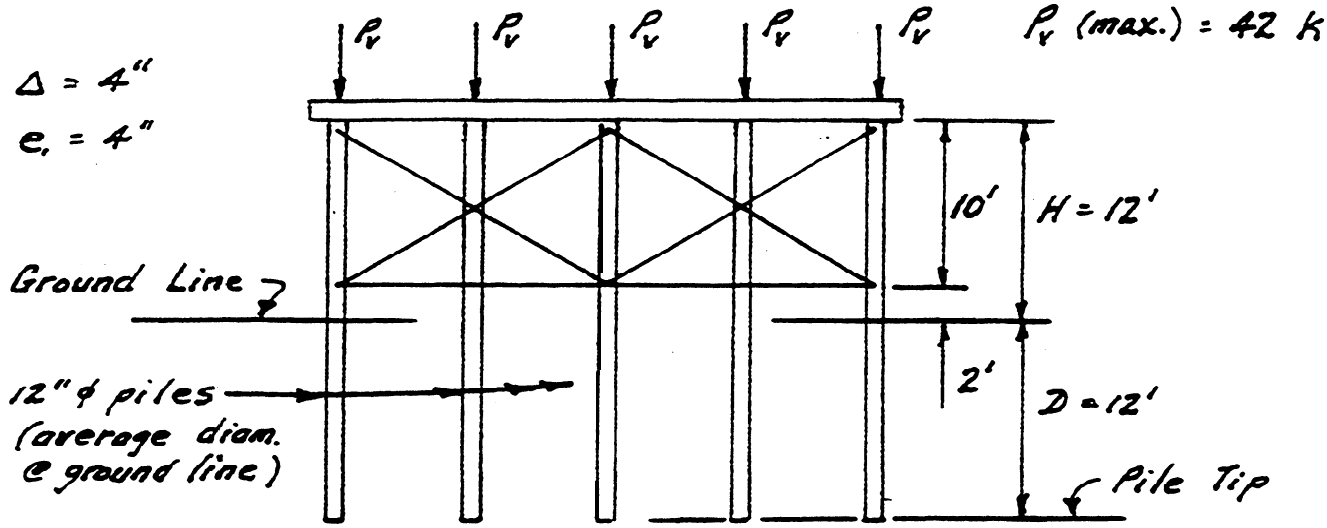
EXAMPLE 14

Investigate Adequacy of Timber Pile Bent Design

Example 14A (Type I Bent)



Preliminary Calculations and Assumptions

1. Pile properties (12"ϕ pile ; r = 6")

$A = \pi r^2 = 113 \text{ in}^2$

$S = \frac{\pi r^3}{4} = 170 \text{ in}^3$

$I = \frac{\pi r^4}{4} = 1018 \text{ in}^4$

2. Required Pile Penetration (Section 7-3.02A)

Minimum $D/H = 0.75$; design $D/H = 12/12 = 1.0$ OK

Minimum D for construction = (0.75)(12.0) = 9.0'

3. Soil Relaxation Factor (Section 7-3.02D)

Assume average soil and 30-day time period.

From Soil Factor Chart (Fig. 7-10) R = 1.25

4. Point of Pile Fixity (Section 7-3.02B)

Y_1 = (4)(pile diam. @ ground line) = (4)(1.0) = 4.0'

Y_2 = (Y_1)(soil relax. factor) = (4.0)(1.25) = 5.0'

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Preliminary Calculations Continued

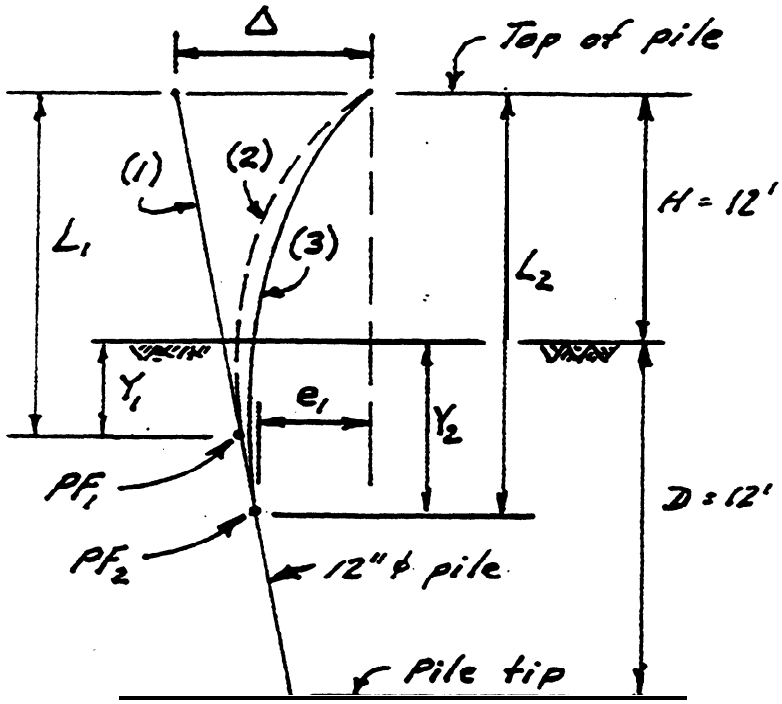
5. Driving Tolerances (Section 7-3.02C)

Max. pile pull = Δ = 4"
Max pile lean = e_1 = 4"
} Values from F/W drawings

6. Modulus of Elasticity (Section 7-3.02E)

Assume E = 1,600,000 psi

Investigate Effect of Pile Pull



Δ = 4" e_1 = 4"

(1) = Driven position
(2) = Initial pulled position
(3) = Position when P_v is applied

$L_1 = H + Y_1 = 12.0 + 4.0 = 16.0'$

$L_2 = H + Y_2 = 12.0 + 5.0 = 17.0'$

Pile Schematic (no scale)

1. Calculate F_1 = force to pull pile into line

$$F_1 = \frac{3EI\Delta}{(12L_1)^3} = \frac{3(1.6\times10^6)(1018)(4)}{(12\times16.0)^3} = 2762 \text{ lbs.}$$

2. Calculate the initial bending stress

$$f_{bp(1)} = \frac{F_1(12L_1)}{S} = \frac{(2762)(12\times16)}{170} = 3119 \text{ psi}$$

3119 psi < 4000 psi allowed. OK

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Pile Pull Continued

3. Calculate F_2 = force after soil relaxes

$$F_2 = \frac{F_1 (L_1)^3}{(L_2)^3} = \frac{2762\,(16.0)^3}{(17.0)^3} = 2303 \text{ lbs.}$$

4. Calculate final bending stress

$$f_{bp(2)} = \frac{F_2\,(12 L_2)}{S} = \frac{2303\,(12 \times 17.0)}{170} = 2762 \text{ psi}$$

Evaluate System Adequacy (Section 7-3.03E)

1. Determine bent type

$L_u = Y_2 + (12.0 - 10.0) = 5.0 + 2.0 = 7.0'$

$L_u/d = 7.0/1.0 = 7 < 8$; $\therefore$ Type I bent

Do not consider design H (Section 7-3.03C)

2. Calc. stress due to vertical load eccentricity

$$f_{be(1)} = \frac{(P_v Y_{e_1})}{S} = \frac{(42000)(4)}{170} = 988 \text{ psi}$$

3. Calc. stress due to axial compression

$$f_c = \frac{P_v}{A} = \frac{42000}{113} = 372 \text{ psi}$$

4. Determine allowable compressive stress

Note: bent supported at the cap in the longitudinal direction.

L_u (in longitudinal direction) $= L_2 = 17.0'$

Equivalent "d" $= \sqrt{A} = \sqrt{113} = 10.6''$

$$L_u/d = \frac{\cancel{170 \times 12}}{10.6} = 19.25$$

$$F_c = \frac{\cancel{480,000}}{(19.25)^2} = 1295 \text{ psi}$$

System Adequacy Continued

5. Solve combined stress expression

$$\frac{f_{bp(2)} + 2f_{be(1)}}{3F_b} + \frac{2f_c}{3F_c} \not< 1.0$$

$$\frac{2762 + 2(988)}{3(1800)} + \frac{2(372)}{3(1295)}$$

$$0.88 + 0.19 = 1.07 > 1.0$$

System fails !!

Options available to make system adequate:

(a) use larger diameter pile

(b) reduce allowable values for Δ and/or e_1

(c) shorten F/W span to reduce P_v

Contractor resubmits design using 14"ϕ piles.

New pile properties	New design values
$A = 154\ in^2$	$Y_1 = (4)(14/12) = 4.67'$
$S = 269\ in^3$	$Y_2 = (1.25)(4.67) = 5.83'$
$I = 1886\ in^4$	$L_1 = H + 4.67 = 16.67'$
	$L_2 = H + 5.83 = 17.83'$

Investigate Effect of Pile Pull

(Refer to sketch on page D-14-2 and previous calcs.)

$$F_1 = \frac{3EI\Delta}{(12L_1)^3} = \frac{3(1.6\times10^6)(1886)(4)}{(12\times16.67)^3} = 4524\ lbs.$$

$$f_{bp(1)} = \frac{F_1(12L_1)}{S} = \frac{(4524)(12\times16.67)}{269} = 3364\ psi$$

3364 < 4000 psi allowable **OK**

$$F_2 = \frac{F_1(L_1)^3}{(L_2)^3} = \frac{(4524)(16.67)^3}{(17.83)^3} = 3697\ lbs.$$

$$f_{bp(2)} = \frac{F_2(12L_2)}{S} = \frac{(3697)(12\times17.83)}{269} = 2941\ psi$$

Evaluate System Adequacy

Check bent type -

L_u = new Y_2 + (12.0 - 10.0) = 5.83 + 2.0 = 7.83'

$L_u/d = \frac{(7.83)(12)}{14} = 6.71 < 8$ **still Type I bent**

$$f_{be(1)} = \frac{(P_v)(e_1)}{S} = \frac{(42000)(4)}{269} = 625 \text{ psi}$$

$$f_c = \frac{P_v}{A} = \frac{42000}{154} = 273 \text{ psi}$$

Allowable F_c -

L_u (longitudinal direction governs) = L_2 = 17.83'

Equivalent "d" = $\sqrt{154}$ = 12.4"

$L_u/d = \frac{17.83 \times 12}{12.4} = 17.25$

$$F_c = \frac{480000}{(17.25)^2} = 1613 \text{ psi} > 1600 \text{ psi}$$ use

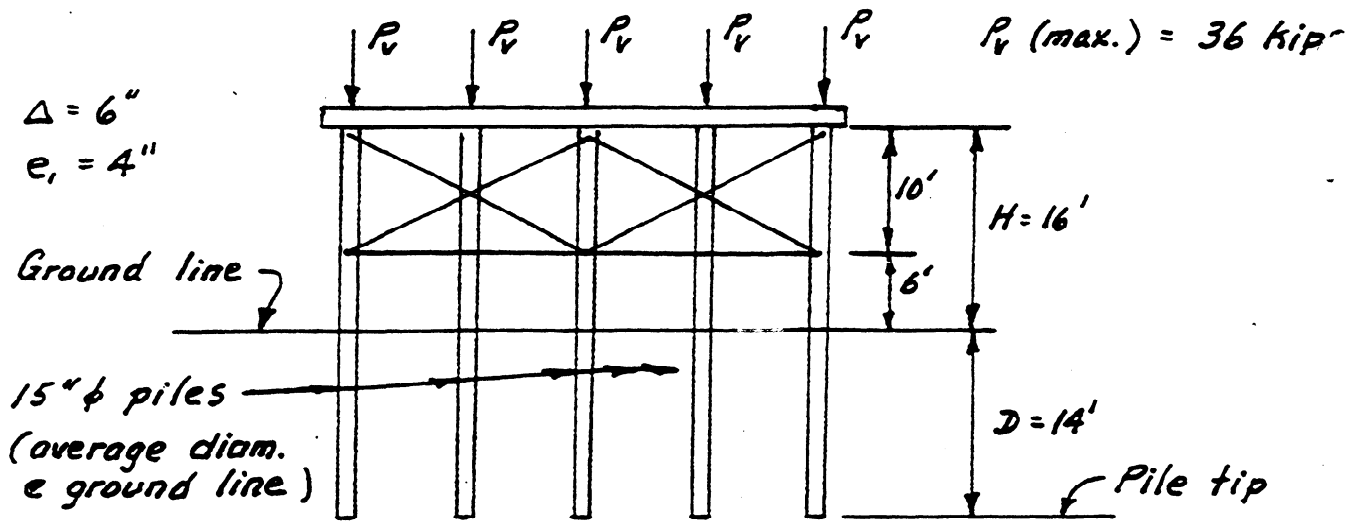
Solve combined stress expression -

$$\frac{f_{bp(2)} + 2f_{be(1)}}{3F_b} + \frac{2f_c}{3F_c} = \frac{2941 + 2(625)}{3(1800)} + \frac{2(273)}{3(1600)}$$

$$= 0.78 + 0.11 = 0.89 < 1.0$$

System is now adequate

Example 14B (Type II Bent)



Preliminary Calculations and Assumptions

1. **Pile properties** (15" ϕ pile; r = 7.5")

   $A = \pi r^2 = 177 \text{ in}^2$

   $S = \pi r^3/4 = 331 \text{ in}^3$

   $I = \pi r^4/4 = 2485 \text{ in}^4$

2. **Required pile penetration** (Section 7-3.02A)

   Minimum $D/H = 0.75$; design $D/H = 14/16 = 0.875$ **OK**

   Minimum D for construction = (0.75)(16.0) = 12.0'

3. **Soil relaxation factor** (Section 7-3.02D)

   Assumptions: (1) normal (average) soil
   (2) 30-day time period

   From Soil Factor Chart (Figure 7-12) R = 1.25

4. **Point of pile fixity** (Section 7-3.02B)

   Y_1 = (4)(ground line pile diameter) = (4)(1.25) = 5.0'

   Y_2 = (Y_1)(soil relax. factor) = (5.0)(1.25) = 6.25'

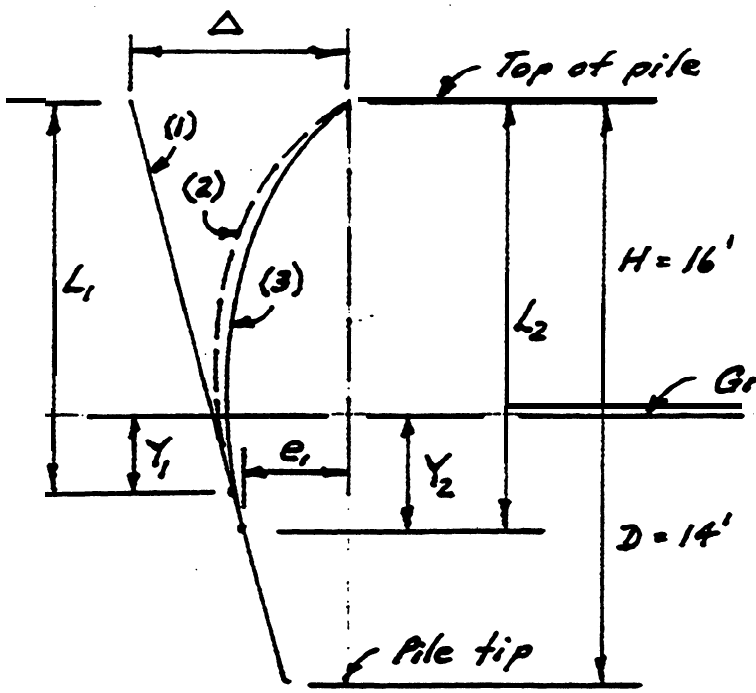
5. <u>Driving tolerances</u> (Section 7-3.02C)

Max. pile pull = Δ = 6" } from F/W drawings
Max. pile lean = e_1 = 4"

6. <u>Modulus of elasticity</u> (Section 7-3.02E)

Assume E = 1,600,000 psi

Effect of Pile Pull (Section 7-3.03A)



(1) Driven position

(2) Initial pulled position

(3) Position when P_v is applied

$Y_1 = 5.0'$; $Y_2 = 6.25'$

$L_1 = H + Y_1 = 21.0'$

$L_2 = H + Y_2 = 22.25'$

Pile Schematic (no scale)

1. <u>Calculate force to pull pile into line</u>

$$F_1 = \frac{3EI\Delta}{(12L)^3} = \frac{3(1.6 \times 10^6)(2485)(6)}{(12 \times 21.0)^3} = 4472 \text{ lbs.}$$

2. <u>Calculate the initial bending stress</u>

$$f_{bp(1)} = \frac{(F_1)(12L_1)}{S} = \frac{(4472)(12 \times 21.0)}{331} = 3405 \text{ psi}$$

3405 psi < 4000 psi allowed - <u>OK</u>

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Pile Pull Continued

3. Calculate force remaining when P_v is applied

$$F_2 = \frac{F_1 (L_1)^3}{(L_2)^3} = \frac{4472\,(21.0)^3}{(22.25)^3} = 3760 \text{ lbs.}$$

4. Calculate relaxed bending stress

$$f_{bp(2)} = \frac{F_2 (12 L_2)}{S} = \frac{3760\,(12 \times 22.25)}{331} = 3033 \text{ psi}$$

Evaluate System Adequacy (Section 3.03E)

1. Determine bent type

$$L_u = Y_2 + (16.0 - 10.0) = 6.25 + 6.0 = 12.25'$$

$$L_u/d = \frac{12.25}{1.25} = 9.8 \qquad \therefore \text{ Type II bent}$$

Consider H but not P-delta (Section 7-3.03C)

2. Calculate stress due to pile lean

$$f_{be(1)} = \frac{P_v (e_1)}{S} = \frac{36000\,(4)}{331} = 435 \text{ psi}$$

3. Calculate stress due to design H

$$H = (0.02 \times 36000) = 720 \text{ lbs.}$$

$$f_{bH} = \frac{(H)(12 L_u)}{S} = \frac{(720)(12.25 \times 12)}{331} = 320 \text{ psi}$$

4. Calculate horiz. displacement

$$X = \frac{H(12 L_u)^3}{3EI} = \frac{720\,(12 \times 12.25)^3}{3(1.6 \times 10^6)(2485)} = 0.19'' = e_2$$

5. Calculate stress due to additional P_v eccentricity

$$f_{be(2)} = \frac{P_v (e_2)}{S} = \frac{36000\,(0.19)}{331} = 21 \text{ psi}$$

System Adequacy Continued

5. Calculate stress due to axial compression

$$f_c = \frac{P_v}{A} = \frac{36000}{177} = 203 \text{ psi}$$

6. Determine allowable compressive stress

Bent is supported at the cap in the longitudinal direction.

L_u (in longitudinal direction) $= L_2 = 22.25'$

Equivalent "d" $= \sqrt{A} = \sqrt{177} = 13.3''$

$$L_u/d = \frac{12 \times 22.25}{13.3} = 20.1$$

$$F_c = \frac{480,000}{(20.1)^2} = 1188 \text{ psi}$$

7. Check pile adequacy using combined stress expression

$$\frac{f_{bp(2)} + 2f_{be(1)} + 2(f_{bH} + f_{be(2)})}{3F_b} + \frac{2f_c}{3F_c} \not> 1.0$$

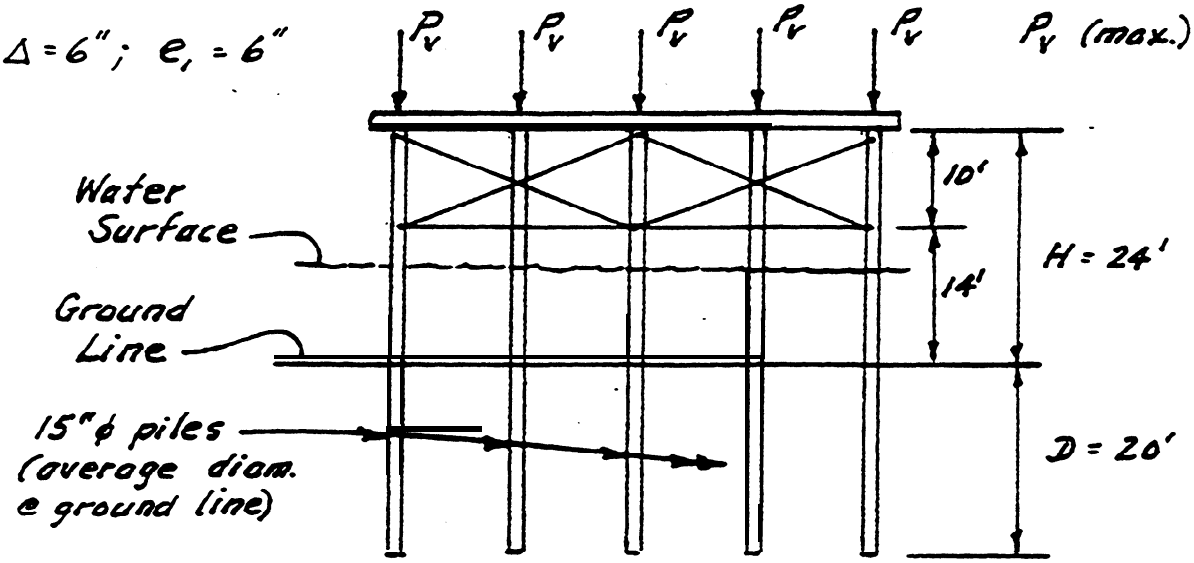
$$\frac{3033 + 2(435) + 2(320 + 21)}{3(1800)} + \frac{2(203)}{3(1188)}$$

$$0.85 + 0.11 = 0.96$$

System is adequate

Example 14C (Type III Bent)

$\Delta = 6''$; $e_1 = 6''$



Preliminary Calculations and Assumptions

1. **Pile properties** (15" ϕ pile; r = 7.5")

   $A = \pi r^2 = 177 \text{ in}^2$

   $S = \pi r^3/4 = 331 \text{ in}^3$

   $I = \pi r^4/4 = 2485 \text{ in}^4$

2. **Required pile penetration** (Section 7-3.02A)

   Minimum $D/H = 0.75$; design $D/H = 20/24 = 0.83$ **OK**

   Minimum D for construction = (0.75)(24) = 18.0'

3. **Soil relaxation factor** (Section 7-3.02D)

   Assumptions: (1) normal (average) soil
   (2) 30-day time period

   From Soil Factor Chart (Figure 7-12) R = 1.25

4. **Point of pile fixity** (Section 7-3.02B)

   Y_1 = (4)(ground line pile diam.) = (4)(1.25) = 5.0'

   Y_2 = (Y_1)(soil relax. factor) = (5.0)(1.25) = 6.25'

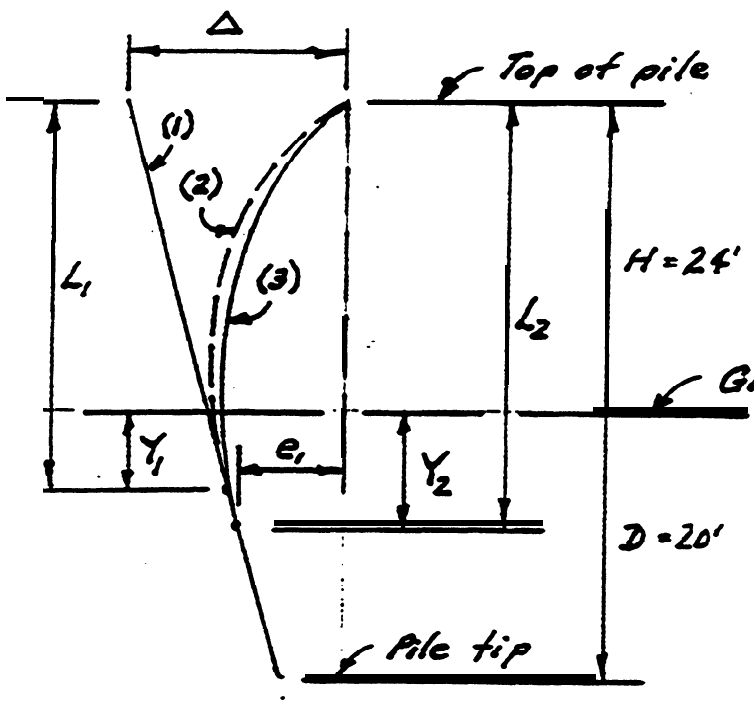
5. <u>Driving tolerances</u> (Section 7-3.02C)

Max. pile pull = Δ = 6" } values from F/W drawings
Max. pile lean = e_1 = 6"

6. <u>Modulus of elasticity</u> (Section 7-3.02E)

Assume E = 1,600,000 psi

Effect of Pile Pull (Section 7-3.03A)



(1) Driven position

(2) Initial pulled position

(3) Position when P_v is applied

$Y_1 = 5.0'$; $Y_2 = 6.25'$

$L_1 = H + Y_1 = 29.0'$

$L_2 = H + Y_2 = 30.25'$

Pile Schematic (no scale)

1. <u>Calculate force to pull pile into line</u>

$$F_1 = \frac{3EI\Delta}{(12L_1)^3} = \frac{3(1.6\times10^6)(2485)(6)}{(12\times29.0)^3} = 1698 \text{ lbs.}$$

2. <u>Calculate the initial bending stress</u>

$$f_{bp(1)} = \frac{F_1(12L_1)}{S} = \frac{(1698)(12\times29.0)}{331} = 1785 \text{ psi}$$

1785 < 4000 psi allowed - <u>OK</u>

Pile Pull Continued

3. Calculate force remaining when P_v is applied

$$F_2 = \frac{F_1 (L_1)^3}{(L_2)^3} = \frac{(1698)(29.0)^3}{(30.25)^3} = 1496 \text{ lbs}$$

4. Calculate the relaxed bending stress

$$f_{bp(2)} = \frac{F_2 (12 L_2)}{S} = \frac{(1496)(12 \times 30.25)}{331} = 1640 \text{ psi}$$

Evaluate System Adequacy (Section 7-3.03E)

1. Determine bent type

$$L_u = Y_2 + (24.0 - 10.0) = 6.25 + 14.0 = 20.25'$$

$$L_u/d = \frac{20.25}{1.25} = 16.2 > 15, \quad \therefore \text{ Type III Bent}$$

Consider P-delta effect (Section 7-3.03D)

2. Calculate stress due to pile lean

$$f_{be_1} = \frac{P_v (e_1)}{S} = \frac{(32000)(6)}{331} = 580 \text{ psi}$$

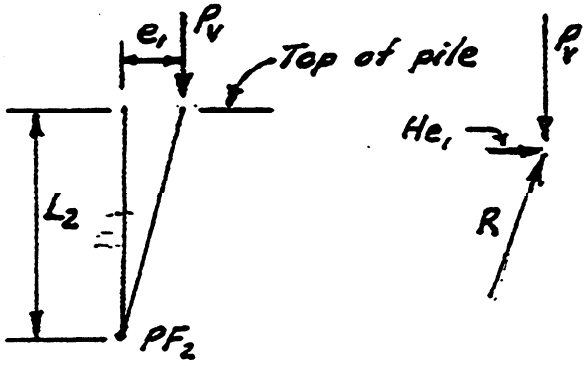
3. Calculate stress due to design H

$$H = (0.02)(32{,}000) = 640 \text{ lbs.}$$

$Y_2 + (24-10)$

$$f_{bH} = \frac{H (12 \times L_u)}{S} = \frac{(640)(12 \times 20.25)}{331} = 470 \text{ psi}$$

4. Calculate horizontal component of P_v reaction



$$He_1 = \frac{P_v (e_1)}{12 L_2}$$

$$He_1 = \frac{(32000)(6)}{(12)(30.25)} = 529 \text{ lbs.}$$

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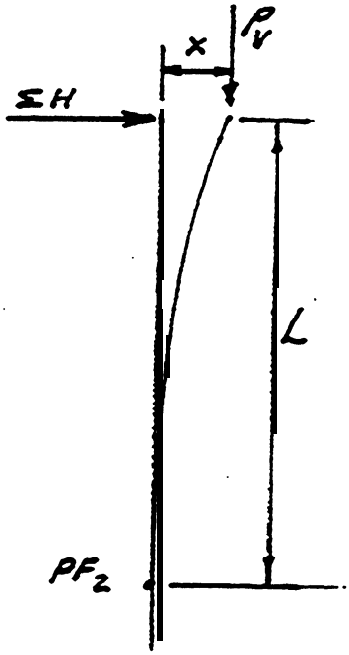
System Adequacy Continued

5. Calculate total horizontal displacement (e_3)



x = displacement due to total H load

$$x = \frac{\Sigma H (L)^3}{3EI}$$

ΣH = design H + He_1

$= 640 + 529 = 1169$ lbs.

$L = Y_2 + (24 - 10) = 20.25' = 243''$

$3EI = 3(1.6 \times 10^6)(2485)$

$= 1.193 \times 10^{10}$

Refer to Section 7-3.03D and Figure 7-15

$$x = \frac{(1169)(243)^3}{3EI} = 1.41'' \qquad H_1 = 1169 + \frac{(32000)(1.41)}{243} = 1355 \text{ lbs.}$$

$$x_1 = \frac{(1355)(243)^3}{3EI} = 1.63'' \qquad H_2 = 1355 + \frac{(32000)(1.63-1.41)}{243} = 1384 \text{ lbs}$$

$$x_2 = \frac{(1384)(243)^3}{3EI} = 1.66''$$

Values within 5 % **STOP**

6. Calculate bending stress due to ΣH displacement

$$f_{be_3} = \frac{P_v(e_3)}{S} = \frac{(32000)(1.66)}{331} = 160 \text{ psi}$$

7. Calculate stress due to axial compression

$$f_c = \frac{P_v}{A} = \frac{32000}{177} = 181 \text{ psi}$$

System Adequacy Continued

8. Determine allowable compressive stress

Bent is supported at the cap in the longitudinal direction.

L_u (in longitudinal direction) $= L_2 = 30.25'$

Equivalent "d" $= \sqrt{A} = \sqrt{177} = 13.3''$

$$L_u/d = \frac{12 \times 30.25}{13.3} = 27.3$$

$$F_c = \frac{480000}{(27.3)^2} = 644 \text{ psi}$$

9. Check pile adequacy using combined stress expression

$$\frac{f_{bp(2)} + 2f_{be(1)} + 2(f_{bH} + f_{be(3)})}{3F_b} + \frac{2f_c}{3F_c} \not> 1.0$$

$$\frac{1640 + 2(580) + 2(470 + 160)}{3(1800)} + \frac{2(181)}{3(644)}$$

$$0.75 + 0.19 = 0.94$$

System is adequate