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Subject: Geotechnical Design Policy CIP-2
Load Resistance Factor Design (LRFD)
Analysis of a standard cast-in-place (CIP) wall shown as Case IV in the ADOT SD 7.01 drawings.

The AASHTO (2012) LRFD Bridge Design Specifications are mandatory for all federally funded projects. This attached policy outlines the analysis of a standard cast-in-place (CIP) wall shown as Case IV in the ADOT SD 7.01 drawings, based on methods specified in AASHTO (2012). The intent of this policy is to present the detailed analysis required by the bridge designer to design a typical cast-in-place wall system assuming a level backfill configuration with a traffic barrier and live load surcharge.

Personnel, both within ADOT and design consultants working on projects that require LRFD for cast-in-place walls, shall follow the attached policy. The designer should contact the ADOT Materials Group for an updated version of this policy in the event any interim revisions are made to AASHTO (2012) or a new edition of AASHTO is issued.

The presented solution illustrates the application of the AASHTO LRFD principles and existing ADOT policies to analyze the external stability of the standard wall system for both the strength (bearing resistance, sliding, and limiting eccentricity), and service limit (settlement) states. Two configurations are presented in the example – one where the heel width is less than the width of the barrier slab, and the other where the heel width is greater than the width of the traffic barrier slab.

If you have any questions regarding this bulletin, please contact Norm Wetz at 602-712-8093 or Jiann-Jong Liu at 602-712-8209.

SUBSTRUCTURE EXAMPLE

ADOT SD 7.01 Case IV Walls

This example illustrates the analysis of a standard cast-in-place (CIP) wall shown as Case IV in the ADOT SD 7.01 drawings. The Case IV walls can be divided into two possible configurations, Case IVa and Case IVb. Case IVa applies when the heel width is less than the width of the traffic barrier slab, which is typical for shorter walls. Case IVb applies when the heel width is greater than the width of the traffic barrier slab, which is typical for taller walls. Typical sections of Case IVa and IVb are shown in Figures 1 and 2, respectively.

The following legend is used for the references shown in the left-hand column:

[2.2.2]	LRFD Specification Article Number
[2.2.2-1]	LRFD Specification Table or Equation Number
[C2.2.2]	LRFD Specification Commentary
[A2.2.2]	LRFD Specification Appendix
[Figure 2.2.2-1]	LRFD Specification Figure Number
[ADOT SD 2.02]	ADOT Standard Drawings Number
[ADOT SF-2]	ADOT Policy Memorandum Number

The LRFD Specification refers to the 6th Edition (2012) of AASHTO LRFD Bridge Design Specification.

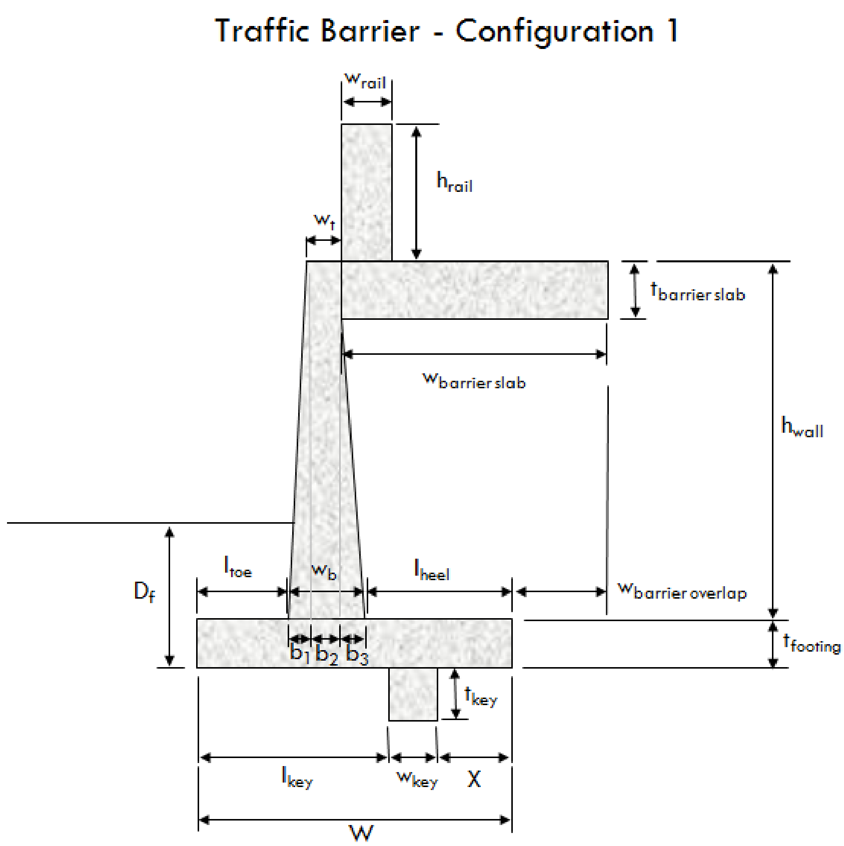


Figure 1 – Case IVa

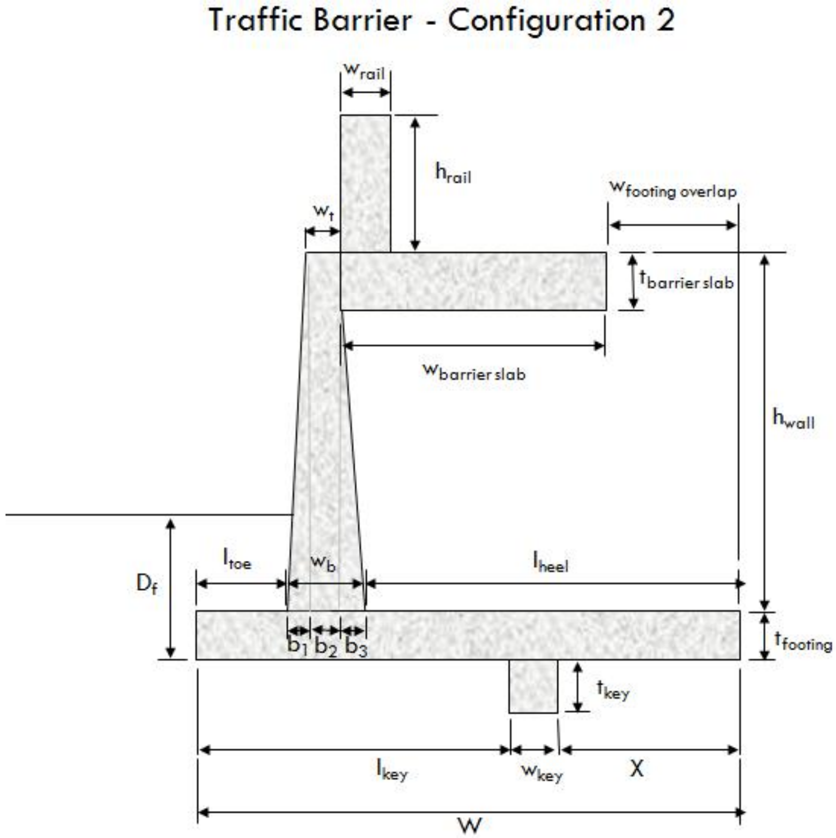


Figure 2 – Case IVb

Substructure

This example demonstrates the analysis of an ADOT SD 7.01 Case IVb wall as described above. Refer to Figure 2 for more detail. Figure 3 represents the applicable loads for the ADOT SD 7.01 Case IVb wall.

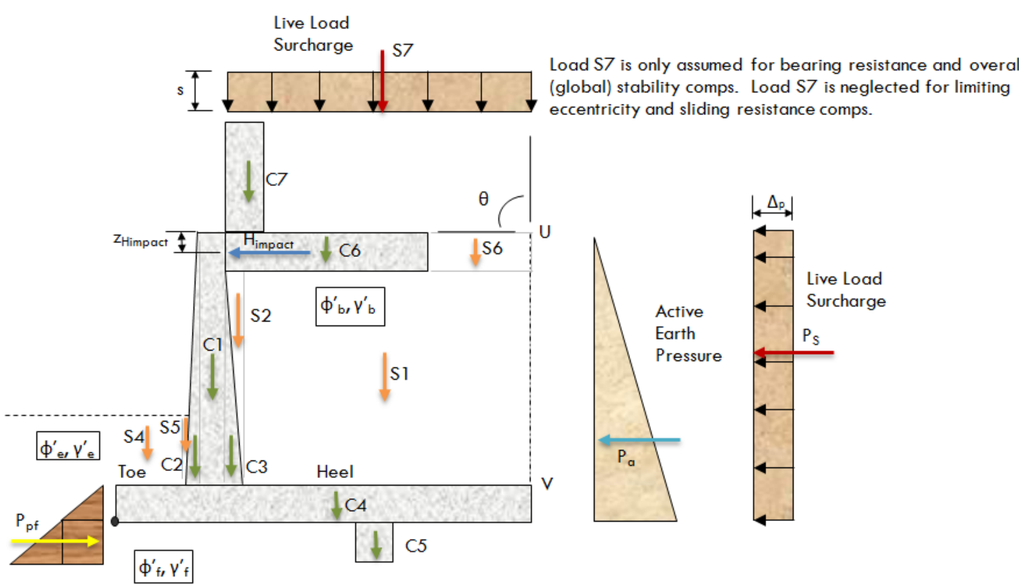


Figure 3 – Case IVb Loads

Figure 2 Definitions

Traffic Barrier

w_{rail}	Traffic Barrier Rail Width
h_{rail}	Traffic Barrier Rail Height
$w_{barrier\ slab}$	Traffic Barrier Slab Width
$t_{barrier\ slab}$	Traffic Barrier Slab Thickness
$\gamma_{barrier}$	Traffic Barrier Concrete Unit Weight
$w_{barrier\ overlap}$	Traffic Barrier Overlap (Case IVa)
$w_{footing\ overlap}$	Footing Overlap (Case IVb)

Wall Footing

D_f	Depth of Embedment
$t_{footing}$	Footing Thickness (Defined as “B” in ADOT SD 7.01)
l_{toe}	Toe Distance to Stem (Defined as “C” in ADOT SD 7.01)
l_{heel}	Heel Distance to Stem (Defined as “E” in ADOT SD 7.01)
W	Footing Width

Wall Shear Key

w_{key}	Shear Key Width (Defined as “1.5 ft” in ADOT SD 7.01)
t_{key}	Shear Key Thickness (Defined as “1.25 ft” in ADOT SD 7.01)
X	Shear Key Distance from Heel

Wall Stem

b_1	Toe Fillet Bottom Thickness
b_2	Middle Bottom Thickness
b_3	Heel Fillet Bottom Thickness
h_{wall}	Wall Height (Defined as “H” in ADOT SD 7.01)
w_b	Bottom Thickness. Summation of b_1, b_2, and b_3 (Defined as “F” in ADOT SD 7.01)
w_t	Top Thickness (Defined as “1 ft” for Case IV walls in ADOT SD 7.01)

Figure 3 Definitions

Backfill Vertical Plane (U-V)

δ	Friction Angle Between Fill and Wall
θ	Backfill Vertical Plane Angle (Plane U-V in Figure 3)

Backslope

β	Backslope Angle ($\beta = 0$ in Figure 3)

Forces

C1	Middle of Stem Concrete Weight
C2	Toe Fillet of Stem Concrete Weight
C3	Heel Fillet of Stem Concrete Weight

C4	Footing Concrete Weight
C5	Shear Key Concrete Weight
C6	Traffic Barrier Slab Concrete Weight
C7	Traffic Barrier Rail Concrete Weight
H_{impact}	Collision Force (Used Only For Extreme Event Analysis)
P_a	Active Earth Pressure
P_s	Lateral Load Due To Live Load Surcharge
P_{pf}	Passive Earth Resistance
S1	Heel Soil Weight
S2	Heel Fillet Soil Weight
S4	Toe Soil Weight
S5	Toe Fillet Soil Weight
S6	Footing Overlap Soil Weight
S7	Live Load Surcharge

<u>Soil Properties</u>

γ'_b	Effective Unit Weight of Backfill Soil
γ'_e	Effective Unit Weight of Embedment Soil
γ'_f	Effective Unit Weight of Foundation Soil
φ'_b	Effective Internal Friction Angle of Backfill Soil
φ'_e	Effective Internal Friction Angle of Embedment Soil
φ'_f	Effective Internal Friction Angle of Foundation Soil
c'_b	Effective Cohesion of Backfill Soil
c'_e	Effective Cohesion of Embedment Soil
c'_f	Effective Cohesion of Foundation Soil

<u>Surcharge</u>

s	Unit Live Load Surcharge

Calculation Definitions

<u>Bearing Stresses</u>

$q_{nf\text{-}ser}$	Factored Net Bearing Resistance (Service I Limit State)
$q_{nf\text{-}str}$	Factored Net Bearing Resistance (Strength I Limit State)
q_{nveu}	Factored Net Equivalent Uniform Vertical Bearing Stress
$q_{nveu\text{-}ser}$	Factored Net Equivalent Uniform Vertical Bearing Stress (Service Limit State)
$q_{nveu\text{-}str}$	Factored Net Equivalent Uniform Vertical Bearing Stress (Strength Limit State)
q_{tveu}	Factored Total Equivalent Uniform Vertical Bearing Stress
$q_{tveu\text{-}ser}$	Factored Total Equivalent Uniform Vertical Bearing Stress (Service I Limit State)
$q_{tveu\text{-}str}$	Factored Total Equivalent Uniform Vertical Bearing Stress (Strength I Limit State)

<u>Concrete Properties</u>

γ_c	Unit Weight of Concrete

Earth Pressure Coefficients

K_{ab}	Active Earth Pressure Coefficient for Backfill Soil
K_{pf}	Passive Earth Resistance Coefficient for Foundation Soil

Eccentricity

B'	Effective Footing Width
B'_{ser}	Effective Footing Width (Service I Limit State)
B'_{str}	Effective Footing Width (Strength I Limit State)
D_b	Distance from Toe of Footing to R_{vb}
$D_{b\text{-}ser}$	Distance from Toe of Footing to $R_{vb\ ser\ I}$
$D_{b\text{-}str}$	Distance from Toe of Footing to $R_{vb\ str\ I}$
D_l	Distance from Toe of Footing to R_{vl}
D_s	Distance from Toe of Footing to R_{vs}
e_b	Eccentricity of R_{vb} with Respect to Bearing Resistance
$e_{b\text{-}ser}$	Eccentricity of $R_{vb\ ser\ I}$ with Respect to Bearing Resistance
$e_{b\text{-}str}$	Eccentricity of $R_{vb\ str\ I}$ with Respect to Bearing Resistance
e_l	Eccentricity of R_{vl} with Respect to Limiting Eccentricity
e_s	Eccentricity of R_{vs} with Respect to Sliding
e_{max}	Maximum Eccentricity

Forces and Moments

M_{C1}	Moment about Toe Due to Force C1
M_{C3}	Moment about Toe Due to Force C3
M_{C4}	Moment about Toe Due to Force C4
M_{C5}	Moment about Toe Due to Force C5
M_{C6}	Moment about Toe Due to Force C6
M_{C7}	Moment about Toe Due to Force C7
M_{S1}	Moment about Toe Due to Force S1
M_{S2}	Moment about Toe Due to Force S2
M_{S4}	Moment about Toe Due to Force S4
M_{S6}	Moment about Toe Due to Force S6
M_{S7}	Moment about Toe Due to Force S7
M_{Pa}	Moment about Toe Due to Force P_a
M_{Ps}	Moment about Toe Due to Force P_s
M_{Ppf}	Moment about Toe Due to Force P_{pf}
M_{Rb}	Factored Resultant Moment about the Toe for Bearing Resistance
$M_{Rb\text{-}ser}$	Factored Resultant Moment about the Toe for Bearing Resistance (Service I Limit State)
$M_{Rb\text{-}str}$	Factored Resultant Moment about the Toe for Bearing Resistance (Strength I Limit State)
M_{Rl}	Factored Resultant Moment about the Toe for Limitng Eccentricity
M_{Rs}	Factored Resultant Moment about the Toe for Sliding

R_f	Factored Friction Resistance Against Sliding
R_{hs}	Factored Horizontal Load for Sliding
R_p	Factored Passive Resistance
R_s	Total Factored Sliding Resistance
R_{vb}	Factored Resultant Vertical Force for Bearing Resistance
$R_{vb\text{-}ser}$	Factored Resultant Vertical Force for Bearing Resistance (Service I Limit State)
$R_{vb\text{-}str}$	Factored Resultant Vertical Force for Bearing Resistance (Strength I Limit State)
R_{vl}	Factored Resultant Vertical Force for Limiting Eccentricity
R_{vs}	Factored Resultant Vertical Force for Sliding

Load Factors

γ_p	Load Factor for Permanent Loads

Miscellaneous

φ'	Effective Internal Friction Angle of Soil
RLR	Resistance:Load Ratio

Resistance Factors

φ_{ep}	Passive Earth Resistance Factor
φ_τ	Resistance Factor for Frictional Component of Sliding

Surcharge

Δ_p	Constant Horizontal Earth Pressure Due to Live Load
h_{eq}	Equivalent Height of Soil for Vehicular Load

Units

The following units were used in this example:

ft	Feet
in	Inches
k	Kips
kcf	Kips Per Cubic Foot
ksf	Kips Per Square Foot
lbs	Pounds

Wall Properties

[ADOT SD 7.01] The following wall properties are based on a 25 ft tall wall:

Wall Footing

D_f	4.333 ft (ADOT SD 7.01 recommends a minimum top cover on the toe of 1.5 ft. For this example 2 ft is used)
$t_{footing}$	2.333 ft
l_{toe}	4 ft
l_{heel}	8 ft
W	14.5 ft

Wall Shear Key

w_{key}	1.5 ft
t_{key}	1.25 ft
X	4.167 ft
l_{key}	$W - X - w_{key}$ = 14.5 ft – 4.167 ft – 1.5 ft = 8.833 ft

Wall Stem

h_{wall}	25 ft
w_t	12 in = 1 ft
b_1	0 in
b_2	12 in = 1 ft
b_3	18 in = 1.5 ft
w_b	30 in = 2.5 ft

[ADOT SD 1.02] **Traffic Barrier Properties**

w_{rail}	1.177 ft (10 1/2 in + 3 5/8 in is assumed to be the average width of the rail due to its non-uniformity)
h_{rail}	3.667 ft
$w_{barrier\ slab}$	6.583 ft
$t_{barrier\ slab}$	2.0 ft
$\gamma_{barrier}$	0.150 kcf
$w_{barrier\ overlap}$ (Case IVa)	0 ft
$w_{footing\ overlap}$ (Case IVb)	2.917 ft ($l_{heel} + b_3 - w_{barrier\ slab}$ = 8.0 ft + 1.5 ft - 6.583 ft = 2.917 ft)

Soil Properties (Assumed for Example)

Backfill

γ'_b	0.120 kcf
φ'_b	33.25 deg
c'_b	0 ksf

Embedment

γ'_e	0.120 kcf
φ'_e	30 deg
c'_e	0 ksf

Foundation

γ'_f	0.120 kcf
φ'_f	34 deg
c'_f	0 ksf

Concrete Properties

γ_c	0.150 kcf

Backslope Properties and Surcharge

Backslope

β	0, since there is no backslope for this example

Backslope Vertical Plane (U-V)

[ADOT SF-2]

δ	0 deg
θ	90 deg

Surcharge

Since traffic is running parallel to the face of the wall, and is located greater than 1.0 feet from the inside of the wall face, h_{eq} can be determined as follows:

[3.11.6.4-2] h_{eq} 2 ft

[ADOT SF-3]

Passive Resistance Factor and Sliding Factors

Footing from Toe to Front of Key

Method/Soil/Condition	Soil on Soil
$\varphi_{\tau 1}$ **[10.5.5.2.2-1]**	0.90
$\tan\varphi'_f = \tan(34\ \text{deg})$	0.6745

Footing from Heel to Front of Key

Method/Soil/Condition	Cast-in-Place Concrete Placed on Sand
$\varphi_{\tau 2}$ **[10.5.5.2.2-1]**	0.80
$\tan\varphi'_f = \tan(34\ \text{deg})$	0.6745

Factored Sliding Coefficient (Weighted)

$\varphi_\tau \tan\varphi'_f = [l_{key}(\varphi_{\tau 1})(\tan\varphi'_f) + (w_{key} + X)(\varphi_{\tau 2})(\tan\varphi'_f)]/W$

$\varphi_\tau \tan\varphi'_f = [(8.833\ \text{ft})(0.90)(0.6745)+(5.667\ \text{ft})(0.80)(0.6745)]/14.5\text{ft}$

$\varphi_\tau \tan\varphi'_f = 0.5807$

Passive Earth Resistance Factor

[10.5.5.2.2-1] φ_{ep} 0.50

Load Factors (γ_p)

Strength I Limit State and Service I Limit State will be used for this example. The following load factors pertain to the Strength I Limit State and Service I Limit State (in actual design all applicable limit states must be considered):

[3.4.1-1] & [3.4.1-2]

Load Categories	Load Factors (Str I)		Load Factors (Ser I)
	Maximum	**Minimum**	
DC: Component and Attachments	1.25	0.90	1.00
EV: Vertical Earth Pressure – Retaining Walls and Abutments	1.35	1.00	1.00
EH: Horizontal Earth Pressure – Active	1.50	0.90	1.00
LS: Live Load Surcharge	1.75	1.75	1.00

Unfactored Loads and Moments

First the unfactored values of loads and moments are calculated. These unfactored values will then be factored as appropriate based on the limit state being analyzed, e.g. sliding, limiting eccentricity or bearing. For the various terms in the equations for unfactored loads and moments refer to Figures 2 and 3 and definitions noted previously in this example.

Load Designations
A summary of the loads for this example are as follows:

Load	Load Category
C1	DC
C2	Not used for this example since $b_1 = 0$
C3	DC
C4	DC
C5	DC
C6	DC
C7	DC
S1	EV
S2	EV
S4	EV (used only for bearing resistance comps)
S5	Not used for this example since $b_1 = 0$
S6	EV
S7	LS (used only for bearing resistance comps)
P_a	EH
P_s	LS
P_{pf}	Passive resistance force, use passive resistance factors
H_{impact}	Used only for Extreme Event Analysis

DC Loads (Unfactored)

Stem

$C1 = b_2\, h_{wall}\, \gamma_c$ = (1 ft)(25 ft)(0.150 kcf) = 3.750 k/ft

$C2 = ½\, b_1\, h_{wall}\, \gamma_c = 0$, since $b_1 = 0$

$C3 = ½\, b_3\, (h_{wall} - t_{barrier\ slab})\, \gamma_c$ = (0.5)(1.5 ft)(25 ft – 2 ft)(0.150 kcf) = 2.588 k/ft

Footing

$C4 = W\, t_{footing}\, \gamma_c$ = (14.5 ft)(2.333 ft)(0.150 kcf) = 5.074 k/ft

Shear Key

$C5 = w_{key}\ t_{key}\ \gamma_c = (1.5\text{ ft})(1.25\text{ ft})(0.150\text{ kcf}) = 0.2813\text{ k/ft}$

Traffic Barrier

$C6 = w_{barrier\ slab}\ t_{barrier\ slab}\ \gamma_{barrier} = (6.583\text{ ft})(2.0\text{ ft})(0.150\text{ kcf}) = 1.975\text{ k/ft}$

$C7 = w_{rail}\ h_{rail}\ \gamma_{barrier} = (1.177\text{ ft})(3.667\text{ ft})(0.150\text{ kcf}) = 0.6474\text{ k/ft}$

EV Loads (Unfactored)

Heel

$S1 = l_{heel}(h_{wall} - t_{barrier\ slab})\ \gamma'_b = (8\text{ ft})(25\text{ ft} - 2\text{ ft})(0.120\text{ kcf}) = 22.08\text{ k/ft}$

$S2 = ½\ b_3\ (h_{wall} - t_{barrier\ slab})\ \gamma'_b = (0.5)(1.5\text{ ft})(25\text{ ft} - 2\text{ ft})(0.120\text{ kcf})$
$= 2.070\text{ k/ft}$

Toe

$S4 = l_{toe}(D_f - t_{footing})\gamma'_e = (4\text{ ft})(4.333\text{ ft} - 2.333\text{ ft})(0.120\text{ kcf})$
$= 0.9600\text{ k/ft}$

$S5 = 0$, since $b_1 = 0$

Overlap

$S6 = w_{footing\ overlap}\ t_{barrier\ slab}\ \gamma'_b = (2.917\text{ ft})(2\text{ ft})(0.120\text{ kcf}) = 0.7001\text{ k/ft}$

EH Loads (Unfactored)

Active Earth Pressure

P_a can be determined by the following equation:

$$P_a = ½\ (K_{ab}\gamma'_b)(h_{wall} + t_{footing})^2$$

[3.11.5.3-1]

$$K_a = \frac{\sin^2(\theta+\varphi')}{\Gamma[\sin^2\theta\sin(\theta-\delta)]}$$

[3.11.5.3-2]

$$\Gamma = \left[1 + \sqrt{\frac{\sin(\varphi'+\delta)\sin(\varphi'-\beta)}{\sin(\theta-\delta)\sin(\theta+\beta)}}\right]^2$$

Since $\delta = \beta = 0$ and $\theta = 90$ deg, the equations for K_a and Γ can be rewritten as follows:

$$\Gamma = [1+\sin(\varphi')]^2$$

$$K_a = \frac{\sin^2(90+\varphi')}{\Gamma} = \frac{\sin^2(90)\cos^2(\varphi')+\cos^2(90)\sin^2(\varphi')}{[1+\sin(\varphi')]^2}$$

$$K_a = \frac{\cos^2(\varphi')}{[1+\sin(\varphi')]^2} = \frac{1-\sin^2(\varphi')}{[1+\sin(\varphi')]^2} = \frac{(1-\sin(\varphi'))(1+\sin(\varphi'))}{[1+\sin(\varphi')]^2} = \frac{1-\sin(\varphi')}{1+\sin(\varphi')}$$

Therefore, $K_{ab} = \frac{1-\sin(\varphi'_b)}{1+\sin(\varphi'_b)} = \frac{1-\sin(33.25)}{1+\sin(33.25)} = 0.2917$

$P_a = ½\ (0.2917)(0.120\text{ kcf})(25\text{ ft} + 2.333\text{ ft})^2 = 13.08\text{ k/ft}$

LS Loads (Unfactored)

Live Load Surcharge

[Figure C11.5.5-3a]

$S7 = s\,(b_3 + l_{heel})$

$$s = h_{eq}\,\gamma'_b = (2\text{ ft})(0.120\text{ kcf}) = 0.2400\text{ ksf}$$

$S7 = (0.2400\text{ ksf})(1.5\text{ ft} + 8\text{ ft}) = 2.280\text{ k/ft}$

Lateral Load Due To Live Load Surcharge

$P_s = \Delta_p\,(h_{wall} + t_{footing})$

$$\Delta_p = K_{ab}\,s = (0.2917)(0.2400\text{ ksf}) = 0.07001\text{ ksf}$$

$P_s = (0.07001\text{ ksf})(25\text{ ft} + 2.333\text{ ft}) = 1.914\text{ k/ft}$

Passive Earth Resistance

Use passive resistance from top of footing to bottom of key. See Figure 3 for more detail.

$$P_{pf} = \frac{K_{pf}\gamma'_f t_{key}^2}{2} + K_{pf}\gamma'_f t_{footing}(t_{key}) + \frac{K_{pf}\gamma'_f t_{footing}^2}{2}$$

[Figure 3.11.5.4-1]

To determine the passive earth resistance, the passive earth resistance coefficient for the foundation soils must be determined. Using θ = 90 deg and φ'_f = 34 deg in the referenced figure, K_{pf} was determined for the ratio of δ/φ'_f = -1.

$K_{pf} = 9.25$ for $\delta/\varphi'_f = -1$

[Figure 3.11.5.4-1]

Using δ = 0, the following values are established:

Reduction Factor for K_{pf} for φ'_f = 30 deg	0.467
Reduction Factor for K_{pf} for φ'_f = 35 deg	0.362

Using linear interpolation, the reduction factor for φ'_f = 34 deg was determined as follows:

Reduction Factor for K_{pf} for φ'_f = 34 deg

$$\frac{(0.467-0.362)}{5} + 0.362 = 0.383$$

K_{pf} for the ratio of δ/φ'_f = 0 is as follows:

$K_{pf} = 0.383(9.25) = 3.54$

The passive earth resistance can now be determined as follows:

$$P_{pf} = \frac{(3.54)(0.120\text{ kcf})(1.25\text{ ft})^2}{2} + (3.54)(0.120\text{ kcf})(1.25\text{ ft})(2.333\text{ ft}) + \frac{(3.54)(0.120\text{ kcf})(2.333\text{ ft})^2}{2} = 2.727\,\frac{\text{k}}{\text{ft}}$$

Moment Arm (From Bottom of Footing at the Toe)
Before the moments due to the loads shown above can be determined, the moment arm must be determined for each load. The following table summarises the moment arms:

Load	Moment Arm Equation		Moment Arm (ft)
C1	$l_{toe} + b_1 + b_2 / 2$	4 ft + 0 + (1 ft) / 2	4.500
C3	$l_{toe} + b_1 + b_2 + b_3 / 3$	4 ft + 0 + 1 ft + (1.5 ft) / 3	5.500
C4	W/2	(14.5 ft) / 2	7.250
C5	$W – X – w_{key} / 2$	14.5 ft – 4.167 ft – (1.5 ft) / 2	9.583
C6	$W – w_{footing\ overlap} – w_{barrier\ slab} / 2$	14.5 ft – 2.917 ft – (6.583 ft) / 2	8.292
C7	$l_{toe} + b_1 + b_2 + w_{rail} / 2$	4 ft + 0 + 1 ft + (1.177 ft) / 2	5.589
S1	$W – l_{heel} / 2$	14.5 ft – (8 ft) / 2	10.50
S2	$l_{toe} + b_1 + b_2 + 2b_3 / 3$	4 ft + 0 + 1 ft + 2(1.5 ft) / 3	6.000
S4	$l_{toe} / 2$	4 ft / 2	2.000
S6	$W – w_{footing\ overlap} / 2$	14.5 ft – (2.917 ft) / 2	13.04
S7	$l_{toe} + b_1 + b_2 + (b_3 + l_{heel}) / 2$	4 ft + 0 + 1 ft + (1.5 ft + 8 ft) / 2	9.750
P_a	$(h_{wall} + t_{footing}) / 3$	(25 ft + 2.333 ft) / 3	9.111
P_s	$(h_{wall} + t_{footing}) / 2$	(25 ft + 2.333 ft) / 2	13.67

Moments (Unfactored) From Bottom of Footing at the Toe
Now that the unfactored loads and moment arms have been determined, the unfactored moments for each contributing force shown in Figure 3 can be determined. The unfactored moment is calculated by multiplying the moment arm with the unfactored load. A counter-clockwise moment is considered to be positive. The following table summarizes the resulting unfactored moments:

	+/-	Moment Arm (ft)	Load (Unfactored) (k/ft)	Moment (Unfactored) (k-ft/ft)
M_{C1}	-	4.500	3.750	-16.88
M_{C3}	-	5.500	2.588	-14.23
M_{C4}	-	7.250	5.074	-36.79
M_{C5}	-	9.583	0.2813	-2.696
M_{C6}	-	8.292	1.975	-16.38
M_{C7}	-	5.589	0.6474	-3.618
M_{S1}	-	10.50	22.08	-231.8
M_{S2}	-	6.000	2.070	-12.42
M_{S4}	-	2.000	0.9600	-1.920
M_{S6}	-	13.04	0.7001	-9.129
M_{S7}	-	9.750	2.280	-22.23
M_{Pa}	+	9.111	13.08	119.2
M_{Ps}	+	13.67	1.914	26.16

Check for Sliding

Factored Vertical Loads For Sliding (Strength I)

Sliding is strength limit check and therefore factored loads are used. Strength I limit state is being used for this example. In actual design, all applicable load combinations must be evaluated. For resisting loads, i.e., loads that are providing resistance to sliding, the minimum load factor will be applied. For activating loads, i.e., loads that contribute to activate sliding, the maximum load factor will be applied. The beneficial contribution of the toe soil weight (shown as S4 in Figure 3) and live load surcharge (shown as S7 in Figure 3) to the resisting forces will be neglected for sliding to create the critical force effect. The following tables summarize the factored loads with respect to sliding:

Factored Vertical Loads for Sliding (Str I)				
	Load Factors		Load (Unfactored) (k/ft)	Factored Load (Str I) (k/ft)
	Max / Min	Factor		
C1	Min	0.90	3.750	3.375
C3	Min	0.90	2.588	2.329
C4	Min	0.90	5.074	4.567
C5	Min	0.90	0.2813	0.2532
C6	Min	0.90	1.975	1.778
C7	Min	0.90	0.6474	0.5827
S1	Min	1.00	22.08	22.08
S2	Min	1.00	2.070	2.070
S6	Min	1.00	0.7001	0.7001
$R_{vs} = \sum$ Factored Vertical Loads				37.74

Factored Horizontal Loads for Sliding (Str I)				
	Load Factors		Load (Unfactored) (k/ft)	Factored Load (Str I) (k/ft)
	Max / Min	Factor		
P_a	Max	1.50	13.08	19.62
P_s	Max	1.75	1.914	3.350
$R_{hs} = \sum$ Factored Horizontal Loads				22.97

Factored Friction Resistance, R_f

$R_f = R_{vs}\ \varphi_\tau \tan\varphi'_f$ = (37.74 k/ft)(0.5807) = 21.92 k/ft

Factored Passive Resistance, R_p

$R_p = P_{pf}\ \varphi_{ep}$ = (2.727 k/ft)(0.50) = 1.364 k/ft

Total Factored Sliding Resistance, R_s

$R_s = R_f + R_p$ = 21.92 k/ft + 1.364 k/ft = 23.28 k/ft

Resistance:Load Ratio (RLR) Against Sliding

The RLR should be greater than 1.

RLR = (Factored resisting forces / Factored activating forces)

= (R_s) / (R_{hs}) = (23.28 k/ft) / (22.97 k/ft) = 1.014

RLR = 1.014. Therefore the wall is ok with respect to sliding.

Check for Limiting Eccentricity

Factored Loads and Moments For Limiting Eccentricity (Strength I)

[ADOT SF-2]

Limiting eccentricity is a strength limit check. The Strength I limit state is being used for this example. In actual design, all applicable load combinations must be evaluated. For resisting loads the minimum load factor will be applied. For activating loads the maximum load factor will be applied. The load factor that is applied to each load is automatically applied to its corresponding moment as well. The beneficial contribution of the toe soil weight (shown as S4 in Figure 3), live load surcharge (shown as S7 in Figure 3), and passive earth resistance (shown as P_{pf} in Figure 3) to the resisting forces and moments will be neglected for limiting eccentricity to create the critical force effect. The following tables summarize the factored loads and moments with respect to limiting eccentricity:

Factored Vertical Loads for Limiting Eccentricity (Str I)				
	Load Factors		Load (Unfactored) (k/ft)	Factored Load (Str I) (k/ft)
	Max / Min	Factor		
C1	Min	0.90	3.750	3.375
C3	Min	0.90	2.588	2.329
C4	Min	0.90	5.074	4.567
C5	Min	0.90	0.2813	0.2532
C6	Min	0.90	1.975	1.778
C7	Min	0.90	0.6474	0.5827
S1	Min	1.00	22.08	22.08
S2	Min	1.00	2.070	2.070
S6	Min	1.00	0.7001	0.7001
$R_{vl} = \sum$ Factored Vertical Loads				37.74

Factored Horizontal Loads for Limiting Eccentricity (Str I)				
	Load Factors		Load (Unfactored) (k/ft)	Factored Load (Str I) (k/ft)
	Max / Min	Factor		
P_a	Max	1.50	13.08	19.62
P_s	Max	1.75	1.914	3.350

Factored Moments for Limiting Eccentricity (Str I)				
	Load Factors		Moment (Unfactored) (k-ft/ft)	Moment (Factored) (k-ft/ft)
	Max / Min	Factor		
M_{C1}	Min	0.90	-16.88	-15.19
M_{C3}	Min	0.90	-14.23	-12.81
M_{C4}	Min	0.90	-36.79	-33.11
M_{C5}	Min	0.90	-2.696	-2.426
M_{C6}	Min	0.90	-16.38	-14.74
M_{C7}	Min	0.90	-3.618	-3.256
M_{S1}	Min	1.00	-231.8	-231.8
M_{S2}	Min	1.00	-12.42	-12.42
M_{S6}	Min	1.00	-9.129	-9.129
M_{Pa}	Max	1.50	119.2	178.8
M_{Ps}	Max	1.75	26.16	45.78
M_{Rl} = (-1)(∑ Factored Moments)				110.3

Distance from Toe to R_{vl}

$D_l = M_{Rl} / R_{vl}$ = (110.3 k-ft/ft) / (37.74 k/ft) = 2.923 ft

Limiting Eccentricity

If the value of the computed eccentricity, e_l, is less than the limiting eccentricity, e_{max}, then the substructure meets the criterion for limiting eccentricity and is therefore safe against overturning.

$e_l = D_l - W/2$ = 2.923 ft – (14.5 ft) / 2 = -4.327 ft = 4.327 ft towards the toe of the wall from the middle of the footing.

[ADOT SF-2] $e_{max} = W/3$ = (14.5 ft)/3 = 4.833 ft

e_{max} = 4.833 ft, which is greater than e_l = 4.327 ft. Therefore the wall is ok with respect to limiting eccentricity.

Check For Bearing Resistance

Factored Loads and Moments For Bearing Resistance

Bearing resistance is a strength limit state check. Also, the vertical live load

[Figure C11.5.5-3a]

surcharge is included for bearing resistance analysis since it will now be contributing to the bearing stresses. Refer to Figure 3 for more detail. The total equivalent uniform vertical bearing stress (q_{tveu}) and net equivavlent uniform bearing stress (q_{nveu}) at the base of the wall can be computed as follows:

[ADOT SF-1]

$q_{tveu} = R_{vb} / B'$

Where R_{vb} = ∑ Factored vertical loads for bearing resistance
$B' = W-2e_b$
W = Wall footing width
e_b = Eccentricty of R_{vb}

[ADOT SF-1]

$q_{nveu} = q_{tveu} - \gamma_p(\gamma'_e D_f)$

[3.4.1-1]

Where γ_p = Load factor of permanent vertical earth pressure (EV). Use the max EV load factor for this case (1.35)
γ'_e = Embedment soil unit weight
D_f = Depth of embedment

The Strength I limit state will be used for this example to determine the bearing resistance. In actual design, all applicable load combinations must be evaluated. It is assumed for this example that the critical combination of load factors for bearing resistance will be when the maximum load factor is applied to all loads. The load factor that is applied to each load is automatically applied to its corresponding moment as well. The beneficial contribution of the passive earth resistance (shown as P_{pf} in Figure 3) to the resisting forces and moments will be neglected for bearing resistance. The following tables summarize the factored loads and moments with respect to bearing resistance:

Factored Vertical Loads for Bearing Resistance				
	Load Factors		**Load (Unfactored) (k/ft)**	**Str I Factored Load (k/ft)**
	Max / Min	**Factor**		
C1	Max	1.25	3.750	4.688
C3	Max	1.25	2.588	3.235
C4	Max	1.25	5.074	6.343
C5	Max	1.25	0.2813	0.3516
C6	Max	1.25	1.975	2.469
C7	Max	1.25	0.6474	0.8093
S1	Max	1.35	22.08	29.81
S2	Max	1.35	2.070	2.795
S4	Max	1.35	0.9600	1.296
S6	Max	1.35	0.7001	0.9451
S7	Max	1.75	2.280	3.990
R_{vb-str} = ∑ Factored Vertical Loads				56.73

Factored Horizontal Loads for Bearing Resistance				
	Load Factors		**Load (Unfactored) (k/ft)**	**Str I Factored Load (k/ft)**
	Max / Min	**Factor**		
P_a	Max	1.50	13.08	19.62
P_s	Max	1.75	1.914	3.350

Factored Moments for Bearing Resistance				
	Load Factors		**Load (Unfactored) (k-ft/ft)**	**Str I Factored Load (k-ft/ft)**
	Max / Min	**Factor**		
M_{C1}	Max	1.25	-16.88	-21.10
M_{C3}	Max	1.25	-14.23	-17.79
M_{C4}	Max	1.25	-36.79	-45.99
M_{C5}	Max	1.25	-2.696	-3.370
M_{C6}	Max	1.25	-16.38	-20.48
M_{C7}	Max	1.25	-3.618	-4.523
M_{S1}	Max	1.35	-231.8	-312.9
M_{S2}	Max	1.35	-12.42	-16.77
M_{S4}	Max	1.35	-1.920	-2.592
M_{S6}	Max	1.35	-9.129	-12.32
M_{S7}	Max	1.75	-22.23	-38.90
M_{Pa}	Max	1.50	119.2	178.8
M_{Ps}	Max	1.75	26.16	45.78
$M_{Rb\text{-}str} = (-1)(\sum \text{Factored Moments})$				272.2

Distance from Toe to $R_{vb\text{-}str}$

$D_{b\text{-}str} = M_{Rb\text{-}str} / R_{vb\text{-}str}$ = (272.2 k-ft/ft) / (56.73 k/ft) = 4.798 ft

Eccentricity

$e_{b\text{-}str} = D_{b\text{-}str} - W/2$ = 4.798 ft – (14.5 ft) / 2 = -2.452 ft = 2.452 ft towards the toe of the wall from the middle of the footing.

Factored Total Equivalent Uniform Vertical Bearing Stress

$B'_{str} = W - 2e_{b\text{-}str}$ = 14.5 ft – 2(2.452 ft) = 9.596 ft

$q_{tveu\text{-}str} = R_{vb\text{-}str} / (B'_{str})$ = (56.73 k/ft) / (9.596 ft)

$q_{tveu\text{-}str}$ = 5.912 ksf

Factored Net Equivalent Uniform Vertical Bearing Stress

$q_{nveu\text{-}str} = q_{tveu\text{-}str} - \gamma_p(\gamma'_e D_f)$ = 5.912 ksf – 1.35(0.120 kcf(4.333 ft))

$q_{nveu\text{-}str}$ = 5.210 ksf

Factored Net Bearing Resistance (Strength I Limit State)

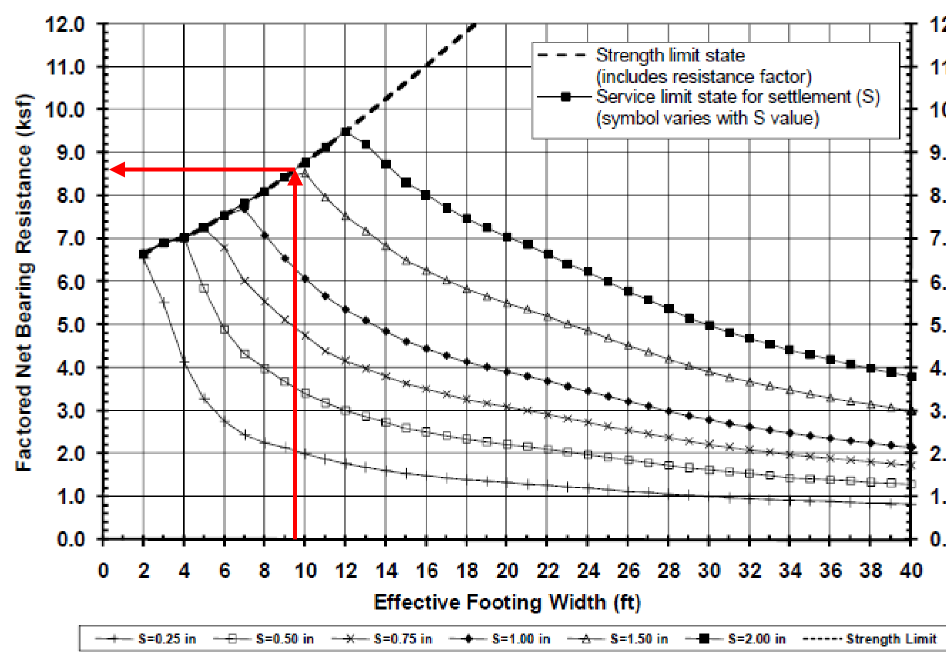
For this example, it is assumed that the site specific soil profile for this example is the same as that which was used in the ADOT SF-1 policy memorandum. Therefore the factored net bearing resistance chart shown as Figure 1 in the ADOT SF-1 policy memorandum is applicable for this example ***(Note that a***

<u>site specific factored net bearing resistance chart will need to be generated for actual design).</u> The factored net bearing resistance chart shown as Figure 1 in the ADOT SF-1 policy memorandum has been included in this example as Figures 5 and 6, to determine $q_{nf\text{-}str}$ and settlement, respectively.

Note that the factored net bearing resistance chart from the ADOT SF-1 policy memorandum was developed for a minimum depth of embedment, D_f, of 6 feet. The depth of embedment analyzed in this example is only 4.333 feet. In actual design a new factored net bearing resistance chart must be developed with a depth of embedment less than or equal to 4.333 feet. However, for demonstration purposes it is assumed that the factored net bearing resistance chart shown in the ADOT SF-1 policy memorandum is sufficient for this example.

Using Figure 5 and B'_{str} equal to 9.596 feet, the following factored net bearing resistance was determined (Note that the solid lines with closed arrows in Figure 5 represent the estimation of $q_{nf\text{-}str}$):

$q_{nf\text{-}str}$ = 8.60 ksf
RLR = (Bearing resistance / Bearing stress) = (8.60 ksf) / (5.210 ksf) = 1.651, which is > 1.00, therefore the wall is ok with respect to bearing resistance.



[4]Figure 1: Example of a Factored Bearing Resistance Chart for a footing of length, L′ = L = 150-ft (no eccentricity) and depth of embedment, D_f = 6-ft with base elevation of 994-ft. The resistance factor of ϕ_b= 0.45 is included in the strength limit state curve. "S" in the legend refers to immediate settlement.

Figure 5 – Factored Net Bearing Resistance Chart Used to Determine $q_{nf\text{-}str}$ (ADOT SF-1)

Check For Settlement

Factored Loads and Moments For Settlement
Settlement is a service limit state check. Also, the live load surcharge is included on top of the wall for settlement analysis since it will now be contributing to the bearing stresses. Refer to Figure 3 for more detail.

The Service I limit state will be used for this example to determine the settlement. In actual design, all applicable load combinations must be evaluated. The beneficial contribution of the passive earth resistance (shown as P_{pf} in Figure 3) to the resisting forces and moments will be neglected. The following tables summarize the factored loads and moments with respect to settlement:

Factored Vertical Loads for Settlement				
	Load Factors		Load (Unfactored) (k/ft)	Ser I Factored Load (k/ft)
	Max / Min	Factor		
C1	N/A	1.00	3.750	3.750
C3	N/A	1.00	2.588	2.588
C4	N/A	1.00	5.074	5.074
C5	N/A	1.00	0.2813	0.2813
C6	N/A	1.00	1.975	1.975
C7	N/A	1.00	0.6474	0.6474
S1	N/A	1.00	22.08	22.08
S2	N/A	1.00	2.070	2.070
S4	N/A	1.00	0.9600	0.9600
S6	N/A	1.00	0.7001	0.7001
S7	N/A	1.00	2.280	2.280
$R_{vb\text{-}ser} = \sum$ Factored Vertical Loads				42.41

Factored Horizontal Loads for Settlement				
	Load Factors		Load (Unfactored) (k/ft)	Ser I Factored Load (k/ft)
	Max / Min	Factor		
P_a	N/A	1.00	13.08	13.08
P_s	N/A	1.00	1.914	1.914

Factored Moments for Settlement				
	Load Factors		Load (Unfactored) (k-ft/ft)	Ser I Factored Load (k-ft/ft)
	Max / Min	Factor		
M_{C1}	N/A	1.00	-16.88	-16.88
M_{C3}	N/A	1.00	-14.23	-14.23
M_{C4}	N/A	1.00	-36.79	-36.79
M_{C5}	N/A	1.00	-2.696	-2.696
M_{C6}	N/A	1.00	-16.38	-16.38
M_{C7}	N/A	1.00	-3.618	-3.618
M_{S1}	N/A	1.00	-231.8	-231.8
M_{S2}	N/A	1.00	-12.42	-12.42
M_{S4}	N/A	1.00	-1.920	-1.920
M_{S6}	N/A	1.00	-9.129	-9.129
M_{S7}	N/A	1.00	-22.23	-22.23
M_{Pa}	N/A	1.00	119.2	119.2
M_{Ps}	N/A	1.00	26.16	26.16
$M_{Rb\text{-}ser}$ = (-1)(∑ Factored Moments)				222.7

Distance from Toe to R_{vb}

$D_{b\text{-}ser} = M_{Rb\text{-}ser} / R_{vb\text{-}ser}$ = (222.7 k-ft/ft) / (42.41 k/ft) = 5.251 ft

Eccentricity

$e_{b\text{-}ser} = D_{b\text{-}ser} – W/2$ = 5.251 ft – (14.5 ft) / 2 = -1.999 ft = 1.999 ft towards the toe of the wall from the middle of the footing.

Factored Total Equivalent Uniform Vertical Bearing Stress

$B'_{ser} = W-2e_{b\text{-}ser}$ = 14.5 ft – 2(1.999 ft) = 10.50 ft

$q_{tveu\text{-}ser} = R_{vb\text{-}ser} / (B'_{ser})$ = (42.41 k/ft) / (10.50 ft))
$q_{tveu\text{-}ser}$ = 4.039 ksf

Factored Net Equivalent Uniform Vertical Bearing Stress

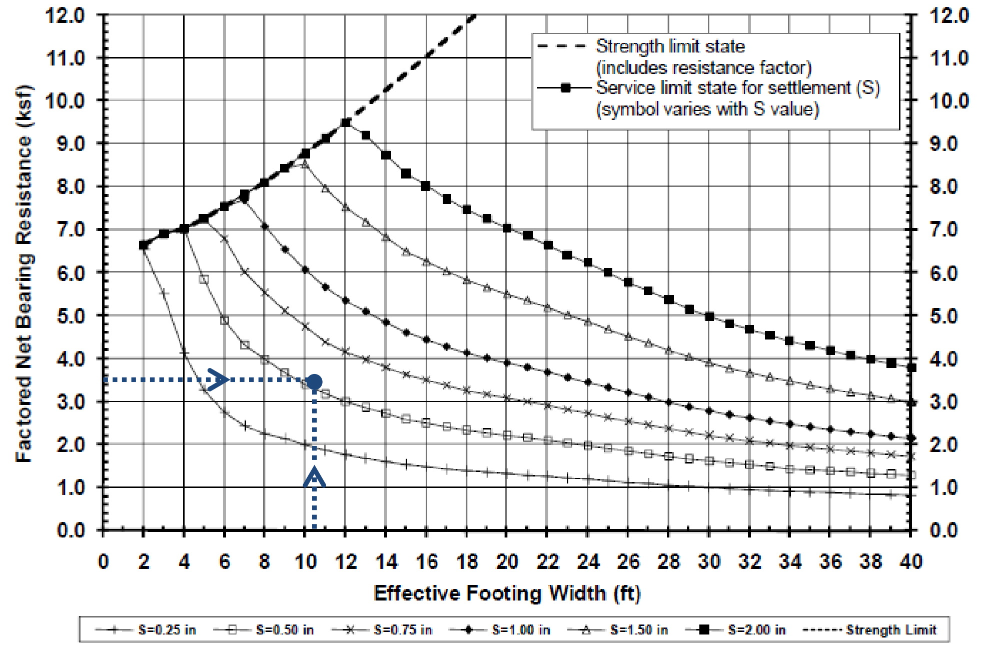
$q_{nveu\text{-}ser} = q_{tveu\text{-}ser} – \gamma_p(\gamma'_e D_f)$ = 4.039 ksf – 1.00(0.120 kcf(4.333 ft))
$q_{nveu\text{-}ser}$ = 3.519 ksf

Estimated Settlement (Service I Limit State)

Using Figure 5, B'_{ser} equal to 10.50 feet, and $q_{nveu\text{-}ser}$ equal to 3.519 ksf, the following estimated settlement was determined (Note that the dashed lines with open arrows in Figure 5 represent the estimation of the settlement):

Estimated Settlement ≈ 0.52 inch

Therefore, the wall can be expected to settle approximately 0.52 inch with the soil profile noted in ADOT SF-1 policy memorandum.



[4]Figure 1: Example of a Factored Bearing Resistance Chart for a footing of length, L′ = L = 150-ft (no eccentricity) and depth of embedment, D_f = 6-ft with base elevation of 994-ft. The resistance factor of ϕ_b= 0.45 is included in the strength limit state curve. "S" in the legend refers to immediate settlement.

Figure 6 – Factored Net Bearing Resistance Chart Used To Determine Settlement (ADOT SF-1)