0.31\ in^2$ — *Area of one deck anchorage reinforcement*

$f_y = 60\ ksi$ — *Yield strength of reinforcing steel*

$N_{sa} := A_{val.mid} \cdot f_y = 18.6\ kip$ — *Steel strength of a single dowel bar*

(ii) Concrete breakout strength (ACI 318 17.4.2):

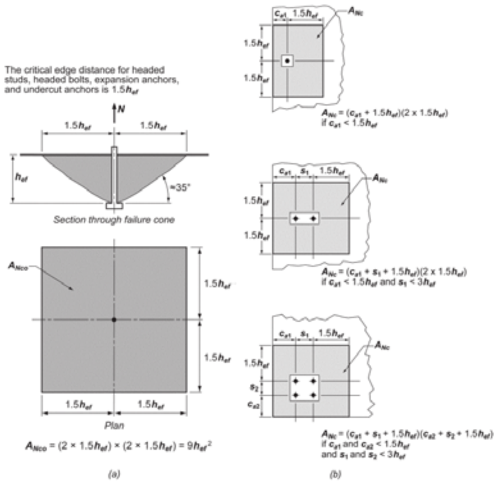


Fig. R17.4.2.1—(a) Calculation of A_{Nco} and (b) calculation of A_{Nc} for single anchors and groups of anchors.

**Figure taken from ACI 318*

$h_{ef} := 4.3125\ in$ *Embedment depth of anchorage bar*

$c_{a.min} := 9\ in$ *Minimum edge distance of anchorage bar*

$1.5 \cdot h_{ef} = 6.469\ in$ *Required edge distance for fully developed concrete projected area*

- A fully developed concrete projected area can be used for the anchorage bars for concrete breakout failure.

$A_{Nc} := 9 \cdot h_{ef}^{\ 2} = 167.379\ in^2$ *Projected concrete failure area of a single anchorage bar based on ACI 318 Figure R17.4.2.1*

$A_{Nco} := 9 \cdot h_{ef}^{\ 2} = 167.379\ in^2$ *Projected concrete failure area of a single anchor with an edge distance equal to or greater than 1.5 hef (ACI 318 Eq. 17.4.2.1c)*

$k_c := 17$ *Coefficient factor for post-installed anchors (ACI 318 17.4.2.2)*

$\lambda := 1.0$ *Concrete weight modification factor*

$f'_c = 4000\ psi$ *Compressive strength of concrete*

$$N_b := k_c \cdot \lambda \cdot \left(\frac{h_{ef}}{in}\right)^{1.5} \cdot \sqrt{\frac{f'_c}{psi}} \cdot in^2 \cdot psi = 9.629\ kip$$

Basic concrete breakout strength of a single anchor in tension in cracked concrete (ACI 318 Eq. 17.4.2.2a)

$\psi_{ed.N} := 1.0$ *Modification factor for edge effects when $C_{a.min}$ > 1.5 hef (ACI 318 17.4.2.5)*

$\psi_{c.N} := 1.4$ *Modification factor for post-installed anchors in un-cracked concrete, where the value of k_c used is 17 (ACI 318 17.4.2.6)*

$c_{ac} := 2 \cdot h_{ef} = 8.625\ in$ — *Critical edge distance of adhesive anchors (ACI 318 17.7.6)*

$\psi_{cp.N} := \frac{c_{a.min}}{c_{ac}} = 1.043$ — *Modification factor for post-installed anchors designed for uncracked concrete without supplementary reinforcement to control splitting (ACI 318 17.4.2.7)*

$$N_{cb} := \frac{A_{Nc}}{A_{Nco}} \cdot \psi_{ed.N} \cdot \psi_{c.N} \cdot \psi_{cp.N} \cdot N_b = 14.066\ kip$$

Nominal concrete breakout strength of a single anchor in tension (ACI 318 Eq. 17.4.2.1a)

(iv) Governing strength of the deck anchorage bars:

$N_{sa} = 18.6\ kip$ — *Steel strength of a single dowel bar*

$N_{cb} = 14.066\ kip$ — *Nominal concrete breakout strength of a single anchor in tension (ACI 318 Eq. 17.4.2.1a)*

$$N_{dowel} := min\left(N_{sa}, N_{cb}\right) = 14.066\ kip$$

<u>Moment capacity of the deck anchorage reinforcement:</u>

$b_c = 12\ in$ — *Unit width of barrier (take as 1 ft per AASHTO Section 13 procedure)*

$S_{va.mid} = 24\ in$ — *Spacing of deck anchorage reinforcement*

$$N_{u.dowel} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot N_{dowel} = 7.033\ kip$$

Unit strength of the deck anchorage bars in tension

$d_{ca.mid} = 9\ in$ — *Extreme distance of tension deck anchorage reinforcement*

$$a_{ca.mid} := \frac{N_{u.dowel}}{0.85 \cdot f'_c \cdot b_c}$$

Depth of Whitney stress block

$$a_{ca.mid} = 0.172 \; in$$

$$M_{ca.mid} := \frac{\left(N_{u.dowel} \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 5.224 \; \frac{kip \cdot ft}{ft}$$

Flexural resistance of the deck anchorage reinforcement

Determine the required slab reinforcement for various thickness:

$$t_{slab} := \begin{bmatrix} 6 \\ 8 \\ 10 \\ 12 \end{bmatrix} in$$

Slab thickness

$$d_{slab} := t_{slab} - 2.3125 \; in = \begin{bmatrix} 3.6875 \\ 5.6875 \\ 7.6875 \\ 9.6875 \end{bmatrix} in$$

Effective depth of slab (assume 2.3125 in. distance from the edge to the center of the reinforcement)

$$jd_{slab} := 0.95 \cdot d_{slab} = \begin{bmatrix} 3.503 \\ 5.403 \\ 7.303 \\ 9.203 \end{bmatrix} in$$

Assume lever arm ratio j as 0.95 for simplicity

$$A_{s.req} := \frac{M_{ca.mid}}{f_y \cdot jd_{slab}} = \begin{bmatrix} 0.0249 \\ 0.0161 \\ 0.0119 \\ 0.0095 \end{bmatrix} \frac{in^2}{in}$$

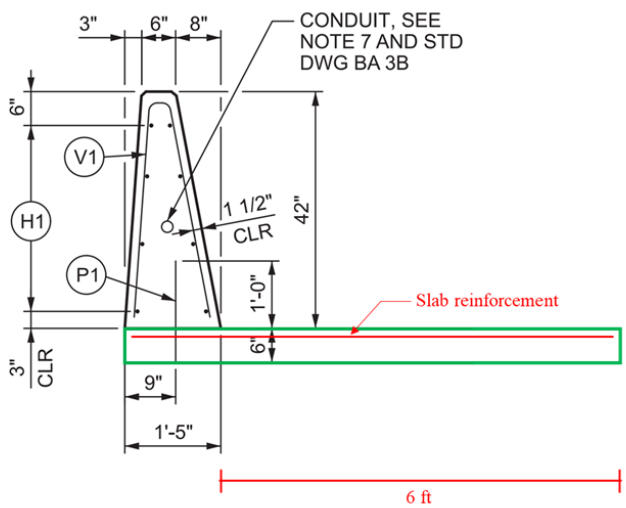
Required reinforcement area per unit width

Required reinforcement spacing for **#5 bar**:

$A_{\#5} := 0.31\ in^2$

For slab thickness, required reinforcement spacing.

$$t_{slab} = \begin{bmatrix} 6 \\ 8 \\ 10 \\ 12 \end{bmatrix} in \qquad S_{s.req.\#5} := \frac{A_{\#5}}{A_{s.req}} = \begin{bmatrix} 12.5 \\ 19.2 \\ 26 \\ 32.8 \end{bmatrix} in$$



SECTION C-C

(7) Summary:

(7a) Strength check of barrier:

Minimum_Height_of_Barrier_Check = "OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

Shear_Capacity_of_Barrier_Check = "OK"

Torsional_Capacity_of_Barrier_Check = "OK"

(7b) Required reinforcement for slab (flat work):

For slab thickness, required reinforcement spacing.

If use **#5 bar**: $t_{slab} = \begin{bmatrix} 6 \\ 8 \\ 10 \\ 12 \end{bmatrix} in$ $S_{s.req.\#5} = \begin{bmatrix} 12.5 \\ 19.2 \\ 26 \\ 32.8 \end{bmatrix} in$