Structural Engineering Procedure No. 17-01

Date: December 27, 2017

Distribution: Bridge Office

PROCEDURE: NEW INTEGRAL END BENT PILE DESIGN PROCEDURE

Contact: Gregory Sanders, Development Section
Aaron Kemna, Senior Structural Engineer, author of simple pile design procedure
Darren Kemna, Senior Structural Engineer, author of rigorous pile design procedure
Al Shawn, Senior Structural Designer, contributor

EPG Status: Simple Pile Design To Be Submitted, Rigorous Pile Design Not To Be Submitted

Effective Date: Immediately For Jobs To Be Designed

Expiration/Duration: Active Until Further Notice

Internal Development Section Job Number: 17-055-DSI

Background and Purpose:

Integral end bent pile loading design was more simple in the past when only axial loading design in accordance with AASHTO 17th Ed. Standard Specifications Allowable Service Design (ASD) was office practice. It was considered adequate for integral concrete bridge lengths up to 600 ft. (500 ft. for steel) and an undefined maximum skew limit (45° to 50°) [(1)]

When AASHTO LRFD Bridge Design Specifications (LRFD) was adopted for bridge substructure design, pile lateral loading design was implemented into office practice. Integral end bent piles were then designed for both loading types until later revised (see e-mail [(2)] below) thus becoming the current office practice.

Current office practice requires comparing both past ASD and LRFD office practices to determine the controlling size and number of piles where either not greater than as determined by ASD is required. While both ASD and LRFD are utilized side by side initially, either ASD or LRFD is supposed to singularly validate the final pile solution.

This has led to confusion with pile designs performed based on either method. Some designs may be only considering ASD. Some designs may show that LRFD can produce less pile axial loading compared with ASD and therefore fewer piles but when combined with LRFD lateral loading may produce the same pile size and numbers as ASD. Some designs may be only considering LRFD in excess of an ASD design check based on atypical bridge parameters of length and skew.

Therefore, to avoid the furtherance of confusion, a firm and clear direction for pile design is necessary. Only pile axial loading design will be required for most bridge layout configurations and it shall follow current ASD practice only.

Past successful integral bridge performance is the strongest rationale in support of a pile axial loading-only, ASD practice. A lack of adequate codification in LRFD to formally address pile design for these structure types is also an issue, however there have been many individual states experimental research studies some of them reviewed for this new direction and are our own empirical successes. It is sufficient to state that an integral end bent on steel piling is a complex resistance system where the sum of all of its parts counteracts primarily its largest loading, thermal movement, but provides also its greatest impediment to understanding because of the coupled component responses to lateral loading.

It should be noted that field inspections do not inspect the bottoms of end bent beam caps nor piles at the beam caps because of inaccessibility, however neither collateral damage due to overstressed piles (front face beam cracks, wing wall cracks, end of slab cracking, beam translation, rotation, settling) nor visibly damaged incidentally exposed piles or underside of beam caps at end bents (when exposed due to scour, erosion) have been reported. In fairness, it should also be noted that there has been individual state efforts in researching integral bridge end bent pile design over many years.

Two methods are proposed. A simple method that will cover more than ninety percent of new bridges to be designed and a rigorous method for handling the remaining ten percent.. The simple method will be submitted to the EPG for incorporation. The rigorous method will be utilized for in-house design with discretionary release to consultants based on the findings from in-house since it is based on the plastic design of piles.

Having a rigorous pile design method allows for two things: retaining knowledge and practice for refined combined end bent pile axial and lateral loading design and a possible pathway forward to longer integral bridges.

---

(1) A quick bridge review shows that ten new integral bridges have skews greater than 45 degrees. Four of these were designed in-house (A7958, A7639, A7622 and A6221), and the greatest skew is 50° (A7639 with 50-foot length and A6221 with 119-foot length). The greatest skew for a consultant-designed integral bridge is 63° (A6430 with 106-foot length).

(2) E-mail to Bridge Division revising then office practice in 2008 to current practice:

Date: 06/30/2008 10:48 AM
Subject: LRFD Substructure Design

The designers/checkers should continue to investigate based on LRFD. The axial loads should be used to determine the number and size of the piles. Then, the lateral stability check should be performed. If this check causes an increase in pile size or an increase in the number of piles, then disregard/ignore this check….since the performance of our integral end bents in the field over the years has been good. Please be sure to have the designers/checkers document in their computations when they ignore the results of this check.

Integral End Bent Simple Pile Design (IEB-SPD or SPD) Procedure:

Follow bridge length and skew restrictions given in flowchart.

Potential end bent total scour and erosion, embankment failure and the like. min tip penetration embed must account for these possible failure conditions as well as any unusual ground conditions/soil properties like weak soils, pockets of strong soil between weak layers, rock ledges and the like.

Seismic design and detailing may require different pile solution and modified integral end bent design.

This procedure does not apply to intermediate pile cap bents.

Simple curved structures following similar length and skew limits are allowed. Complex thermal movements may require rigorous procedure.

LRFD format with LRFD load factors and a modified resistance factor is utilized to represent ASD with a factor of safety of four, however it is not reliability based as is LRFD. Either format produces same results mathematically.

Applicable: *For Simple Procedure*

Pile minimum penetration into ground – research would suggest longer minimum penetrations like 30 to 50 feet based on pile and soil types in order to affirm pile response and stability. While agreement was reached to leave the minimum at 15 feet, there is encouragement to go deeper. Most end bent pile penetrations will exceed 15 feet. For pile in rock, 15 feet would be sufficient with at least 5 feet into precored rock. This can control minimum tip penetration (elevation) for plan reporting

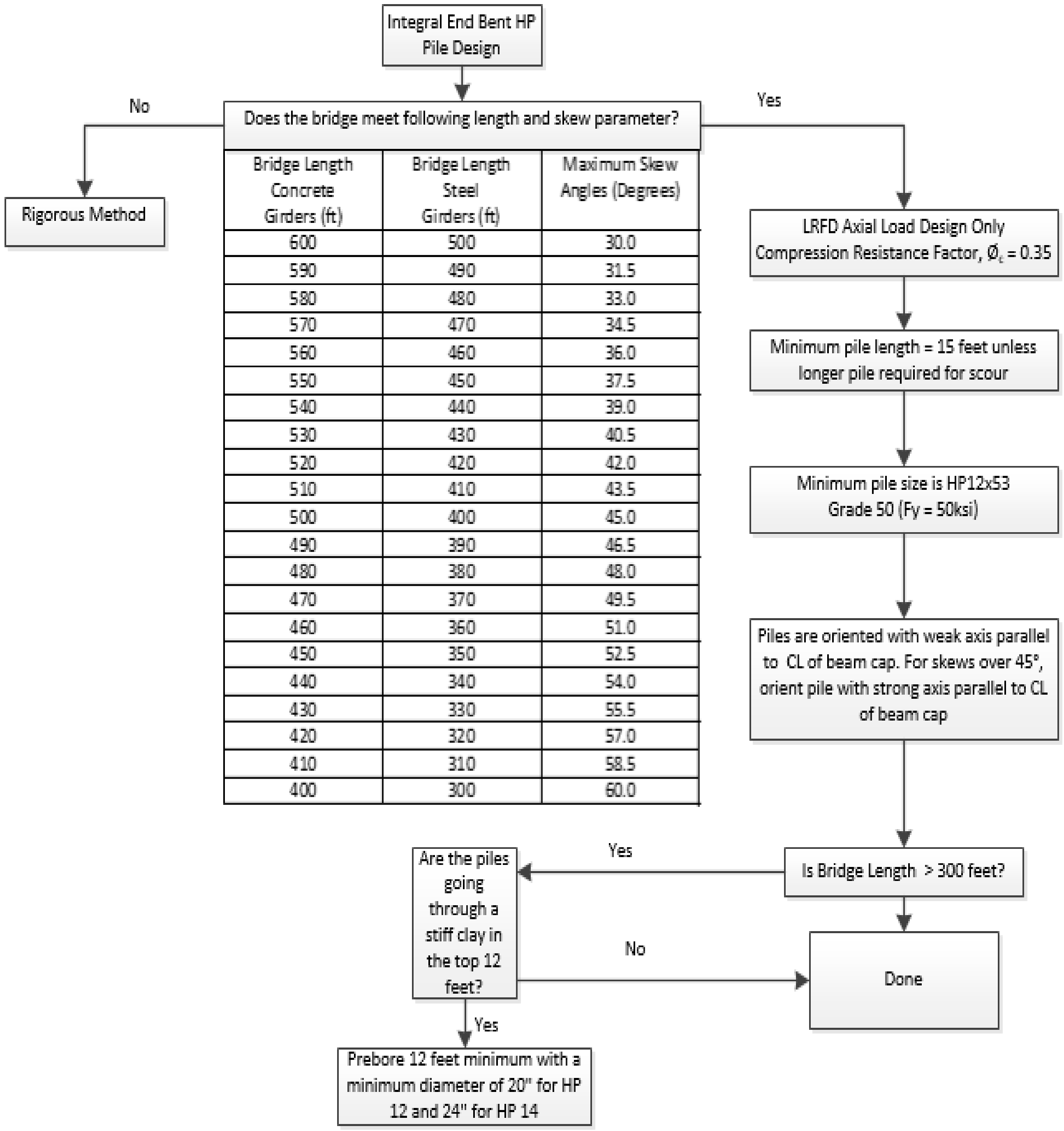
Pile size minimum based on controlling pile response at bottom of cap and will also extend corrosion and service life

Rotating piles for heavy bridge skews

Required standard preboring and size of prebore

Follow EPG 751.35 for pile spacing limits; four pile minimum is still standard

---



Bridge Length Concrete Girders (ft)	Bridge Length Steel Girders (ft)	Maximum Skew Angles (Degrees)
600	500	30.0
590	490	31.5
580	480	33.0
570	470	34.5
560	460	36.0
550	450	37.5
540	440	39.0
530	430	40.5
520	420	42.0
510	410	43.5
500	400	45.0
490	390	46.5
480	380	48.0
470	370	49.5
460	360	51.0
450	350	52.5
440	340	54.0
430	330	55.5
420	320	57.0
410	310	58.5
400	300	60.0

Using a resistance factor of 0.35 and a load factor of 1.4* is equivalent to limiting pile axial stresses to 0.25fy using a load factor of 1.0 (ASD). This will provide a factor of safety of 4 for axial loading without consideration for lateral loadings.

*Actual factor of safety considering DL/LL=2, $\gamma L=1.75$ and $\gamma D=1.25$ is $1.4167/\varphi$ (NCHRP Report 507, 2004)

Integral End Bent Rigorous Pile Design (IEB-RPD or RPD) Procedure:

The following procedure shall be used for designing end bent piles for integral bridges that exceed the bridge length and/or skew limits allowed for SPD but not more 600 ft. (concrete) and 500 ft. (steel). The number of piles determined from this procedure shall not be less than the number determined from SPD. This procedure is developed for typical integral end bents which include the following features:

- Turned back wings
- Pile penetration at least 15 feet below bottom of beam
- Pile embedment at least 18 inches into beam
- HP piles oriented with weak or strong axis parallel to beam
- Closed ended CIP piles
- MSE abutment walls
- Standard integral end bent reinforcement*

*This procedure does not cover reinforcement design for the beam cap, diaphragm and wings. Bridge lengths and skews not shown for SPD can consider additional design calculations; reliance on past successful performance up to bridge length limits and skews in excess of limits for SPD is valid. Reference the article "*Integral Abutments for Steel Bridges*", Vol. II, Chap. 5, Highway Structures Design Handbook, pp. 13-14.

Applicable: *For Rigorous Procedure*

Elastic and plastic design of HP and CIP piles

Service and strength limit approach

Correctly changed LRFD 3.4.1 load factor TU for steel substructure design from 0.5 to 1.0

Changed location of load action of wind load on live load, braking load and centrifugal load to roadway surface (was 6 feet above roadway surface) (17-058-DSI)

Modifies load factor TU for bridge longitudinal thermal movement for piles (based on presumed end bent rotation and calculated movement vs. measured movement from other states experimental research studies)

Reviewed temperature range extremes and service loading considerations

Utilizes concrete filled steel tube (CFST) design method in LRFD

Follow EPG 751.35 for pile spacing limits; four pile minimum is still standard

---

1. Find Bottom of Beam Elevation. This can typically be determined using the minimum beam depth (3 feet) below the lowest beam seat elevation. For sloped beam caps the average bottom of beam elevation is recommended.

2. Determine the preliminary HP pile size or CIP diameter (use SPD).
   Note: Larger pile sizes or diameters may behave less integral. A rule of thumb for pile fixity is the embedment length should be twice the pile diameter. Our standard 18" embedment does not meet this standard, but a fixed connection will be assumed for HP10, 12 & 14 piles and all CIP Piles.

3. Determine the equivalent cantilever column height, L, for longitudinal force distribution analysis. Assume top of pile fixity at the bottom of the beam cap. The following steps should be considered:

- Estimate the pile length from DRIVENPILES for friction piles (see Item 25).
- Estimate the distance to the thermal origin. Calculate the bridge longitudinal deflection for temperature fall at CL bearing. Temperature Rise will not control the design of symmetric pile shapes.

  $\Delta_{TU} = \gamma_{TU}\, \alpha L\, \Delta_{Tfall}$
  Where $\gamma_{TU} = 0.8$ (LRFD 3.4.1 Use of 1.0 not implemented)

  Note: First, the value for γ_{TU} considers that equal thermal movements will not be realized at the tops of piles due to differential flexing of the abutment beam/diaphragm. One study showed differences in lateral thermal movement for exterior and interior girder lines. Secondly, the fixed pile head condition is conservative since some rotation of the abutment is expected although not significant according to one study. However, a small rotation can relieve significant pile stress. Lastly, several studies report that measured lateral displacements at integral end bents are less than calculated displacements. For comparison with LRFD 3.4.1 both HP and CIP piles should be treated as steel members. The γ_{TU} factor of 0.5 for concrete substructures does not apply. Use 1.0.

  Note: For bridges of symmetry (spans, support and soil stiffnesses) the thermal origin is equidistant from either end and a longitudinal force distribution analysis will not be necessary. (Pile deflections due to thermal movement will likely control the design for bridge lengths greater than 200 ft.)

- Determine the thermal displacement/pile deflection vectors for HP piles (in-plane and out-of-plane bending) if piles are skewed. Not applicable for CIP piles because of symmetrical axes; bridge longitudinal thermal displacement (parallel to traffic) should be used.

- Determine the soil depth to the point of fixity (POF) for each axis of bending using LPILE. This analysis is iterative with the longitudinal force distribution analysis required to locate the thermal point of origin. The POF should be assumed where the slope of the pile deflection changes from negative to positive as shown in figure 1. For more information regarding LPILE input, see Item 14. For determining the effective column height used in the stiffness distribution the pile may be assumed to remain elastic. Do not use the procedure outlined in Item 18.

  Note: The lateral pile deflection should go back to zero above the bottom of pile. This ensures a fixed condition, but does not represent the location of the point of fixity as stated above.

P.O.F = 28’

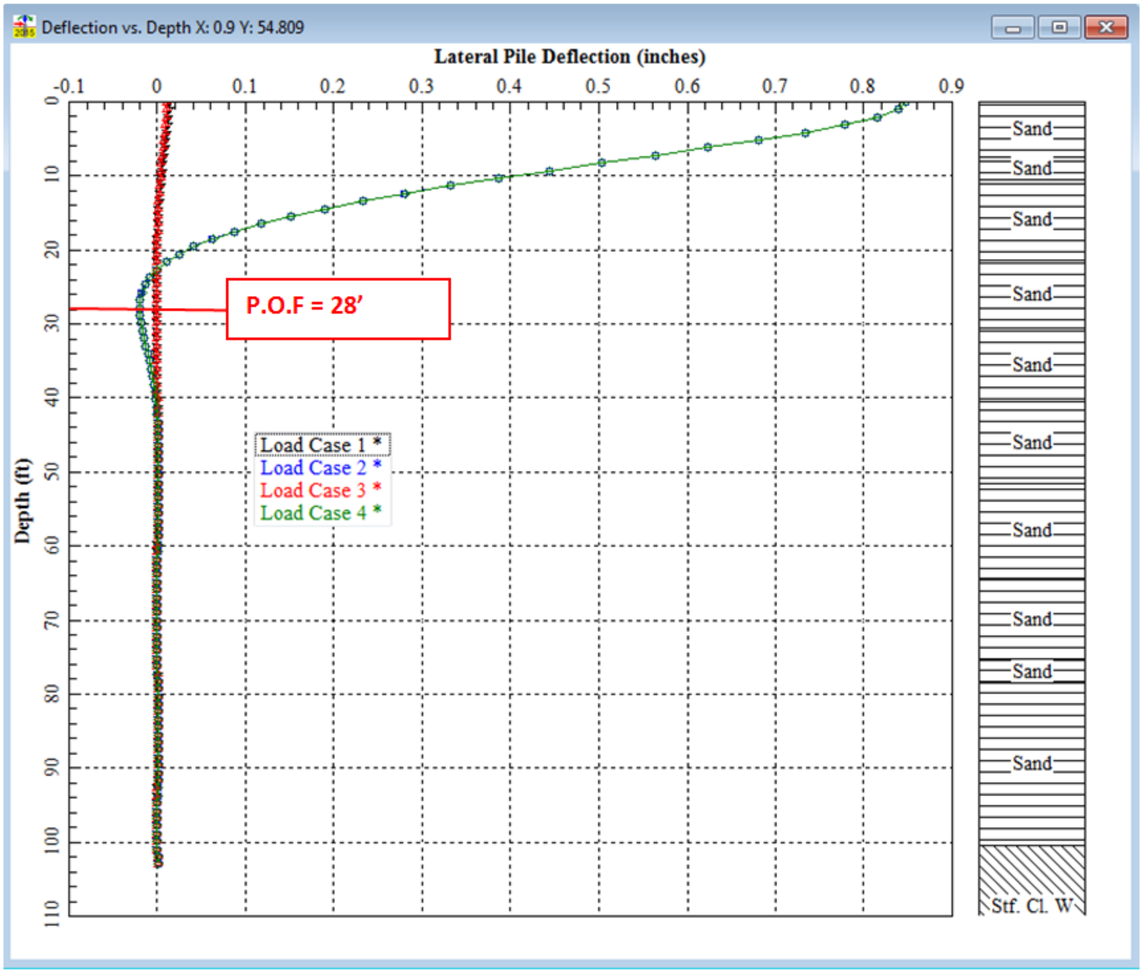


Figure 1 – Lateral pile deflection graph from LPILE showing point of fixity as derived from the load cases that include temperature deflection.

- The column heights, L_1 and L_2, can be taken as the distance between the POF and the bottom of the beam for out-of-plane and in-plane deflections respectively (longitudinal for CIP Piles). POF will likely be different between the in-plane and out-of-plane bending analyses.

4. Run a longitudinal force distribution analysis to determine the percentage of force to be distributed to the end bent and to confirm the location of the thermal origin. The in-house longitudinal force distribution analysis program may be used for bents that are modeled as fixed-free columns.

   - Determine the resultant moment of inertia of the pile group using the procedure outlined for column bents in EPG 751.2.4.5. The following is a list of design differences for HP-Pile abutments.
     - $I_2 = I_{y\text{-}y}$, $I_1 = I_{x\text{-}x}$…(Standard Pile Orientation)
     - $J = 1/3[2b_f t_f^3 + (d - 2t_f)t_w^3]$…approximate

Table 1 – Torsional Constant for Common HP Piles

Pile Type	HP10x42	HP12x53	HP14x73
Torsional Constant, J (in^4)	0.81	1.12	2.01

    - $G = E_s/(2(1 + \nu)) = 11{,}197$ ksi
    - $S_1 = 12EI_2/L_1^3$

- A composite modulus of elasticity should be entered for CIP Piles (see Table 1). Since the modulus of elasticity is used for bending stiffness the effective modulus of elasticity should be weighted based on the moment of inertias of the unfilled pipe and concrete core (do not use a weighted modulus based on the areas). Use the nominal pipe dimensions. Do not include the section and corrosion losses discussed in Item 15.

  Note: This value should match the value entered into LPILE.

- When determining the resultant moment of inertia of a CIP pile bent the Shear Modulus, G, should be determined using a weighted average of the torsional rigidities, J*G, of the steel pipe and the concrete core.

  Note: For symmetric pile arrangements the magnitude of the torsional stiffness, St, of each pile does not affect the resultant bent stiffness.

5. Include vertical dead loads, DC and DW. Include FWS for superstructure and approach slab. DC includes the following:

    - Self-weight of beam cap, diaphragm, corner braces and wings
    - Dead loads from superstructure analysis: slab, barrier, girders, etc.
    - 50% of the approach slab
    - Barrier load on end bent
    - Avoid duplicative/redundant loading

6. Include vertical live loads from the superstructure analysis. Consider 12-foot lanes, fully loaded and apply the multiple presence factor. Do not use dynamic load allowance (Impact) for pile design. Live loads on the approach slab may be ignored.

Note: Steps 7 thru 10 are shown for completion, but may be insignificant for large bridge lengths where temperature deflection is considerably greater.

7. Superstructure Wind Loads (WS): Superstructure wind shall be calculated in the longitudinal and transverse direction as shown in EPG 751.2.2.3. Longitudinal wind is distributed to the bent based on the distribution analysis discussed in Item 4 and the transverse wind is distributed using the tributary span length (1/2 end span).

    - To account the for the difference between load application point and top of pile modeled in LPILE, load magnification may be considered based on the ratio of the distances from the point of fixity. The point of fixity calculated in Step 3 may be used for in-plane and out-of-plane bending.
    - Load application point for longitudinal forces shall be applied at the mid-depth of the superstructure height (exclude the barrier curb height).
    - Load application point for transverse forces shall be applied at the center of the superstructure height (including barrier curb).

8. Wind on Live Load (WL): Wind on Live Load shall be calculated in the longitudinal and transverse directions as shown in EPG 751.2.2.3. Longitudinal wind is distributed to the bent based on the distribution analysis discussed in Item 4 and the transverse wind is distributed using the tributary span length (1/2 end span).

    - Similar to WS, load magnification should be considered.
    - Load application point for longitudinal forces shall be applied at the top of slab.
    - Load application point for transverse forces shall be applied at the top of slab.

9. Longitudinal Braking Force (BR): Braking force shall be calculated in the longitudinal direction as shown in EPG 751.2.2.6. The total braking force shall be calculated assuming the bridge is fully loaded with 12-foot lanes and the multiple presence factor shall be applied. The number of lanes may be reduced if the bridge is not expected to carry one-directional traffic in its lifetime and as approved by the SPM. The controlling force should be distributed to the end bent using the percentage determined in the longitudinal force distribution analysis.

    - Similar to WS, load magnification should be considered.
    - Load application point for longitudinal forces shall be applied at the top of slab.

10. Centrifugal Force (CE): Centrifugal force shall be calculated in the transverse/radial direction for horizontally curved bridges as shown in EPG 751.2.2.6. The total centrifugal force shall be calculated assuming the bent is fully loaded with 12-foot lanes and the multiple presence factor shall be applied. When multiple traffic lanes are present the Radius of Curvature may be taken as the average radius of the lanes or at centerline of structure. The centrifugal force factor, C, should always be applied to the total Design Truck weight (72K) unless a larger load is specified on the Design Layout.

    - Similar to WL, load magnification should be considered.
    - Load application point for radial forces shall be applied at the top of slab.

11. Uniform Temperature (TU): The temperature <u>deflection</u> should be calculated as discussed in Item 3 or EPG 751.2.4.7.

    - Use a 0.8 factor to adjust the theoretical temperature deflection to the expected deflection at top of pile.
    - Abutment rotation is conservatively ignored primarily because a refined analysis is required.
    - Minimum design temperatures have historically followed both Procedure A and B in LRFD 3.12.2.1 and 3.12.2.2 for thermal movement calculations using -30°F and -10°F for steel and concrete girders respectively. However, for end bent pile design either procedure which gives a higher minimum design temperature may be used, i.e. -10°F and 0°F for steel and concrete girders.

12. Factor loads: Use LRFD Strength I and Strength V load combinations.

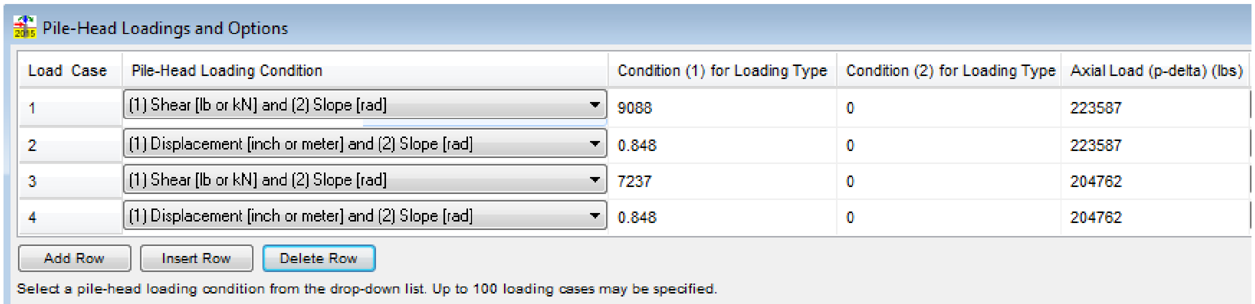
13. Resolve load vectors. Horizontal loads should be oriented to be orthogonal to the bent longitudinal axis. For skewed bents the following equations may be used:

$$P_{Normal} = P_{Long}\mathrm{Cos}(skew) + P_{Tran}\mathrm{Sin}(skew)$$
$$P_{Parallel} = P_{Long}\mathrm{Sin}(skew) + P_{Tran}\mathrm{Cos}(skew)$$

where “Normal” and “Parallel” refer to the direction of the applied load with respect to the longitudinal axis of the beam cap. All horizontal and vertical loads should be equally distributed to all piles in a beam cap.

14. **LPILE Analysis (Elastic Design):** LPILE will analyze a single pile embedded in varying soil strata with forces applied at the top of pile model. The following guidelines should be considered:

- Static loading of an Elastic Section
- Enter modification factors for p-y curves per LRFD 10.7.2.4 to account for group effects. Do not use for pre-bore into rock.
- Enter the pile section length with the top of pile modeled at bottom of beam and bottom of pile modeled at actual bottom of pile location. Note: The section length may be reduced for pile lengths greater than 50’ or a single stiff soil layer may be used below 50’ as soils at this depth are unlikely to affect the analysis. Also see Step 3.
- Separate files are required for strong-axis and weak axis bending.
- Ground slope is assumed to be flat.
- Soil layers should be entered using properties from the best data available. EPG Table 751.9.2.4.1 may be referenced if more reliable values are not provided in the Borings Report. The water table shall be considered for the effective unit weights of the soil entered. The water table location may be used as provided by the Borings report at time of drilling. Otherwise the water table may be assumed at the ordinary high water elevation. Note: “Stiff Clay with Free Water” should only be used where free water flow is found and is not applicable for any stiff clay under the water table.
- Pre-bore is specified typically for drivability concerns but may also be used to reduce stresses on the piles by oversizing the pre-bore holes. The global soil strata should be used for standard pre-bore holes. When oversized holes are specified for pre-bore the properties of a loose sand filler should be used.
- For a standard integral end bent the Pile-Head Loading Condition is assumed to be fixed so a shear force or deflection with no slope is entered. Piles should be designed for the Strength I and Strength V limit states. Four separate pile-head load conditions are required. Each limit state requires the temperature deflection to be separated from the other load cases that use shear forces.



Load Case	Pile-Head Loading Condition	Condition (1) for Loading Type	Condition (2) for Loading Type	Axial Load (p-delta) (lbs)
1	(1) Shear [lb or kN] and (2) Slope [rad]	9088	0	223587
2	(1) Displacement [inch or meter] and (2) Slope [rad]	0.848	0	223587
3	(1) Shear [lb or kN] and (2) Slope [rad]	7237	0	204762
4	(1) Displacement [inch or meter] and (2) Slope [rad]	0.848	0	204762

Select a pile-head loading condition from the drop-down list. Up to 100 loading cases may be specified.

- The controlling moment shall be recorded for each pile-head load condition. The design moments are then determined for each limit state by summing the results for the deflection and shear force cases. The maximum moment can be found at the end of the Output text file or a moment vs. depth profile can be used if a more accurate location is deemed necessary.

- A composite modulus of elasticity should be entered for CIP Piles as discussed in Item 4 (see Table 2 or 3).

15. Pile Axial Resistance (Elastic Design): Piles should be checked for the structural axial resistance at the bottom of the pile. Piles shall be assumed to be fully braced for any soil type as long as appropriate scour protection is used.

    - The PNDC check is unlikely to control so the most conservative resistance factor may be assumed for all cases (i.e…assume pile point reinforcement is required).
    - For CIP Piles the provisions for Concrete-Filled Tubes may be used (PNDC = 0.85f'cAc + FyAst). This equation can be derived from LRFD Eq. 6.9.5.1-1 assuming a fully braced pile with no reinforcing bars. The metal shell area should be determined assuming both 12.5% section loss due to fabrication tolerances as well as a 1/16" loss due to corrosion. The concrete core diameter is calculated using the nominal pile diameter and nominal shell thickness. The minimum shell thickness shall be determined from the drivability analysis outlined in Item 25 and EPG 751.36.

16. Combined Axial Compression and Flexure (Elastic Design): Interaction equations as outlined in LRFD 6.9.2.2 shall be checked.

    - Steel H-Piles: The nominal flexural resistance about the weak axis is equal to the plastic section capacity (Mn = FyZ). The nominal flexural resistance about the strong axis is equal to the elastic section capacity (Mn = FyS). These equations are derived from LRFD Eq. 6.12.2.2.1-1 and LRFD Eq. 6.10.8.2.2-1 or 6.10.8.2.3-1 for fully braced piles.
    - CIP Piles: The nominal flexural resistance about any axis is dependent on the pile diameter to shell thickness ratio (D/t) per AASHTO LRFD 6.12.2.3.2. The equations for nominal flexural resistance, Mps or Myc, may be calculated using the plastic section modulus or elastic section modulus of the shell respectively. Local buckling need not be considered since the concrete fill prevents the steel shell from buckling. Separate analyses about the x and y axes are not warranted for CIP Piles.

Table 2 – Design Values for Common CIP Pile (Grade 2, Fy = 35ksi, f'c = 4ksi)

Pile Dia.	**Shell Thick.**	^{1}**A$_s$** In^2	**A$_c$** In^2	**E$_{eff}$** ksi	^{2}**PNDC** k	**r$_s$** in	^{3}**F$_e$** ksi	**E$_e$** ksi	**Z** In^3	**S** In^3	**D/t**	**M$_{ps}$** k-ft	**M$_{yc}$** k-ft
14"	¼"	6.73	143.1	5869	721	4.83	107.4	60027	29.2	22.7	88.1	85.3	66.2
	3/8"	11.33	137.9	7348	865	4.78	76.4	46745	48.7	37.6	51.7	142.2	109.5
	½"	15.84	132.7	8763	1006	4.73	63.5	41213	67.5	51.6	36.5	196.8	150.4
	5/8"	20.27	127.7	10116	1144	4.68	56.4	38181	85.5	64.8	28.2	249.3	189.0
16"	¼"	7.71	188.7	5595	911	5.54	118.3	64690	38.4	29.9	100.9	112.0	87.1
	3/8"	13.00	182.7	6901	1076	5.49	82.8	49488	64.2	49.6	59.2	187.2	144.6
	½"	18.20	176.7	8158	1238	5.44	68.0	43155	89.1	68.3	41.8	253.3	199.3
	5/8"	23.32	170.9	9367	1397	5.39	59.9	39683	113.1	86.2	32.3	329.9	251.3
20"	¼"	9.67	298.7	5210	1354	6.95	140.0	74018	60.5	47.2	126.5	176.5	137.5
	3/8"	16.33	291.0	6267	1561	6.90	95.6	54973	101.5	78.6	74.3	296.0	229.4
	½"	22.91	283.5	7294	1766	6.85	77.1	47039	141.3	108.9	52.5	412.2	317.7
	5/8"	29.40	276.1	8290	1968	6.80	66.9	42689	180.1	138.0	40.5	525.2	402.5
24"	3/8"	19.67	424.6	5840	2132	8.31	108.4	60460	147.3	114.4	89.3	429.5	333.6
	½"	27.62	415.5	6707	2379	8.27	86.1	50924	205.6	158.9	63.2	599.6	463.5
	5/8"	35.49	406.5	7553	2624	8.22	73.9	45696	262.5	202.0	48.8	765.7	589.2
	¾"	43.27	397.6	8377	2866	8.17	66.2	42395	318.2	243.7	39.7	928.0	710.8

[1] Area of steel shell, As, assumes a 12.5% deduction and 1/16" deduction in wall thickness

[2] Structural Nominal Axial Design Capacity for fully braced piles only

[3] Applicable for the non-reinforced portion of the pile only

Note: The difference between Eeff and Ee is that the former is used for sections transformed into concrete and the latter is for sections transformed into steel.

Table 3 – Design Values for Common CIP Pile (Grade 3, Fy = 45ksi, f'c = 4ksi)

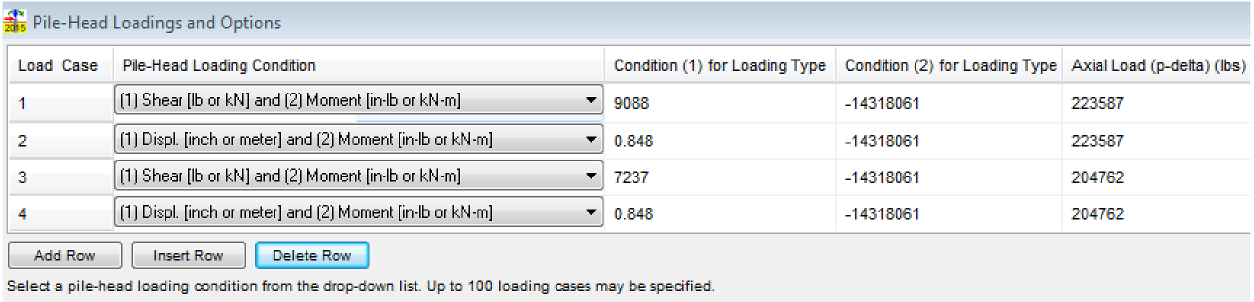
Pile Dia.	**Shell Thick.**	^{1}**A$_s$** In^2	**A$_c$** In^2	**E$_{eff}$** ksi	^{2}**PNDC** k	**r$_s$** in	^{3}**F$_e$** ksi	**E$_e$** ksi	**Z** In^3	**S** In^3	**D/t**	**M$_{ps}$** k-ft	**M$_{yc}$** k-ft
14"	¼"	6.73	143.1	5869	789	4.83	117.4	60027	29.2	22.7	88.1	109.6	85.1
	3/8"	11.33	137.9	7348	979	4.78	86.4	46745	48.7	37.6	51.7	182.8	140.8
	½"	15.84	132.7	8763	1164	4.73	73.5	41213	67.5	51.6	36.5	253.0	193.4
	5/8"	20.27	127.7	10117	1346	4.68	66.4	38181	85.5	64.8	28.2	320.5	243.0
16"	¼"	7.71	188.7	5595	988.3	5.54	128.3	64690	38.4	29.9	100.9	144.0	112.0
	3/8"	13.00	182.7	6901	1206	5.49	92.8	49488	64.2	49.6	59.2	240.7	185.9
	½"	18.20	176.7	8158	1420	5.44	78.0	43155	89.1	68.3	41.8	334.1	256.2
	5/8"	23.32	170.9	9367	1630	5.39	69.9	39683	113.1	86.2	32.3	424.2	323.1
20"	¼"	9.67	298.7	5210	1451	6.95	150.0	74018	60.5	47.2	126.5	226.9	176.8
	3/8"	16.33	291.0	6267	1725	6.90	105.6	54973	101.5	78.6	74.3	380.5	294.9
	½"	22.91	283.5	7294	1995	6.85	87.1	47039	141.3	108.9	52.5	530.0	408.4
	5/8"	29.40	276.1	8290	2262	6.80	76.9	42689	180.1	138.0	40.5	675.3	517.5
24"	3/8"	19.67	424.6	5840	2329	8.31	118.4	60460	147.3	114.4	89.3	552.2	428.9
	½"	27.62	415.5	6707	2656	8.27	96.1	50924	205.6	158.9	63.2	770.9	595.9
	5/8"	35.49	406.5	7553	2979	8.22	83.9	45696	262.5	202.0	48.8	984.5	757.6
	¾"	43.27	397.6	8377	3299	8.17	76.2	42395	318.2	243.7	39.7	1193.2	913.9

17. If pile design fails the elastic check outlined in steps 14 thru 16, than assume the pile goes plastic at the bottom of beam cap. The pile will then be checked to prevent in-ground hinging resulting in an unstable pile. Technically, the elastic analysis isn't necessary, but is provided in case an elastic design is deemed necessary.

18. **LPILE Analysis (Plastic Design):** LPILE will analyze a single pile embedded in varying soil strata with forces applied at the top of pile model. The following guidelines should be considered:

    - Static loading of an Elastic Section
    - Enter modification factors for p-y curves per LRFD 10.7.2.4 to account for group effects. Do not use for pre-bore into rock.
    - Enter the pile section length with the top of pile modeled at bottom of beam and bottom of pile modeled at actual bottom of pile location.
    - Separate files are required for strong-axis and weak axis bending.
    - Ground slope is assumed to be flat.
    - Soil layers should be entered using properties from the best data available. EPG Table 751.9.2.4.1 may be referenced if more reliable values are not provided in the Borings Report. The water table shall be considered for the effective unit weights of the soil entered. The water table location may be used as provided by the Borings report at time of drilling. Otherwise the water table may be assumed at the ordinary high water elevation. Note: "Stiff Clay with Free Water" should only be used where free water flow is found and not applicable for any stiff clay under the water table.
    - Pre-bore is specified typically for drivability concerns but may also be used to reduce stresses on the piles by oversizing the pre-bore holes. The global soil strata should be used for standard pre-bore holes. When oversized holes are specified for pre-bore the properties of the loose sand filler should be used.
    - When the elastic check fails, the top of pile is assumed to go plastic in the weak axis for HP piles and the resultant axis for CIP Piles. The Pile-Head Loading Condition for the strong axis of HP Piles is the same as the condition used for the Elastic check. The "deflection and moment" Pile-Head Loading Condition is used to model a fully plasticized section at top of pile where the Moment value entered should be equal to the Plastic Section capacity of the weak axis of an HP-Pile or any axis for a CIP Pile. The lateral force effects from all forces other than temperature may be ignored. Piles should be designed for the Strength I limit state. Strength V will not control since the axial load is lower.

      Note: The strong axis for HP Piles is not allowed to go plastic. If the LPILE strong-axis analysis results in a moment at any section of the pile exceeding the plastic moment capacity about the strong-axis a redesign is required.



Load Case	Pile-Head Loading Condition	Condition (1) for Loading Type	Condition (2) for Loading Type	Axial Load (p-delta) (lbs)
1	(1) Shear [lb or kN] and (2) Moment [in-lb or kN-m]	9088	-14318061	223587
2	(1) Displ. [inch or meter] and (2) Moment [in-lb or kN-m]	0.848	-14318061	223587
3	(1) Shear [lb or kN] and (2) Moment [in-lb or kN-m]	7237	-14318061	204762
4	(1) Displ. [inch or meter] and (2) Moment [in-lb or kN-m]	0.848	-14318061	204762

Select a pile-head loading condition from the drop-down list. Up to 100 loading cases may be specified.

<u>Note:</u> The shear or deflection value entered above must have the opposite sign as the value entered for moment to model an <u>initially</u> fixed head condition.

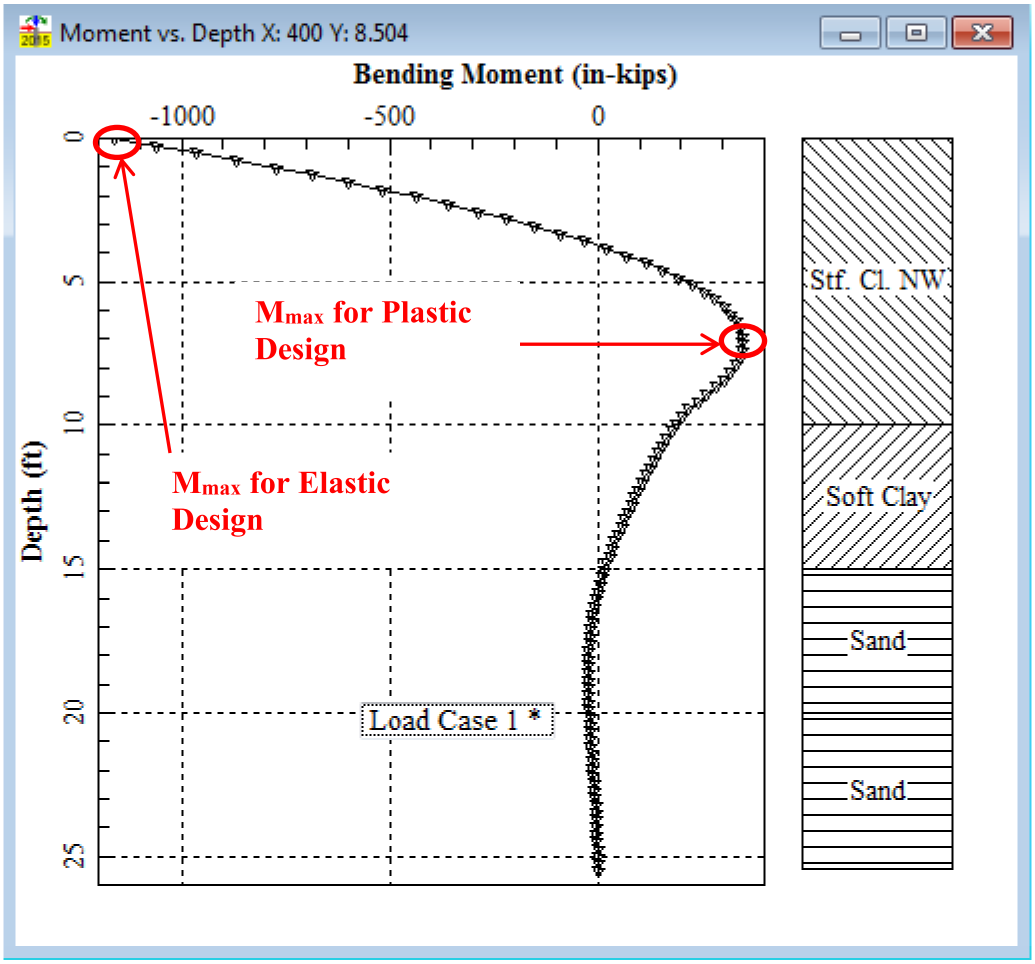


Figure 1 – Typical bending moment graph assuming elastic behavior over full depth of pile

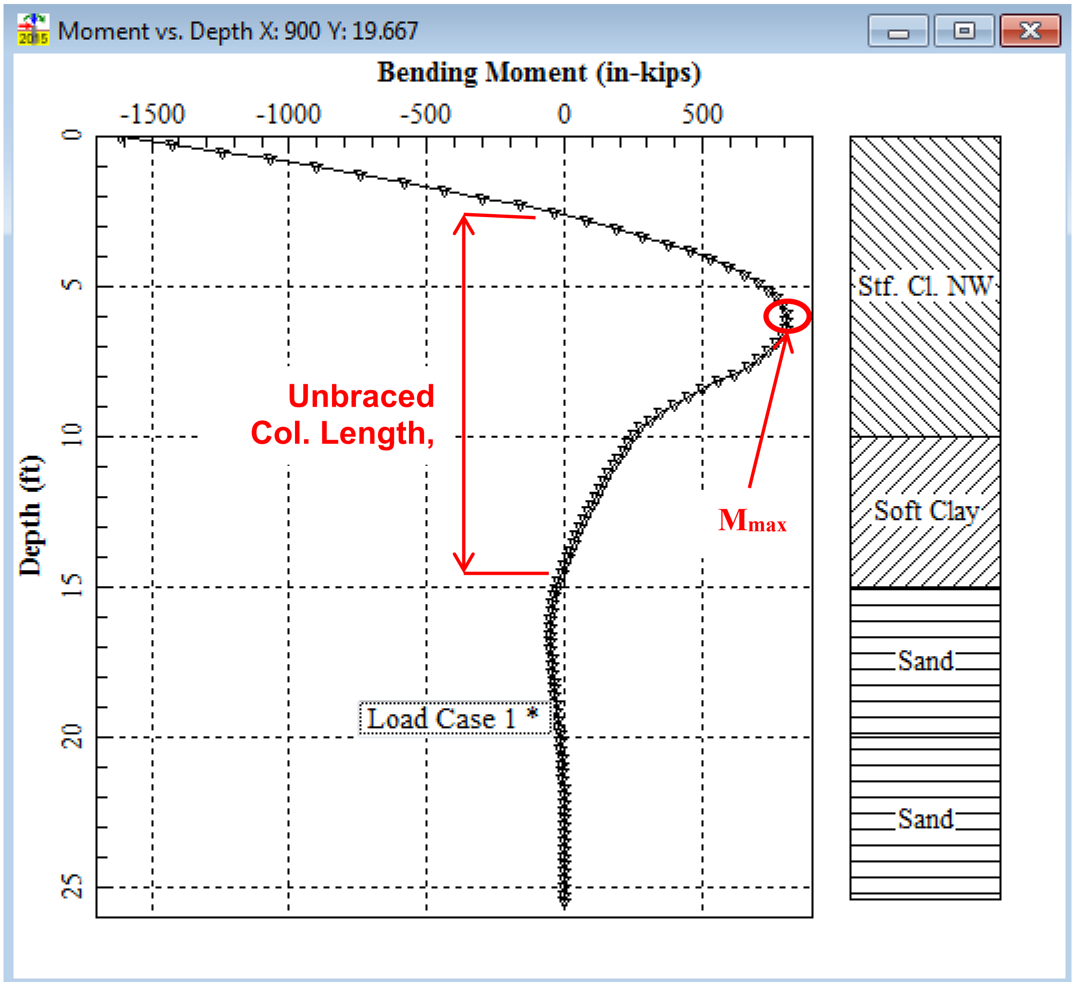


Figure 2 – Typical bending moment graph assuming plastic behavior at top of pile.

- The pile length between points of zero moment should be analyzed as an unbraced column. Use the Moment vs. Depth graph for the plastic analysis to determine the column height.
- The controlling moments shall be recorded for each axis of analysis. Use the maximum moment between points of zero moment for each analysis (plastic and elastic).

19. Pile Axial Resistance (Plastic Design): Check the structural axial resistance over the unbraced length of pile (see LRFD 6.9.5.4.2 and 6.9.4)

- Use the resistance factor for undamaged pile in accordance with LRFD 6.5.4 Since this axial check does not occur at the bottom of the pile the larger resistance factors, φ_C, may be used as specified in LRFD 6.5.4 for undamaged piles.
- Calculate Q which is the slender element reduction factor used for determining P_o equal to 1.0 for HP10x42, HP12x53 and HP14x73 piles. Note: Calculation of Q for an HP14x73 results in a value of 0.97.
- The elastic critical buckling resistance shall be taken equal to the flexural buckling resistance specified in AASHTO LRFD 6.9.4.1.2. Ignore torsional buckling because it will not control over flexural buckling. The effective length factor, K, can conservatively be taken as 1.0 for a pinned-pinned column.

- CIP Piles: LRFD article 6.9.5.1 should be used. The steel pipe area should be determined assuming both 12.5% section loss due to fabrication tolerances as well as a 1/16" loss due to corrosion but shall not be less than 4% of the total area of pile. The concrete core diameter is calculated using the nominal pile diameter and nominal pipe thickness. The minimum pipe thickness shall be determined from the drivability analysis (see Item 25).

20. Check interaction equations for combined axial compression and flexure (plastic design) in accordance with LRFD 6.9.2.2.

    - HP Piles: Calculate the nominal flexural resistance about the weak axis in accordance with LRFD 6.12.2.2.1. The nominal flexural resistance about the strong axis shall be taken as the lesser of the local buckling resistance in accordance with LRFD 6.10.8.2.2 and the lateral torsional buckling resistance in accordance with LRFD 6.10.8.2.3.
    - CIP Piles: The nominal flexural resistance about any axis is dependent on the pile diameter to thickness ratio (D/t) in accordance with LRFD 6.12.2.3.2. The unbraced length is only used in determining the Pile Axial Resistance and does not affect the flexural resistance. The equations for the nominal flexural resistance using Mps or Myc may be calculated using the plastic section modulus or elastic section modulus of the unfilled pipe respectively. Local buckling need not be considered since the concrete fill prevents the steel shell from buckling. Separate analyses about the x and y axes are not warranted for CIP Piles. Note: LRFD 6.9.6.3.2 and C6.12.2.3.3 provide complicated equations for composite concrete filled steel tubes (CFST) that are not expected to result in significant cost savings. However, they could account for an increase in the elastic design capacity and a minimal effect on the plastic design check. If the plastic design check is used the capacity at the top of pile should include the reinforcing bars while the unbraced column check should exclude the reinforcing bars.

Table 4 – Design Values for Common HP Piles (Grade 50)

	HP 10x42	HP 12x53	HP 14x73
Nominal Flexural Resistance about the Weak axis, M_{ny} (k-ft)	82.53	114.14	189.27
Web Load Shedding Factor, R_b	1	1	1
Hybrid Factor, R_h	1	1	1
Local Buckling Resistance, F_{nc} (ksi)	43.88	39.90	38.61
Effective Radius of Gyration for Lateral Torsional Buckling, r_t (in)	2.70	3.22	3.92
Limiting Unbraced Length for Uniform Bending, L_p (in)	65.07	77.65	94.33
Limiting Unbraced Length considering Compression-Flange Residual Stress Effects, L_r (in)	244.35	291.57	354.19
*Moment gradient modifier, C_b	1	1	1

*Values are applicable for the unbraced column check and may vary for other applications.

21. CIP Piles: Determine pile lengths using DRIVENPILES.

22. Calculate Rndr in accordance with EPG 751.36.5.10 and LRFD 10.7.7.

23. Perform drivability analysis in accordance with EPG 751.36.5.11 and LRFD 10.7.8 for steel piles in order to limit driving stresses for either HP piles or unfilled pipe piles. Note 1: This analysis is also utilized to check that practical refusal does not occur 1.) before a pile reaches hard/strong rock, 2.) before the required length determined by DRIVENPILES, or 3.) before a required minimum tip penetration (elevation). Note 2: For oversized prebored holes, frictional side resistance should be assumed as non-contributing.

Comments, questions or suggestions should be directed to the Development Section.