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Subject: Geotechnical Design Policy CIP-1
Load Resistance Factor Design (LRFD)
Analysis of a standard cast-in-place (CIP) wall shown as Case III 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 III 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 sloping backfill configuration.

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 (settlement) limit states.

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 III Walls

This example illustrates the analysis of a standard cast-in-place (CIP) wall shown as Case III in the ADOT SD 7.01 drawings. A typical section of a Case III wall is shown in Figure 1.

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.

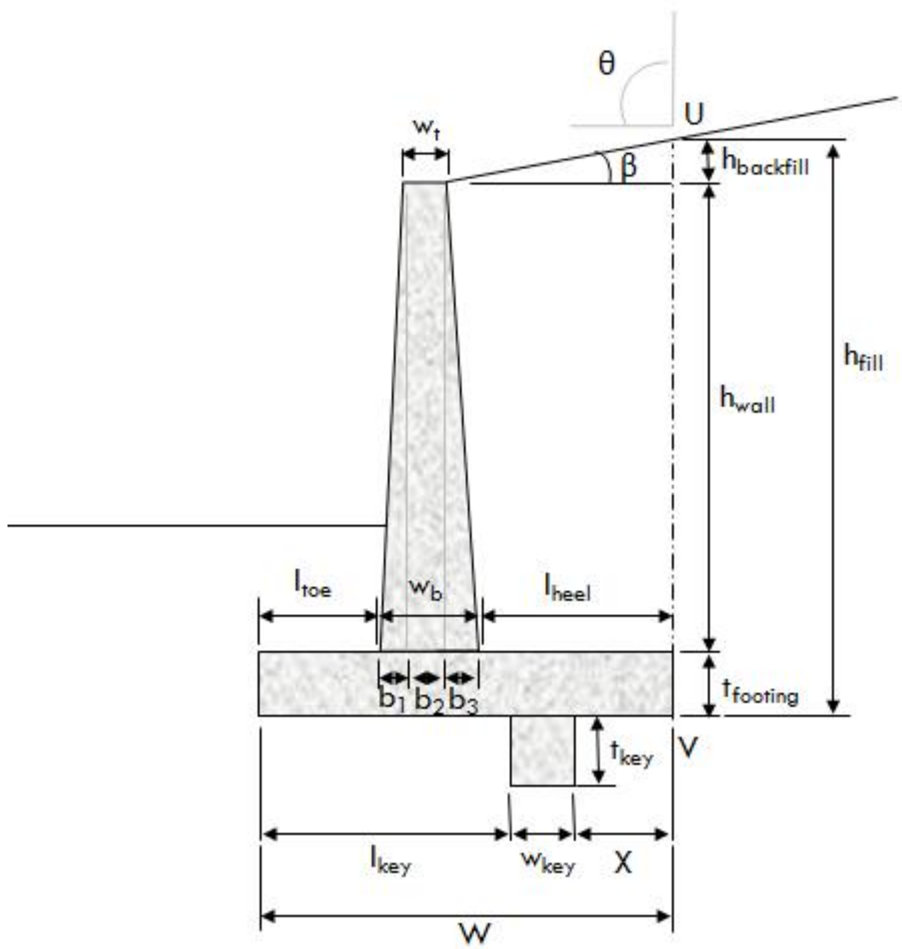


Figure 1 – ADOT SD 7.01 Case III Wall

Substructure

[ADOT SD 7.01]

This example demonstrates the analysis of an ADOT SD 7.01 Case III wall with a maximum backslope of 2:1. Refer to Figure 1 for more detail. Figure 2 represents the applicable loads for the ADOT SD 7.01 Case III wall.

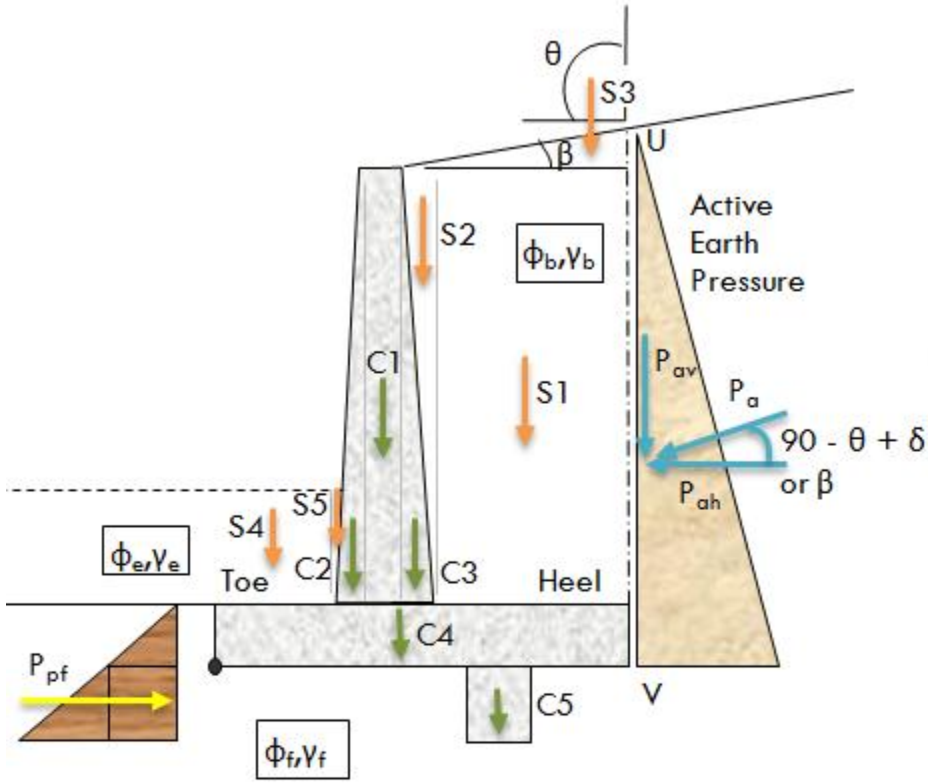


Figure 2 – ADOT SD 7.01 Case III Wall Loads

Definitions

<u>Backfill Vertical Plane (U-V)</u>

δ	Friction Angle Between Fill and Wall
θ	Backfill Vertical Plane Angle (Plane U-V on Figure 2)

[Figure 3.11.5.3-1]

<u>Backslope</u>

β	Backslope Angle
$h_{backfill}$	Height Above Top of Wall Along Plane U-V Due to Backslope

<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
$q_{tveu-ser}$	Factored Total Equivalent Uniform Vertical Bearing Stress (Service I Limit State)
$q_{tveu-str}$	Factored Total Equivalent Uniform Vertical Bearing Stress (Strength I Limit State)

Concrete Properties

γ_c	Unit Weight of Concrete

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-ser}	Distance from Toe of Footing to $R_{vb\ ser\ I}$
D_{b-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-ser}	Eccentricity of $R_{vb\ ser\ I}$ with Respect to Settlement
e_{b-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

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
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_{S1}	Moment about Toe Due to Force S1
M_{S2}	Moment about Toe Due to Force S2
M_{S3}	Moment about Toe Due to Force S3
M_{S4}	Moment about Toe Due to Force S4
M_{Pah}	Moment about Toe Due to Force P_{ah}
M_{Pav}	Moment about Toe Due to Force P_{av}
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 Settlement
$M_{Rb\text{-}str}$	Factored Resultant Moment about the Toe for Bearing Resistance
M_{Rl}	Factored Resultant Moment about the Toe for Limiting Eccentricity
M_{Rs}	Factored Resultant Moment about the Toe for Sliding
P_a	Active Earth Pressure
P_{ah}	Horizontal Component of P_a
P_{av}	Vertical Component of P_a
P_{pf}	Passive Earth Pressure
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 Settlement
$R_{vb\text{-}str}$	Factored Resultant Vertical Force for Bearing Resistance
R_{vl}	Factored Resultant Vertical Force for Limiting Eccentricity
R_{vs}	Factored Resultant Vertical Force for Sliding
S1	Heel Soil Weight
S2	Heel Fillet Soil Weight
S3	Backslope Soil Weight
S4	Toe Soil Weight
S5	Toe Fillet Soil Weight

Load Factors

γ_p	Load Factor for Permanent Loads

Miscellaneous

RLR	Resistance:Load Ratio

Resistance Factors

Φ_{ep}	Passive Earth Pressure Resistance Factor
Φ_τ	Resistance Factor for Frictional Component of Sliding

Soil Properties

γ_b	Unit Weight of Backfill Soil
γ_e	Unit Weight of Embedment Soil
γ_f	Unit Weight of Foundation Soil
φ_b	Internal Friction Angle of Backfill Soil
φ_e	Internal Friction Angle of Embedment Soil
φ_f	Internal Friction Angle of Foundation Soil
c_b	Cohesion of Backfill Soil
c_e	Cohesion of Embedment Soil
c_f	Cohesion of Foundation Soil

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

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)

Wall Properties

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

Wall Footing

D_f	6.0 ft (ADOT SD 7.01 recommends a minimum top cover on the toe of 1.5 ft. For this example 2 ft was used)
$t_{footing}$	4.0 ft
l_{toe}	3.667 ft
l_{heel}	10.58 ft
W	17.0 ft

Wall Shear Key

w_{key}	1.5 ft
t_{key}	1.25 ft
X	4.833 ft
l_{key}	$W - X - w_{key} = 17.0\text{ ft} - 4.833\text{ ft} - 1.5\text{ ft} = 10.67\text{ ft}$

Wall Stem

h_{wall}	25 ft
w_t	10 in = 0.8333 ft
b_1	0 in
b_2	10 in = 0.8333 ft
b_3	23 in = 1.917 ft
w_b	33 in = 2.750 ft

Soil Properties

Backfill

γ_b	120 pcf
φ_b	33.25 deg
c_b	0 ksf

Embedment

γ_e	120 pcf
φ_e	30 deg
c_e	0 ksf

Foundation

γ_f	120 pcf
φ_f	34 deg
c_f	0 ksf

Concrete Properties

γ_c	150 pcf

Backslope Properties and Surcharge

Backslope

β	26.57 deg, (Assuming max backslope of 2:1)
$h_{backfill}$	$(b_3 + l_{heel})\tan\beta$ = (1.917 ft + 10.58 ft)tan(26.57) = 6.250 ft

Backslope Vertical Plane (U-V)

	δ	26.57 deg, (since θ = 90 deg, $\delta = \beta$)
[ADOT SF-2]	θ	90 deg

[ADOT SF-3] **Passive Resistance Factor and Sliding Factors**

Footing from Toe to Key

	Method/Soil/Condition	Soil on Soil
[10.5.5.2.2-1]	$\Phi_{\tau 1}$	0.90
	$\tan\varphi_f$ = tan(34 deg)	0.6745

Footing from Heel to Key

	Method/Soil/Condition	Cast-in-Place Concrete Placed on Sand
[10.5.5.2.2-1]	$\Phi_{\tau 2}$	0.80
	$\tan\varphi_f$ = tan(34 deg)	0.6745

Factored Sliding Coefficient (Weighted)

$\Phi_\tau \tan\varphi_f = [l_{key}(\Phi_{\tau 1})(\tan\varphi_f) + (w_{key} + X)(\Phi_{\tau 2})(\tan\varphi_f)]/W$

$\Phi_\tau \tan\varphi_f = [(10.67\text{ ft})(0.90)(0.6745)+(6.333\text{ ft})(0.80)(0.6745)]/17.0\text{ft}$

$\Phi_\tau \tan\varphi_f = 0.5820$

Passive Earth Pressure Resistance Factor

[10.5.5.2.2-1] Φ_{ep} 0.50

[3.4.1-1] & [3.4.1-2]

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 shall be considered):

Load Categories	Load Factors (Str I)		Load Factors (Ser I)
	Maximum	Minimum	
DC: Concrete Weight	1.25	0.90	1.00
EV: Soil Weight	1.35	1.00	1.00
EH: Active Earth Pressure	1.50	0.90	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 1 and 2 and definitions noted earlier.

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
S1	EV
S2	EV
S3	EV
S4	EV (only used for bearing resistance comps)
S5	EV (only used for bearing resistance comps)
P_a	EH
P_{pf}	Passive Resistance Force, use Passive Resistance Factors

DC Loads (Unfactored)

Stem

$C1 = b_2 h_{wall} \gamma_c$ = (0.8333 ft)(25 ft)(0.150 kcf) = 3.125 k/ft

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

$C3 = ½ b_3 h_{wall} \gamma_c$ = (0.5)(1.917 ft)(25 ft)(0.150 kcf) = 3.594 k/ft

Footing

$C4 = W t_{footing} \gamma_c$ = (17.0 ft)(4.0 ft)(0.150 kcf) = 10.20 k/ft

Shear Key

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

EV Loads (Unfactored)

Heel

$S1 = l_{heel}(h_{wall}) \gamma_b$ = (10.58 ft)(25 ft)(0.120 kcf) = 31.74 k/ft

$S2 = ½ (h_{wall})(b_3) \gamma_b$ = (0.5)(25 ft)(1.917 ft)(0.120 kcf) = 2.876 k/ft

$S3 = ½ (b_3 + l_{heel})(h_{backfill}) \gamma_b$

= (0.5)(1.917 ft + 10.58 ft)(6.250 ft)(0.120 kcf) = 4.686 k/ft

Toe

$S4 = l_{toe}(D_f – t_{footing})\gamma_e$

= (3.667 ft)(6.0 ft – 4.0 ft)(0.120 kcf) = 0.8801 k/ft

S5 = 0, since $b_1 = 0$

EH Loads (Unfactored)

Active Earth Pressure

P_a can be determined by the following equation:

$$P_a = ½ (K_{ab}\gamma_b)(h_{wall} + h_{backfill} + t_{footing})^2$$

[3.11.5.3-1]

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

[3.11.5.3-1]

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

With δ = β = 26.57 deg, θ = 90 deg, and φ_b = 33.25 deg, K_a and Γ are determined as follows:

$$\Gamma = \left[1+\sqrt{\frac{\sin(33.25+26.57)\sin(33.25-26.57)}{\sin(90-26.57)\sin(90+26.57)}}\right]^2 = 1.835$$

$$K_a = \frac{\sin^2(90+33.25)}{1.835[\sin^2(90)\sin(90-26.57)]} = 0.4261$$

P_a = (0.5)(0.4261)(0.120 kcf)(25 ft + 6.250 ft + 4.0 ft)^2 = 31.77 k/ft

With P_a at an angle of β, P_a can be broken up into its horizontal and vertical components by the following equations:

$$P_{ah} = P_a\cos\beta = (31.77\text{ k/ft})\cos(26.57) = 28.41\text{ k/ft}$$
$$P_{av} = P_a\sin\beta = (31.77\text{ k/ft})\sin(26.57) = 14.21\text{ k/ft}$$

Note that the passive earth pressure is categorized as and EH load and the EH load factors apply to both the horizontal and vertical components of the passive earth pressure. Therefore, even though the vertical component is a vertical force, the EH load factor still applies.

Passive Earth Resistance

Use passive resistance from top of footing to bottom of key. See Figure 2 for more detail. The passive earth resistance can be determined by the following equation:

$$P_{pf} = \frac{K_{pf}\gamma_f t_{key}^2}{2} + K_{pf}\gamma_f t_{key}\left(t_{footing}\right) + \frac{K_{pf}\gamma_f t_{footing}^2}{2}$$

Since the face of the key is vertical and the passive resistance will be resisting the horizontal forces, it is conservatively assumed that for the passive wedge only, δ = β = 0.

[Figure 3.11.5.4-1]

To determine passive earth pressure coefficient for the foundation soils, the referenced figure was used. Using θ = 90 deg and φ_f = 34 deg in the referenced figure, K_{pf} was determined for the ratio of $\delta/\varphi_f = 1$.

$$K_{pf} = 9.25 \text{ for } \delta/\varphi_f = 1$$

[Figure 3.11.5.4-1]

Using δ = 0 deg for the passive wedge, the following values are established for $\delta/\varphi_f = 0$:

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 $\delta/\varphi_f = 0$ is as follows:

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

The passive earth pressure can now be determined as follows:

$$P_{pf} = \frac{(3.54)(0.120\ \text{kcf})(1.25\ \text{ft})^2}{2} + (3.54)(0.120\ \text{kcf})(1.25\ \text{ft})(4.0\ \text{ft}) + \frac{(3.54)(0.120\ \text{kcf})(4.0\ \text{ft})^2}{2} = 5.854\ \frac{\text{k}}{\text{ft}}$$

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	$l_{toe} + b_1 + b_2 / 2$	3.667 ft + 0 + (0.8333 ft) / 2	4.084
C3	$l_{toe} + b_1 + b_2 + b_3 / 3$	3.667 ft + 0 + 0.8333 ft + (1.917 ft) / 3	5.139
C4	W/2	(17.0 ft) / 2	8.500
C5	$W – X – w_{key} / 2$	17.0 ft – 4.833 ft – (1.5 ft) / 2	11.42
S1	$W – l_{heel} / 2$	17.0 ft – (10.58 ft) / 2	11.71
S2	$l_{toe} + b_1 + b_2 + 2b_3 / 3$	3.667 ft + 0 + 0.8333 ft + 2(1.917 ft) / 3	5.778
S3	$W – (b_3 + l_{heel}) / 3$	17.0 ft – (1.917 ft + 10.58 ft)/3	12.83
S4	$l_{toe} / 2$	3.667 ft / 2	1.834
P_{ah}	$(h_{backfill} + h_{wall} + t_{footing}) / 3$	(6.250 ft + 25 ft + 4.0 ft) / 3	11.75
P_{av}	W	17.0 ft	17.00

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 2 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}	-	4.084	3.125	-12.76
M_{C3}	-	5.139	3.594	-18.47
M_{C4}	-	8.500	10.20	-86.70
M_{C5}	-	11.42	0.2813	-3.212
M_{S1}	-	11.71	31.74	-371.7
M_{S2}	-	5.778	2.876	-16.62
M_{S3}	-	12.83	4.686	-60.12
M_{S4}	-	1.834	0.8801	-1.614
M_{Pah}	+	11.75	28.41	333.8
M_{Pav}	-	17.00	14.21	-241.6

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 should 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 contributing to activate sliding, the maximum load factor will be applied. Such a combination of load factors should 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	3.125	2.813
C3	Min	0.90	3.594	3.235
C4	Min	0.90	10.20	9.180
C5	Min	0.90	0.2813	0.2532
S1	Min	1.00	31.74	31.74
S2	Min	1.00	2.876	2.876
S3	Min	1.00	4.686	4.686
P_{av}	Max	1.50	14.21	21.32
$R_{vs} = \sum$ Factored Vertical Loads				76.10

Factored Horizontal Loads for Sliding (Str I)				
	Load Factors		Load (Unfactored) (k/f)	Factored Load (Str I) k ft)
	Max / Min	Factor		
P_{ah}	Max	1.50	28.41	42.62
$R_{hs} = \sum$ Factored Horizontal Loads				42.62

Factored Friction Resistance, R_f

$R_f = R_{vs}\ \Phi_\tau \tan\varphi_f$ = (76.10 k/ft)(0.5820) = 44.29 k/ft

Factored Passive Resistance, R_p

$R_p = P_{pf}\ \Phi_{ep}$ = (5.854 k/ft)(0.50) = 2.927 k/ft

Total Factored Sliding Resistance, R_s

$R_s = R_f + R_p$ = 44.29 k/ft + 2.927 k/ft = 47.22 k/ft

Resistance:Load Ratio (RLR) Against Sliding
The RLR should be greater than 1.

RLR = (Factored Resisting Forces / Factored Activating Forces)
= $(R_s) / (R_{hs})$ = (47.22 k/ft) / (42.62 k/ft) = 1.108

RLR = 1.108. Therefore the wall is ok with respect to sliding.

Check for Limiting Eccentricity

Factored Loads and Moments For Limiting Eccentricity (Strength I)
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 should be evaluated. For resisting loads the minimum load factor will be applied. For activating loads the maximum load factor will be applied. The same load factor that is applied to each load is applied to its corresponding moment as well. The beneficial contribution of the Passive Earth Pressure (shown as P_{pf} in Figure 2) 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:

[ADOT SF-2]

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	3.125	2.813
C3	Min	0.90	3.594	3.235
C4	Min	0.90	10.20	9.180
C5	Min	0.90	0.2813	0.2532
S1	Min	1.00	31.74	31.74
S2	Min	1.00	2.876	2.876
S3	Min	1.00	4.686	4.686
P_{av}	Max	1.50	14.21	21.32
$R_{vl} = \sum$ Factored Vertical Loads				76.10

Factored Horizontal Loads for Limiting Eccentricity (Str I)				
	Load Factors		Load (Unfactored) (k/ t)	Factored Load (Str I) (k/ft)
	Max / Min	Factor		
P_{ah}	Max	1.50	28.41	42.62

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	-12.76	-11.48
M_{C3}	Min	0.90	-18.47	-16.62
M_{C4}	Min	0.90	-86.70	-78.03
M_{C5}	Min	0.90	-3.212	-2.891
M_{S1}	Min	1.00	-371.7	-371.7
M_{S2}	Min	1.00	-16.62	-16.62
M_{S3}	Min	1.00	-60.12	-60.12
M_{Pah}	Max	1.50	333.8	500.7
M_{Pav}	Max	1.50	-241.6	-362.4
M_{Rl} = (-1)(∑ Factored Moments)				419.2

Distance from Toe to R_{vl}

$D_l = M_{Rl} / R_{vl}$ = (419.2 k-ft/ft) / (76.10 k/ft) = 5.509 ft

Limiting Eccentricity

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

$e_l = D_l – W/2$ = 5.509 ft – (17.0 ft) / 2 = -2.991 ft = 2.991 ft towards the toe of the wall from the middle of the footing.

[ADOT SF-2] $e_{max} = W[1/3 – \beta/320]$ = (17.0 ft)[1/3 – 26.57/320] = 4.255 ft

e_{max} = 4.255 ft, which is greater than e_l = 2.991 ft. Therefore the wall is ok with respect to limiting eccentricity.

<u>Check For Bearing Resistance</u>

Factored Loads and Moments For Bearing Resistance

Bearing resistance is a strength limit state check. 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 should 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 same load / resistance factor that is applied to each load is applied to its corresponding moment as well. The beneficial contribution of the Passive Earth Pressure (shown as P_{pf} in Figure 2) 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	3.125	3.906
C3	Max	1.25	3.594	4.493
C4	Max	1.25	10.20	12.75
C5	Max	1.25	0.2813	0.3516
S1	Max	1.35	31.74	42.85
S2	Max	1.35	2.876	3.883
S3	Max	1.35	4.686	6.326
S4	Max	1.35	0.8801	1.188
P_{av}	Max	1.50	14.21	21.32
$R_{vb\text{-}str} = \sum$ Factored Vertical Loads				97.07

Factored Horizontal Loads for Bearing Resistance				
	Load Factors		**Load (Unfactored) (k/ft)**	**Str I Factored Load (k/ft)**
	Max / Min	**Factor**		
P_{ah}	Max	1.50	28.41	42.62

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	-12.76	-15.95
M_{C3}	Max	1.25	-18.47	-23.09
M_{C4}	Max	1.25	-86.70	-108.4
M_{C5}	Max	1.25	-3.212	-4.015
M_{S1}	Max	1.35	-371.7	-501.8
M_{S2}	Max	1.35	-16.62	-22.44
M_{S3}	Max	1.35	-60.12	-81.16
M_{S4}	Max	1.35	-1.614	-2.179
M_{Pah}	Max	1.5	333.8	500.7
M_{Pav}	Max	1.5	-241.6	-362.4
$M_{Rb\text{-}str}$ = (-1)(∑ Factored Moments)				620.7

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

$D_{b\text{-}str} = M_{Rb\text{-}str} / R_{vb\text{-}str}$ = (620.7 k-ft/ft) / (97.07 k/ft) = 6.394 ft

Eccentricity

$e_{b\text{-}str} = D_{b\text{-}str} - W/2$ = 6.394 ft – (17.0 ft) / 2 = -2.106 ft = 2.106 ft towards the toe of the wall from the middle of the footing.

Factored Total Equivalent Uniform Vertical Bearing Stress

$B'_{str} = W - 2e_{b\text{-}str}$ = 17.0 ft – 2(2.106 ft) = 12.79 ft

$q_{tveu\text{-}str} = R_{vb\text{-}str} / (B'_{str})$ = (97.07 k/ft) / (12.79 ft)
$q_{tveu\text{-}str}$ = 7.590 ksf

Factored Net Equivalent Uniform Vertical Bearing Stress

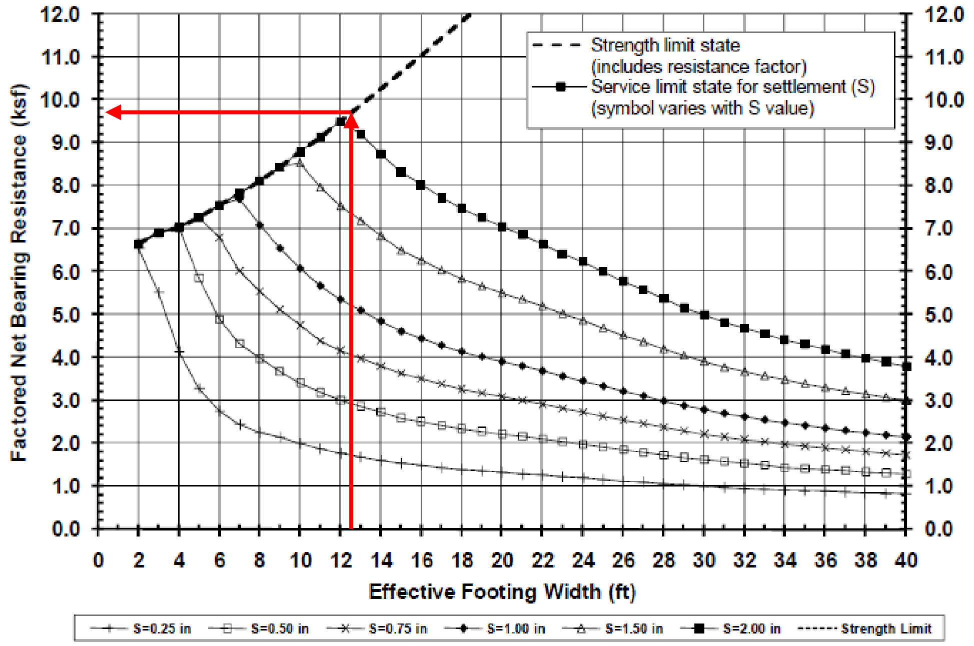
$q_{nveu\text{-}str} = q_{tveu\text{-}str} - \gamma_p(\gamma_e D_f)$ = 7.590 ksf – 1.35(0.120 kcf(6.0 ft))
$q_{nveu\text{-}str}$ = 6.618 ksf

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 memo . Therefore the Factored Net Bearing Resistance Chart shown as Figure 1 in the ADOT SF-1 policy memo is applicable for this example ***(Note that a site specific Factored Net Bearing Resistance Chart will need to be generated for actual design).*** The Factored Net Bearing Resistance Chart shown as Figure 1 in the ADOT SF-1 policy memo has been included in this example as Figures 5 and 6.

Using Figure 3 and B'_{str} equal to 12.79 feet, the following factored net bearing resistance was determined (Note that the solid lines with closed arrows in Figure 3 represent the estimation of $q_{nf\text{-}str}$):

$q_{nf\text{-}str}$ = 9.70 ksf
RLR = (Resistance / Stress) = (9.70 ksf) / (6.618 ksf) = 1.466, 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 3 – Factored Net Bearing Resistance Chart Used to Determine $q_{nf\text{-}str}$ (ADOT SF-1)

<u>Check For Settlement</u>

Factored Loads and Moments For Settlement

Settlement is a service limit state check. The Service I limit state will be used for this example to determine the settlement. In actual design, all applicable load combinations should be evaluated. The beneficial contribution of the Passive Earth Pressure (shown as P_{pf} in Figure 2) 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	3.125	3.125
C3	N/A	1.00	3.594	3.594
C4	N/A	1.00	10.20	10.20
C5	N/A	1.00	0.2813	0.2813
S1	N/A	1.00	31.74	31.74
S2	N/A	1.00	2.876	2.876
S3	N/A	1.00	4.686	4.686
S4	N/A	1.00	0.8801	0.8801
P_{av}	N/A	1.00	14.21	14.21
$R_{vb\text{-}ser} = \sum$ Factored Vertical Loads				71.59

Factored Horizontal Loads for Settlement				
	Load Factors		Load (Unfactored) (k/ft)	Ser I Factored Load (k/ft
	Max / Min	Factor		
P_{ah}	N/A	1.00	28.41	28.41

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	-12.76	-12.76
M_{C3}	N/A	1.00	-18.47	-18.47
M_{C4}	N/A	1.00	-86.70	-86.70
M_{C5}	N/A	1.00	-3.212	-3.212
M_{S1}	N/A	1.00	-371.7	-371.7
M_{S2}	N/A	1.00	-16.62	-16.62
M_{S3}	N/A	1.00	-60.12	-60.12
M_{S4}	N/A	1.00	-1.614	-1.614
M_{Pah}	N/A	1.00	333.8	333.8
M_{Pav}	N/A	1.00	-241.6	-241.6
$M_{Rb\text{-}ser} = (-1)(\sum$ Factored Moments)				479.0

Distance from Toe to R_{vb}

$D_{b\text{-}ser} = M_{Rb\text{-}ser} / R_{vb\text{-}ser}$ = (479.0 k-ft/ft) / (71.59 k/ft) = 6.691 ft

Eccentricity

$e_{b\text{-}ser} = D_{b\text{-}ser} – W/2$ = 6.691 ft – (17.0 ft) / 2 = -1.809 ft = 1.809 ft towards the toe of the wall from the middle of the footing.

Factored Total Equivalent Uniform Vertical Bearing Stress

$B'_{ser} = W\text{-}2e_{b\text{-}ser} = 17.0 \text{ ft} - 2(1.809 \text{ ft}) = 13.38 \text{ ft}$

$q_{tveu\text{-}ser} = R_{vb\text{-}ser} / (B'_{ser}) = (71.59 \text{ k/ft}) / (13.38 \text{ ft}))$

$q_{tveu\text{-}ser} = 5.351 \text{ ksf}$

Factored Net Equivalent Uniform Vertical Bearing Stress

$q_{nveu\text{-}ser} = q_{tveu\text{-}ser} - \gamma_p(\gamma_e D_f) = 5.351 \text{ ksf} - 1.00(0.120 \text{ kcf}(6.0 \text{ ft}))$

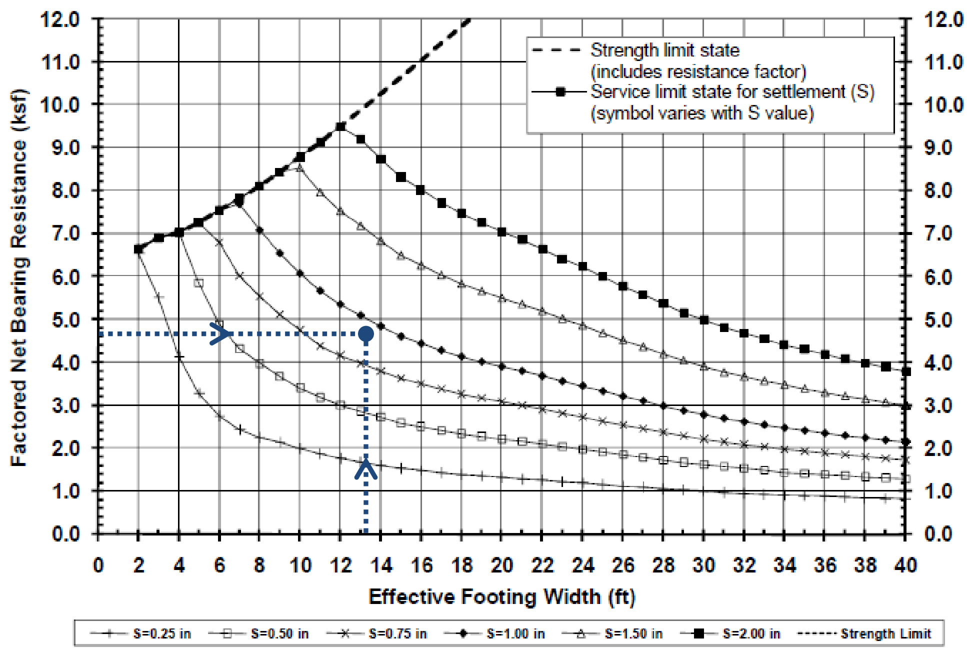
$q_{nveu\text{-}ser} = 4.631 \text{ ksf}$

Estimated Settlement (Service I Limit State)

Using Figure 4, B'_{ser} equal to 13.38 feet, and $q_{nveu\text{-}ser}$ equal to 4.631 ksf, the following estimated settlement was determined (Note that the dashed lines with open arrows in Figure 4 represent the estimation of the settlement):

Estimated Settlement ≈ 0.90 in.

Therefore, the wall can be expected to settle less than 1 inch with a soil profile the same as ADOT SF-1 policy memo.



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