EXCALIBUR™

TECHNICAL DOCUMENT

MacLean™ POWER SYSTEMS

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I. OVERVIEW

The MPS Excalibur Displacement Pile (EDP) system offers the advantages of Displacement Piles with greater load support than other commonly available systems. EDP's can be installed in limited access areas where specialized equipment for other deep foundation systems may be required and become less economical. Overhead access, limited site availability, low disturbance installations, and less grout are all situations where the EDP can be a valuable tool for the engineer and contractor.

II. KEY COMPONENTS

Steel Shaft

Commonly stocked pile shafts are listed in below in Table 1. Pile shaft sizes may be selected based on many factors including axial and lateral loading, site access, overhead access, and other site specific limitations. Each pile shaft is made of high-grade steel that may be coupled or threaded together on site. The selection of different pile shaft diameters and lengths allows the engineer and contractor to provide a site-specific design that can provide the most economical solution for each challenge.

Couplings

The central steel shaft sections are coupled together using either traditional bolted pipe sleeves or threaded couplings that do not require hardware. Both coupling systems have been safely and effectively utilized in both the non-grouted and grouted displacement pile systems. Threaded couplings require an additional reusable rubber grout plug as shown in Figure 1 to be placed at each coupling joint prior to installation. A single plug can be used to install several piles and is specific to the dimensions of the steel shaft. It is used to form a seal between the pile and installation tooling.

Figure 1: Typical grout plug shown on the ground and in a threaded coupling

Pile Driver Plate(s)

Commonly stocked plates with properties are shown below in Table 1. The driver plate may be used to assist with installation of the pile to the required depth, create an annulus for the pile grout column, and be used as an end bearing element, if required. Driver plate diameters and thicknesses depend on project specific requirements and loads.

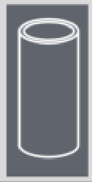
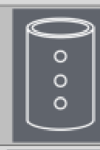
Pile Shaft 	Diameter	4.5" - 12.75"
	Length	5' - 40'
	Wall Thickness	0.290" - 0.545"
	Material Strength	80ksi
Coupling Type	Bolted	
	Threaded	
Driver Plate 	Diameter	8" - 30"
	Pitch	6"
	Thickness	1/2" - 3/4"
	Material Strength	50ksi

TABLE 1: Common shafts and drive plates

Grout

A typical grout column is shown in Figure 2. A neat grout mix with Portland Cement and potable water may be used for the grout column. Once the drive plate(s) is in full contact with the ground, pressure grouting can begin. The drive plate and grout displaces the soil around the diameter of the shaft at approximately the same diameter as the driver plate(s). This results in a continuous grout column around the annulus of the pile shaft. Grout flow and delivery pressure should be monitored to ensure that proper grout distribution is being achieved.

Terminations

The EDP system offers flexibility for terminations. The termination transfers compression, tension, and shear loadings from the structure to the deep foundation pile. Common pile caps can be placed in reinforced concrete pads, structurally connected to steel framing by bolting, welding or threading, and can be easily installed by the same crew that installed the pile. Custom pile caps can be designed and fabricated upon request.

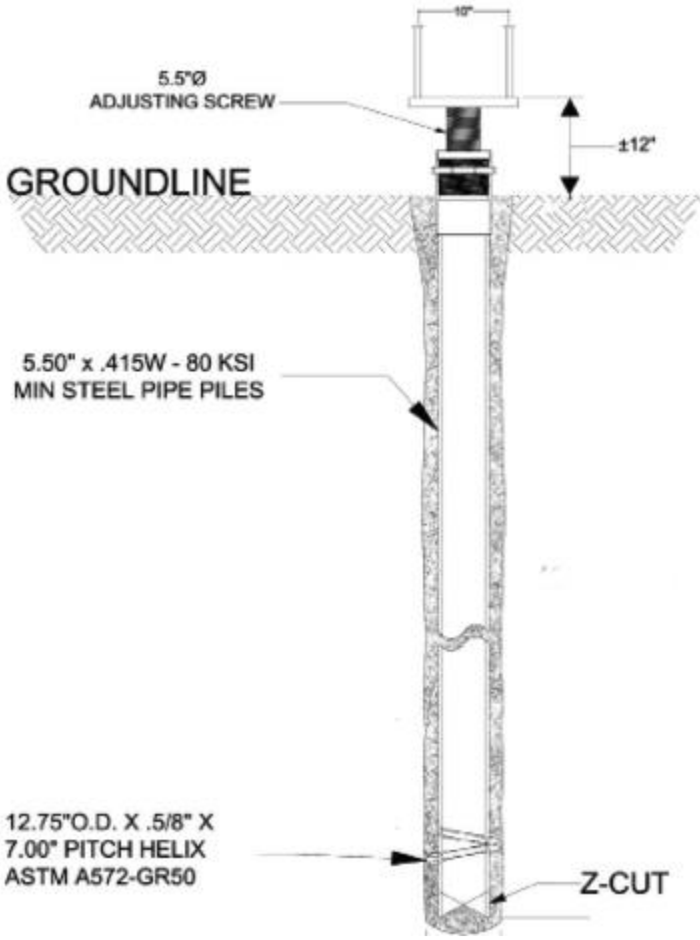


FIGURE 2: Typical pressure grouted displacement pile

III. COMMON APPLICATIONS

The EDP has been used successfully in traditional Displacement Pile situations such as limited site access for large equipment, low overhead room and low installation disturbance applications. It can be used in building, bridge, highway and utility applications, among others.

The EDP has shown real value in these traditional situations where axial loads exceed the capacities traditional piles. The larger cross section and higher grade steel of the EDP also offers much higher lateral and moment capacities than traditional Displacement Piles.

IV. DESIGN METHODOLOGY

The EDP shall be designed to meet the specified loads as shown on the drawings. The structural design processes listed below will assist the engineer in limiting the stresses in the EDP to acceptable values for commonly used codes and design guides. The geotechnical design must consider not only load transfer to suitable soil but also deflection criteria for the specific project.

Structural Design

The allowable load on the pile shall consider the mechanical strength of the pile components. There are several design approaches, this design guide will consider the International Building Code (IBC) 2012.

For compression loads of an un-grouted pile:

(IBC 2012 – Table 1810.3.2.6)

$$P_{c-allowable} = 0.6 * f_y * A_s$$

Where:

$P_{c\text{-allowable}}$ = Allowable Compressive Load (kips)

f_y = Minimum Yield Stress of Pile Shaft (ksi)

A_s = Area of Steel Shaft (remove corrosion if required) (in^2)

Minimum material stresses of EDP piles vary and should be confirmed with MPS. If the pile is being used in end bearing on the driver plates the mechanical capacity of the driver plate(s) should also be checked against the loads.

For compression loads on a grouted pile:

(IBC 2012 – Table 1810.3.2.6)

$$P_{allcomp} = 0.4 * f_y * A_s + 0.33 * f_c' * A_{ginside} + 0.3 * f_c' * A_{goutside} * r_{outside}$$

Where:

$P_{allcomp}$ = allowable compressive load of composite pile (kips)

f_y = minimum yield stress of pile shaft (ksi)

A_s = area of steel (remove corrosion if required) (in^2)

f'_c = specified grout compressive stress (ksi)

$A_{ginside}$ = area of grout inside steel shaft (in^2)

$A_{goutside}$ = area of grout outside of steel shaft (in^2)

$r_{outside}$ = grout outer area reduction factor = 0.7

Minimum grout stresses are typically set on a project basis and may be set in a local building code. Confirmation of utilizing grout outside the EDP steel shaft should be verified against specific project requirements and local building codes.

For tension loads on a pile:

(IBC 2012 – Table 1810.3.2.6)

$$P_{t-allowable} = 0.6 * f_y * A_s$$

Where:

$P_{t\text{-allowable}}$ = allowable tension load (kips)

f_y = minimum yield stress of pile shaft (ksi)

A_s = area of steel (remove corrosion if required) (in^2)

Alternatively, the design may also use the design methodology given in the FHWA publication No. FHWA NHI-05-39, Displacement Pile Design and Construction dated December 2005.

For compression loads of an un-grouted pile:

(FHWA Equation 5-1)

$$P_{c-allowable} = 0.47 * f_y * A_s$$

Where:

$P_{c\text{-allowable}}$ = allowable compressive load (kips)

f_y = minimum yield stress of pile shaft (ksi)

A_s = area of steel (remove corrosion if required) (in^2)

For compression loads on a grouted pile:

(FHWA Equation 5-1)

$$P_{allcomp} = 0.47 * f_{yshaft} * A_s + 0.4 * f_c' * (A_{ginside} + A_{goutside} * r_{outside})$$

Where:

$P_{allcomp}$ = allowable compressive load of composite pile (kips)

f_y = minimum yield stress of pile shaft (ksi)

A_s = area of steel (remove corrosion if required) (in^2)

f'_c = specified grout compressive stress (ksi)

$A_{ginside}$ = area of grout inside steel shaft (in^2)

$A_{goutside}$ = area of grout outside of steel shaft (in^2)

$r_{outside}$ = grout outer area reduction factor = 0.7

Minimum grout stresses are typically set on a project basis and may be set in a local building code. Confirmation of utilizing grout outside the EDP steel shaft should be verified against specific project requirements and local building codes.

For tension loads on a pile:

(FHWA Equation 5-2)

$$P_{t-allowable} = 0.55 * f_y * A_s$$

Where:

$P_{t\text{-}allowable}$ = allowable tension load (kips)

f_y = minimum yield stress of pile shaft (ksi)

A_s = area of steel (remove corrosion if required) (in^2)

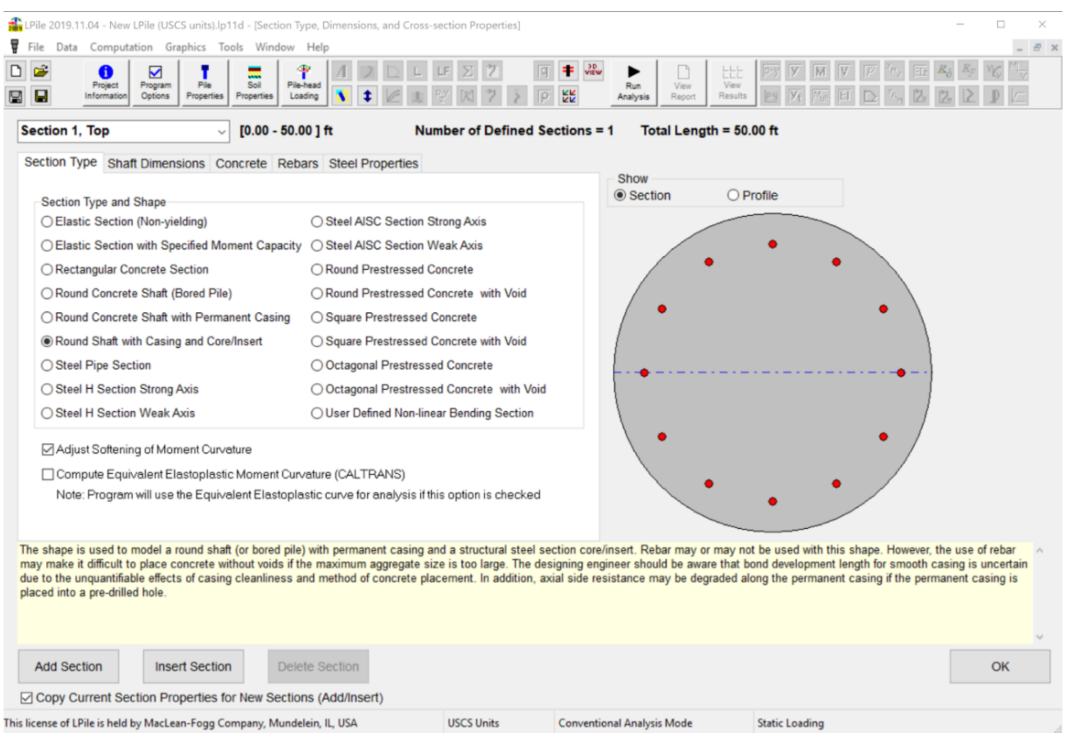
Lateral Loads and Flexure Design

When EDP piles are subjected to lateral and/or moment loading, the resultant flexural stresses should be determined from the pile/soil interaction using lateral load analysis program such as ALLPILE, LPILE, or equal commercially available computer software. The analysis will require preliminary EDP length, structural capacity and site specific soil properties.

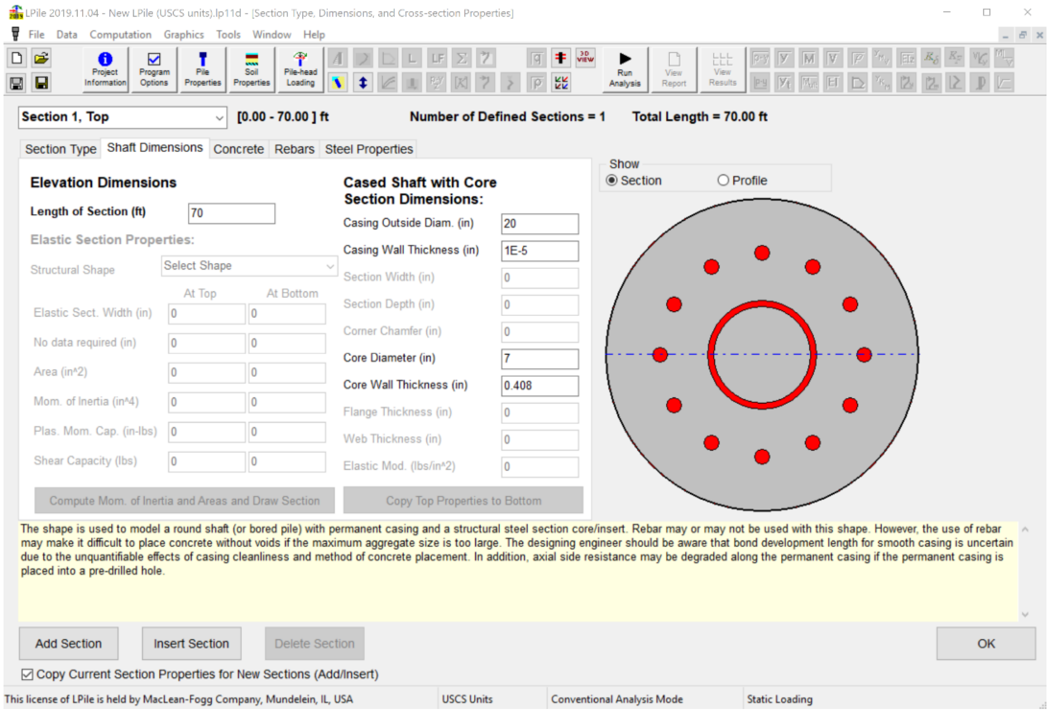
Flexural stresses with axial stresses should be checked against allowable stresses of the pile material as required by project or local building codes. The American Institute of Steel Construction (AISC) 360 manual specifically addresses combined axial and flexural loading. One commonly used design uses ALLPILE and is shown below.

LPILE Data entry

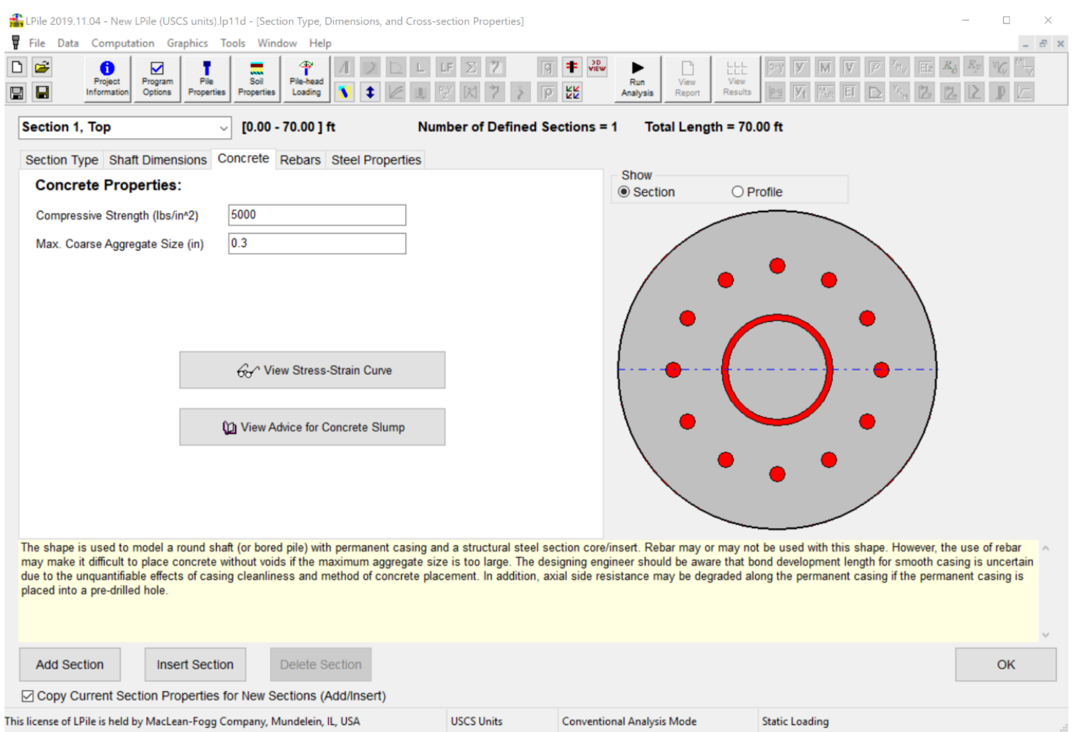
Step 1 – Select 'Pile Properties' and round shaft with casing and core/insert under 'Section Type



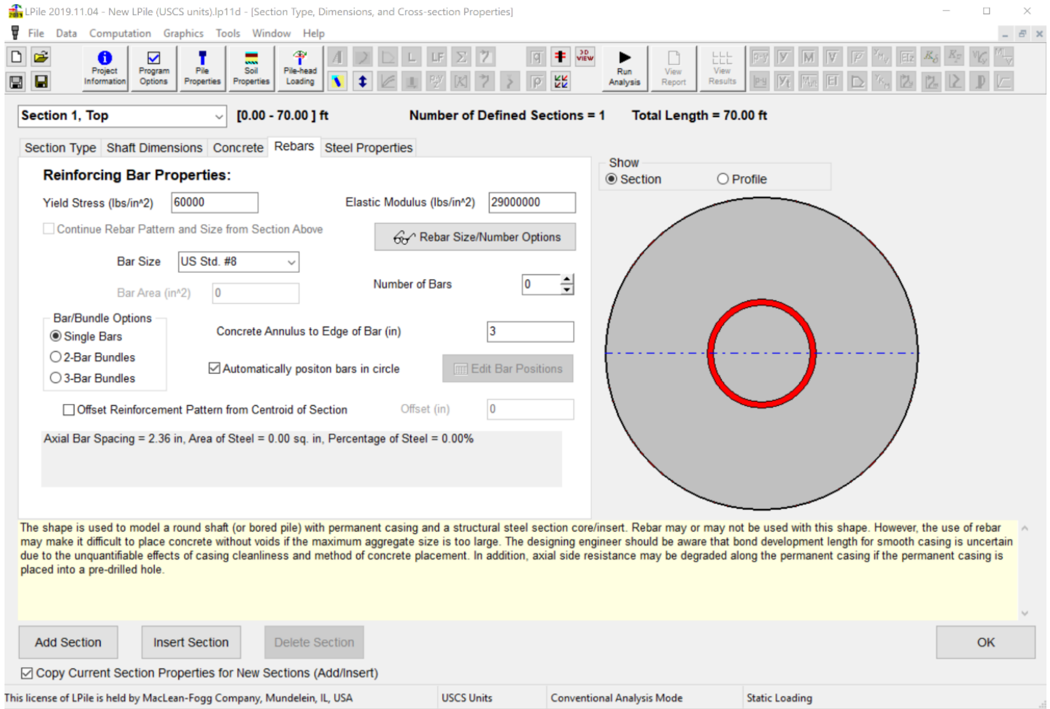
Step 2 – Input anticipated pile length, outside grout diameter, and EDP shaft dimensions on the 'Shaft Dimensions' tab. Enter a near zero outer casing thickness.



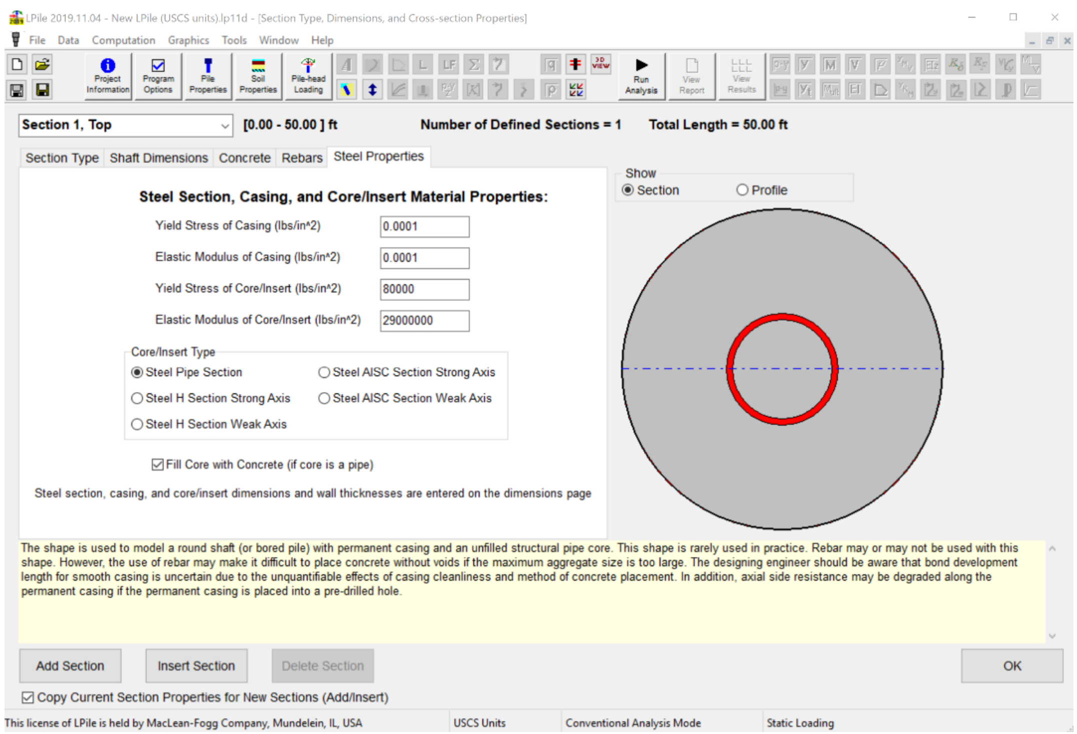
Step 3 – Input grout properties under 'Concrete' tab. We recommend using 4,000 to 5,000 psi grout compressive strength.



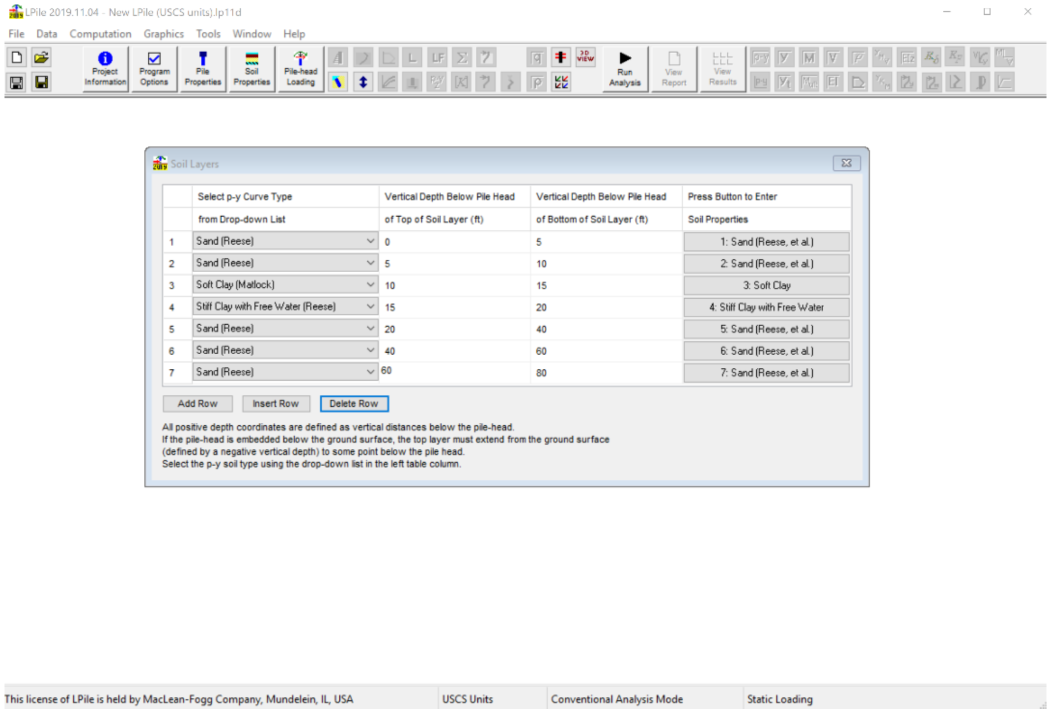
Step 4 – Input rebar properties under ‘Rebars’ tab. In most cases, rebar will not be used in addition to the steel pipe shaft.



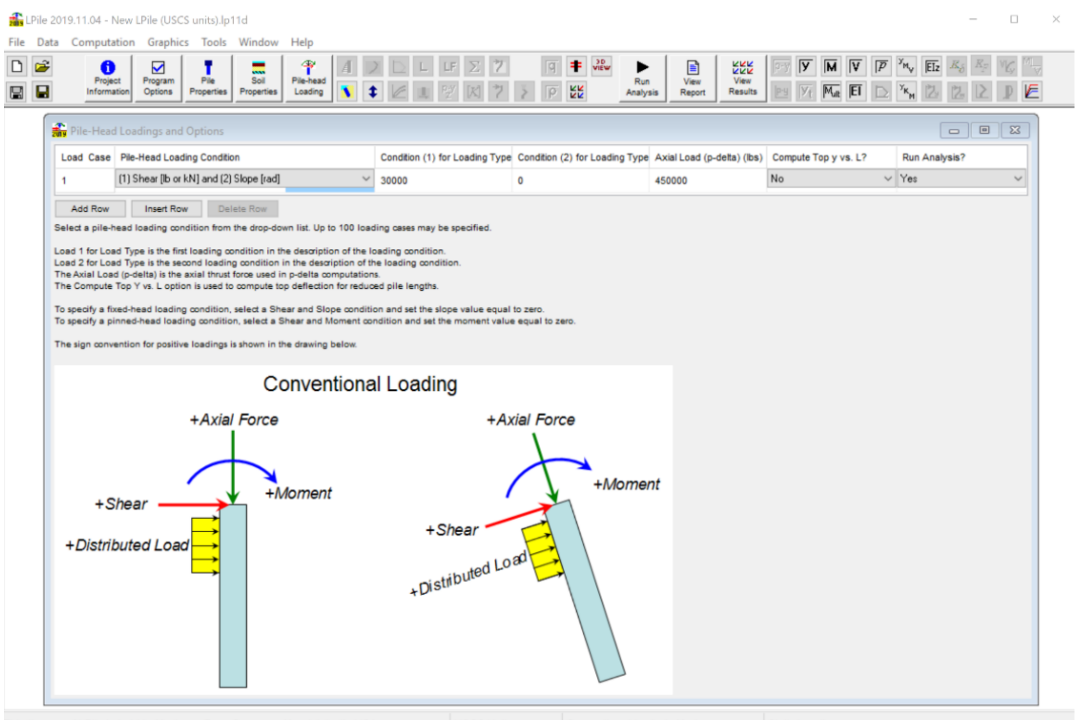
Step 5 – Enter steel casing and core material properties under ‘Steel Properties’ tab. Enter near zero values for the outer casing material properties.



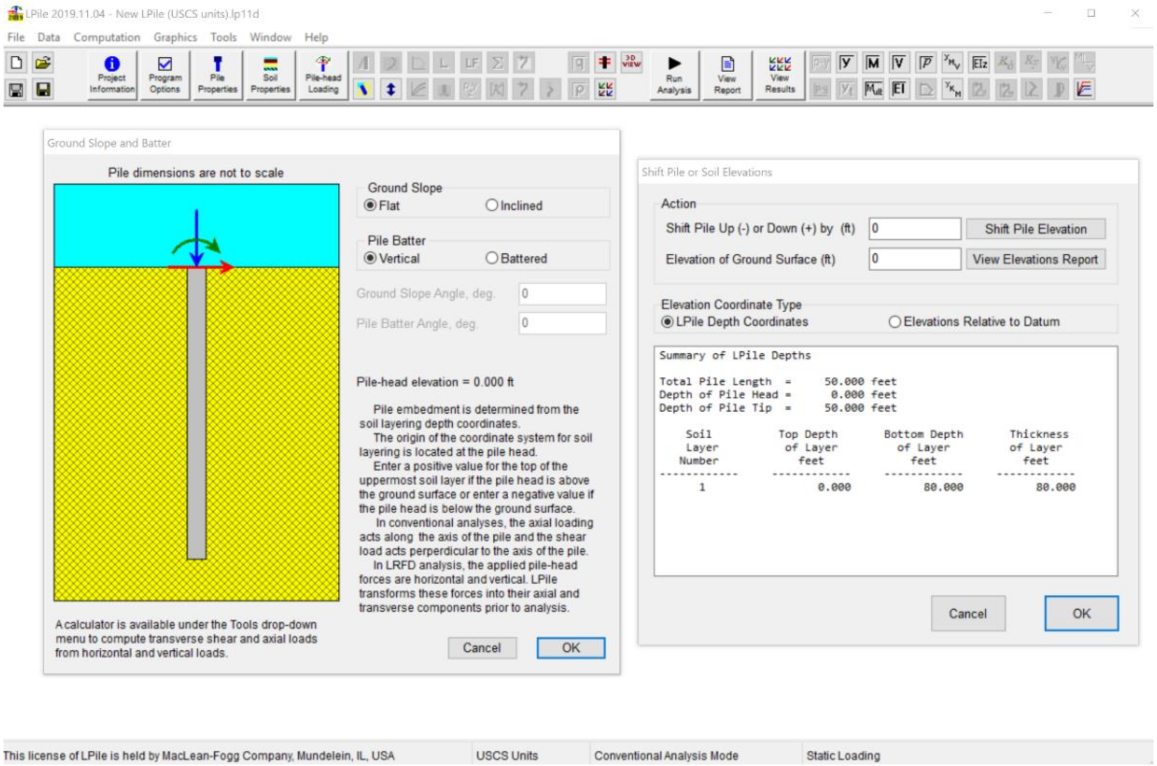
Step 6 – Transcribe soils information and properties (unit weight, cohesion, friction angle, etc.) from desired boring log to the ‘Soil Properties’ window.



Step 7 – Enter pile head end condition as well as lateral and axial loading values in the ‘Pile-head Loading’ window.



Step 8 – The defaults of a plumb pile with its head at grade can be altered in the 'Ground Slope and Batter' window to the right of 'Pile-head Loading' should the design specify the piles to be battered pile or a pile head terminating above/below the current grade.



LPILE Results

Once the pile, soils, and loading information has been input the analysis can be performed to determine how the pile will perform in the field. The program provides several useful graphs showing the anticipated pile deflection and forces vs. pile depth. The depth of pile fixity can be found from these graphs. LPILE also provides a summary report which includes the maximum forces and deflection of the pile head.

<u>Force and Deflection vs Depth Graphs</u>

```
Output Summary for Load Case No. 1:

Pile-head deflection                =     0.19224748 inches
Computed slope at pile head         =       0.000000 radians
Maximum bending moment              =      -1702109. inch-lbs
Maximum shear force                 =         30000. lbs
Depth of maximum bending moment     =       0.000000 feet below pile head
Depth of maximum shear force        =       0.000000 feet below pile head
Number of iterations                =             14
Number of zero deflection points    =              4


--------------------------------------------------------------------------------
            Summary of Pile-head Responses for Conventional Analyses
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Definitions of Pile-head Loading Conditions:

Load Type 1: Load 1 = Shear, V, lbs, and Load 2 = Moment, M, in-lbs
Load Type 2: Load 1 = Shear, V, lbs, and Load 2 = Slope, S, radians
Load Type 3: Load 1 = Shear, V, lbs, and Load 2 = Rot. Stiffness, R, in-lbs/rad.
Load Type 4: Load 1 = Top Deflection, y, inches, and Load 2 = Moment, M, in-lbs
Load Type 5: Load 1 = Top Deflection, y, inches, and Load 2 = Slope, S, radians


Load Load             Load                   Axial   Pile-head  Pile-head  Max Shear Max Moment
Case Type  Pile-head  Type      Pile-head  Loading  Deflection  Rotation    in Pile    in Pile
 No.  1    Load 1      2        Load 2       lbs      inches     radians     lbs       in-lbs
---- ----- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ----------
  1  V, lb    30000.   S, rad        0.00   450000.     0.1922       0.00     30000.  -1702109.


Maximum pile-head deflection = 0.1922474767 inches
```

<u>Summary of Maximum Deflection and Forces</u>

Flexural Capacity Check

The engineer should analyze the results for the project specific requirements. The deflection of the pile head should be checked against project specific allowable deflection. If deflection requirements are not met the engineer may choose a larger cross section for the entire pile or possibly use a larger, reinforced casing in the upper section of the pile shaft. Normally this casing would be placed at a minimum depth of fixity as shown in the above graph.

The structural capacity of the pile section should be verified either by the software or by the engineer. The lateral loads will impart a flexural stress on the pile near the top which should be checked against allowable stresses on the pile cross section. Most piles also have axial loads with lateral loads and the combined stresses from both loads should be checked against allowable stresses in the pile shaft. One equation that may be used comes from Chapter H of the American Institute of Steel Construction Manual (AISC 360):

AISC 360 Equation H1-1a: $\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_r}{M_c}\right) \leq 1.0$ When $\frac{P_r}{P_c} \geq 0.2$

AISC 360 Equation H1-1b: $\frac{P_r}{2P_c} + \left(\frac{M_r}{M_c}\right) \leq 1.0$ When $\frac{P_r}{P_c} < 0.2$

Where:

P_r = required axial strength (kips)

P_c = available axial strength (kips)

M_r = required flexural strength (from lateral analysis) (kip-in)

M_c = available flexural strength (kip-in)

If the combined stresses from the above equation are satisfied while keeping the pile head deflection below the allowable limit for the project, the geotechnical design of the pile can be completed.

Buckling Check

Where EDP piles are installed through low strength soils, a critical buckling load may be calculated using lateral analysis software or checked with traditional engineering formulas for buckling of an unbraced column. The designer is encouraged to read section 1810.2.1 of the IBC for further information. The FHWA Displacement Pile Design and Construction Manual also suggests the following equation to determine if buckling of the pile is a potential concern:

(FHWA Equation 5-28)

$$P_{cr} = \frac{\pi^2 EI}{l^2} + \frac{E_s l^2}{\pi^2}$$

Where:

P_{cr} = critical buckling load (kips)

E = Modulus of Elasticity of Steel (ksi)

I = Moment of Inertia of Steel Shaft (in^4)

l = Unsupported Length of Pile or Thickness of Weak Soil Layer

E_s = soil's lateral reaction modulus over the unsupported length per FHWA Tables 5-12 & 5-13

Table 5-12. Elastic Constants of Various Soils Based on Soil Type (modified after AASHTO, 2002).

Soil Type	Range of Equivalent Elastic Modulus, kPa (ksf)
Clay	
Soft sensitive	2,400 - 14,400 (50 - 300)
Medium stiff	14,400 - 48,000 (300 – 1,000)
Very stiff	48,000 - 96,000 (1,000 – 2,000)
Loess	14,400 - 57,500 (300 – 1,200)
Silt	1,900 - 19,000 (40 – 400)
Fine sand	
Loose	7,600 - 11,500 (160 – 240)
Medium dense	11,500 - 19,000 (240 – 400)
Dense	19,000 - 29,000 (400 – 600)
Sand	
Loose	9,600 - 29,000 (200 – 600)
Medium dense	29,000 - 96,000 (600 – 1,000)
Dense	96,000 - 76,000 (1,000 – 1,600)
Gravel	
Loose	29,000 - 76,000 (600 – 1,600)
Medium dense	76,000 - 96,000 (1,600 – 2,000)
Dense	96,000 - 192,000 (2,000 – 4,000)

Table 5-13. Elastic Constants of Various Soils Based on SPT N Value (modified after AASHTO, 2002).

Soil Type	Equivalent Elastic Modulus, kPa (ksf)
Silts, sandy silts, slightly cohesive mixtures	400 $(N_1)_{60}$ (8 $(N_1)_{60}$)
Clean fine to medium sands and slightly silty sands	700 $(N_1)_{60}$ (14 $(N_1)_{60}$)
Coarse sands and sands with little gravel	1,000 $(N_1)_{60}$ (20 $(N_1)_{60}$)
Sandy gravels	1,200 $(N_1)_{60}$ (24 $(N_1)_{60}$)

In addition to calculating the critical buckling load from Equation, the soil strength limit for buckling can be calculated by:

(FHWA Equation 5-29)

$$E_s^{LIMIT} = \frac{1}{\left[\frac{4I}{A^2}\right]\left[\frac{E}{f_y^2}\right]}$$

Where:

E_s^{LIMIT} = lower limit of soil's lateral reaction modulus

I = moment of inertia, steel only (in^4)

A = area of steel (in^2)

E = modulus of elasticity of steel (ksi)

f_y = minimum yield stress of pile shaft (ksi)

If the result of Equation FHWA Equation 5-29 is less than the measured or assumed Soil Modulus, then buckling is not a concern. If E_s^{LIMIT} is greater than the soil modulus, then buckling of the pile shaft should be examined further by calculating the allowable stress on the Displacement Pile section.

(FHWA Equation 5-30 – 5-32)

$$P_{c-allowable} = \left(0.4 * f_c' * A_g + 0.47 * f_y * A_s\right) * \frac{F_a}{0.47 * f_y}$$

$$if\ 0 < \frac{K * l}{r_t} \leq C_c, F_a = \frac{f_y}{FS} * \left[1 - \frac{\left(\frac{K * l}{r_t}\right)^2}{2 * C_c^2}\right]$$

$$if\ \frac{K * l}{r_t} > C_c, F_a = \frac{\pi^2 * E}{FS * \left({K * l}/{r_t}\right)^2}$$

Where:

$$C_c = \sqrt{\frac{2 * \pi^2 * E}{f_y}}$$

K = Effective length factor, assumed equal to 1

l = unsupported pile length (ft)

r_t = radius of gyration, steel only = $(I/A)^{0.5}$ (in^3)

FS = factor of safety = 2.12

f_y = minimum yield stress of pile shaft (ksi)

Geotechnical Design

EDP piles typically transfer load to the surrounding soil in skin friction and/or end bearing. Each project has site specific soil properties, and these should be known before calculating pile geotechnical capacity. The soil properties should be listed in the project geotechnical report. If time is permitted, the designer should request skin friction and/or end bearing values from the geotechnical engineer. If values are not given in the geotechnical report, the designer may use the following for skin friction on a grouted pile:

(FHWA Equation 5-9)

$$P_{G-allowable} = \frac{\alpha_{bond}}{FS} * \pi * D_b * L_b$$

Where:

$P_{G\text{-}allowable}$ = Allowable Skin Friction (kips)

α_{bond} = Adhesion Factor

FS = Factor of Safety

D_b = Diameter of Drill Hole (in)

L_b = Length of Pile in Bonded Layer (in)

FHWA Table 5-3 can be used to find appropriate α_{bond} values to use in the above formula based on the site's subsurface soil conditions. EDP piles perform in the range of a Type B Displacement Pile. The designer is encouraged to use judgement with these values and apply to appropriate factor of safety to the design.

Table 5-3. Summary of Typical α_{bond} (Grout-to-Ground Bond) Values for Micropile Design.

Soil / Rock Description	Grout-to-Ground Bond Ultimate Strengths, kPa (psi)			
	Type A	Type B	Type C	Type D
Silt & Clay (some sand) (soft, medium plastic)	35-70 (5-10)	35-95 (5-14)	50-120 (5-17.5)	50-145 (5-21)
Silt & Clay (some sand) (stiff, dense to very dense)	50-120 (5-17.5)	70-190 (10-27.5)	95-190 (14-27.5)	95-190 (14-27.5)
Sand (some silt) (fine, loose-medium dense)	70-145 (10-21)	70-190 (10-27.5)	95-190 (14-27.5)	95- 240 (14-35)
Sand (some silt, gravel) (fine-coarse, med.-very dense)	95-215 (14-31)	120-360 (17.5-52)	145-360 (21-52)	145-385 (21-56)
Gravel (some sand) (medium-very dense)	95-265 (14-38.5)	120-360 (17.5-52)	145-360 (21-52)	145-385 (21-56)
Glacial Till (silt, sand, gravel) (medium-very dense, cemented)	95-190 (14-27.5)	95-310 (14-45)	120-310 (17.5-45)	120-335 (17.5-48.5)
Soft Shales (fresh-moderate fracturing, little to no weathering)	205-550 (30-80)	N/A	N/A	N/A
Slates and Hard Shales (fresh-moderate fracturing, little to no weathering)	515-1,380 (75-200)	N/A	N/A	N/A
Limestone (fresh-moderate fracturing, little to no weathering)	1,035-2,070 (150-300)	N/A	N/A	N/A
Sandstone (fresh-moderate fracturing, little to no weathering)	520-1,725 (75.5-250)	N/A	N/A	N/A
Granite and Basalt (fresh-moderate fracturing, little to no weathering)	1,380-4,200 (200-609)	N/A	N/A	N/A

Type A: Gravity grout only
Type B: Pressure grouted through the casing during casing withdrawal
Type C: Primary grout placed under gravity head, then one phase of secondary "global" pressure grouting
Type D: Primary grout placed under gravity head, then one or more phases of secondary "global" pressure grouting

For un-grouted piles, the below equations can be used to estimate the skin friction resistance between the steel and soil. A friction reduction factor of 0.6 is used for the steel to soil interface (Bowles 1996).

(DFI Equations 5, 6, and 7)

$$Q_s = 0.6 * \pi * D_s * f_s * L_f$$

$$Cohesive\ Soils: f_s = \alpha * c$$

$$Noncohesive\ Soils: f_s = \beta * \sigma'_v$$

Where:

Q_s = Skin Friction (kips)

D_s = Diameter of Shaft (in)

f_s = Friction or Adhesion Between Soil and Pile (psf)

α = Adhesion Factor

c = Soil Cohesion (psf)

σ'_v = Effective Overburden Pressure (psf)

β = K * tan(δ)

K = At-Rest Earth Pressure Coefficient

δ = Friction Angle Between Pile and Soil (degrees)

End bearing may be utilized when the EDP pile is terminated in very stiff or dense soil or on rock. End bearing values should be attained from the geotechnical engineer or use presumptive values from the IBC or local building codes where applicable. When the EDP is terminated in very stiff/dense soil or rock, the end bearing may be calculated using Terzaghi's general bearing capacity equation.

$$Q_{ult} = A_{plate}(cN_c + q'N_q + 0.5\gamma' B N_\gamma)$$

Where:

Q_{ult} = Ultimate Axial Capacity of the Soil (kips)

A_{plate} = Area of Driver Plate (sf)

c = Soil Cohesion (psf)

q' = Effective Overburden Pressure (psf)

B = Driver Plate Diameter (in)

γ' = Effective Unit Weight of Soil (pcf)

N_c , N_q, and N_γ are bearing capacity factors

Often the third term is neglected in the bearing capacity equation because the calculated value from this portion is small in relation to the other terms. Like any deep foundation, load tests may be performed to confirm design assumptions for skin friction and end bearing. The following section discusses recommended EDP load testing procedures.

Design Consideration: Downdrag

Downdrag forces, or negative skin friction, should be considered in the overall pile design when one or more of the following criteria is met per Briaud and Tucker (1997). Downdrag can also occur even if the below conditions are not met.

1. Total settlement of the ground surface will exceed 4"
2. Settlement of the ground surface after deep foundations are installed will exceed 0.4"
3. The height of the embankment to be placed on the ground surface exceeds 6.5'
4. Thickness of the compressible soil layer exceeds 30'
5. The water table will be lowered by more than 12'
6. The piles will be longer than 80'

It should also be noted that liquefaction or seismically-induced settlement can cause downdrag forces to act on a pile. It is recommended that a computer program such as Ensoft's TZPILE be used to determine the magnitude of the downdrag forces. A step by step procedure for downdrag analysis can be found in FHWA-NHI-16-009.

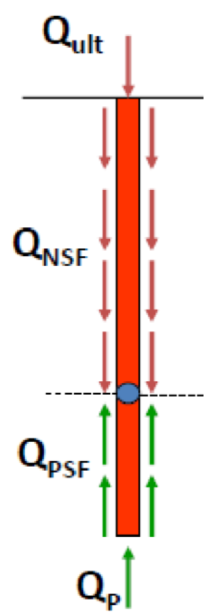


Figure 3: Force summary of a pile with negative skin friction

As shown in Figure 3, the ultimate geotechnical capacity of the pile should be designed such that it is sufficient to resist the combination of downdrag and static loading. Only the tip resistance of the pile and side friction resistance developed below the lowest layer of soil contributing to the downdrag shall be used.

To reduce the magnitude of downdrag forces, the following practices may be considered:

1. Preload the soil to induce settlement prior to installing the piles
2. Embed the uppermost driver plate 5' or 3 times the plate's diameter, whichever is larger, below the lowest layer of soil contributing to downdrag
3. Review the feasibility of installing piles with smaller shafts (this may require placing additional piles)
4. Install the piles with an unbonded zone (no external grout column) that passes through the lowest layer of soil contributing to downdrag. This can be accomplished by maintaining a small amount of grout flow

through the nose of the pile to ensure that the grout port does not become plugged with soil/debris. Grout can then be pumped at the required pressure to achieve the desired grout column in the bonded zone below the lowest layer of soil contributing to downdrag.

V. Installation Procedure

The pile length and drilling criteria will be established by the geotechnical engineer and verified through load testing of pre-production piles. The installation should be evaluated by the engineer using the following criteria to achieve the required ultimate axial and/or lateral load capacities.

Documentation

The pile installation record (Appendix A) is to be filled out completely during the installation of each pre-production and production pile to ensure that they are being installed to the predetermined standards.

The following information should be recorded prior to pile installation:

- Pile location
- Nearest soil boring
- Drill rig pressure to torque conversion factor
- Start elevation
- Design elevation
- Grout mix
- Grout 28 day UCS (psi)

During pile installation, the torque and grout delivery should be recorded at one foot increments. The installation can be considered complete when the design depth has been reached and/or the pile tip is embedded sufficiently into the bearing layer. A representative of the owner should review and sign off on piles terminating shallower than the design depth. Load testing of shallow production piles may be required to determine if the pile is generating sufficient load resistance.

VI. Load Testing

EDP load testing is performed on pre-production piles to verify the calculated geotechnical capacity of the pile as well as verifying any design assumptions that were made. The location of the pre-production load test is to be determined by the owner's geotechnical engineer. Supplementary load testing of a percentage of production piles may be required to provide quality assurance means that the EDP installation procedures are being followed and the piles are performing as expected. Refer to your local building codes for pile testing requirements.

It shall be permitted to evaluate load tests of deep foundation elements using any of the following methods (IBC 2012):

1. Davisson Offset Method
2. Brinch-Hansen 90% Criterion
3. Butler-Hoy Criterion
4. Other methods *approved* by the *building official*

Load Test Equipment

The pre-production load test proposal shall be in general conformance with ASTM D-1143 for compression loading, ASTM D-3689 for tension loading, and ASTM D-3966 for lateral loading. Each test requires a hydraulic jack acting on the test pile, a reaction beam, and a reaction anchors/cribbing system to perform.

The hydraulic jack system shall be capable of increasing or decreasing the applied load incrementally and holding each load for a duration of time. The incremental control shall allow for small adjustments which may be necessary to maintain the applied load for a sustained "hold" period. A pressure gauge connected to a hydraulic jack pump is used to monitor the load. The reaction beam and anchor/cribbing system shall be designed to have sufficient strength and capacity to distribute the test loads safely to the ground outside of the soil mass impacted by the test pile. The direction of the applied load shall be collinear with the EDP and reaction system always.

For compression and tension tests, dial gauges are positioned on an independent reference beam whose supports are located a distance of five times the pile diameter, not less than 8 feet, from the test pile. It is recommended that three dial gauges are positioned around the test pile at an equal distance from the pile center. These will be used to measure EDP vertical and/or lateral movement throughout the load test and shall have an accuracy of at least +/- 0.001" with a minimum travel sufficient to measure all test pile movements without requiring resetting the gauges. The dial gauges shall be positioned so their stems are parallel with the vertical axis of the test pile. The stem may rest on a smooth level plate placed perpendicular to the pile and located at the pile head.

Per FHWA Displacement Pile Design, "For lateral load testing, it is recommended to install an inclinometer in the Displacement Pile to obtain Displacement Pile lateral movement data with depth. This can be accomplished by installing the inclinometer to a depth of 10 to 20 Displacement Pile diameters. Specific termination depth should be based on lateral pile analyses performed during design."

Grout Testing

14 grout samples shall be created and the water to cement ratio and accelerator type recorded. Two samples shall be tested and their unconfined compressive strength (UCS) results taken on day 1, 2, 3, 4, 5, 8, and 28. The average of UCS shall be taken each day and graphed in order to verify the increased compressive strength of the grout mix. The average results of the day 1 through 8 tests may be used to extrapolate the projected 28-day UCS.

Compression/Tension Load Tests

The pre-production test pile's installation methods, procedures, equipment, and overall length shall be identical to those of the planned production piles to the extent practical or where approved exceptions are made by the owner. The pre-production test proposal shall provide the minimum following information:

- Type and accuracy of hydraulic equipment
- Type and accuracy of load measuring equipment
- Type and accuracy of pile-head deflection equipment
- General description of load reaction system, including description of reaction anchors or cribbing
- Calibration report for hydraulic jack, pump, pressure gauge, hoses, and fittings.

The test sequence shall be as shown in Appendix B to the extent practical.

If the pre-production pile does not meet the design requirements, the owner's representative, with input from the contractor, may modify the pile design and/or installation methods and retest the modified pile. These modifications include, but are not limited to, installing replacement piles, modifying the installation methods and equipment, increasing the installation torque, changing the helix configuration, changing the pile shaft, digger plate, or grout material grade.

When preparing for a compression test, (Figure 4) it is recommended that a minimum clear distance of 5 times the diameter of the largest driver plate or 8', whichever is larger, be maintained from the test pile to the reaction piles.

Tension tests (Figure 5) do not require reaction anchors and instead utilize cribbing.

The hydraulic jack is placed under the test beam for compression tests and over the test beam for tension tests.

Install the test EDP to the target installation torque and/or depth.

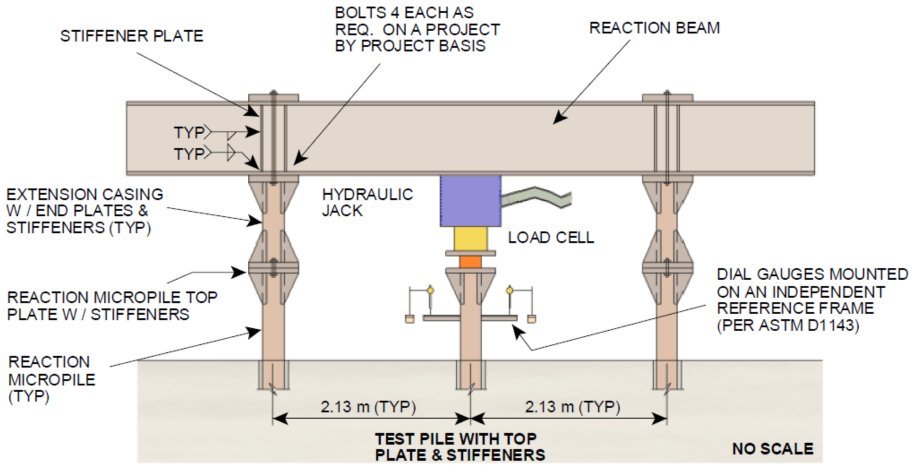
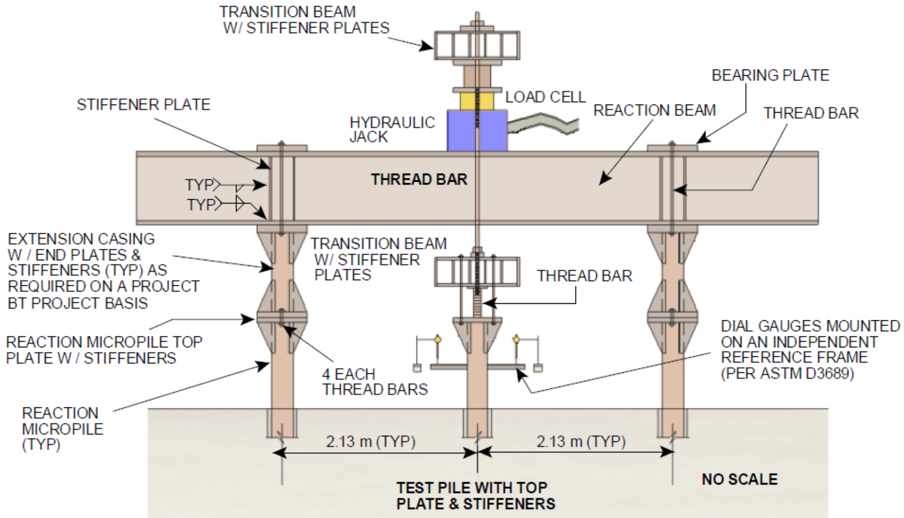


Figure 4: Compression Load Test Arrangement (ASTM D1143) – FHWA Displacement Pile Design & Construction



Note: 2.13 m = 7 ft

Figure 5: Tension Load Test Arrangement (ASTM D3689) – FHWA Displacement Pile Design & Construction

Testing Program

A bearing plate shall be placed between the jack and the reaction frame to ensure full contact between the jack piston and test beam. All surfaces shall be clean and smooth to provide full contact.

The hydraulic jack shall be positioned co-axially with the pile head to minimize eccentric loading at the beginning of the test such that the unloading and repositioning of the jack during the test is not required.

The hydraulic jack shall be sufficiently capable of applying a load not less than two times the proposed design load (DL). The stroke of the jack shall not be less than the theoretical elastic shortening of the pile when the maximum test load is exerted on it.

Assemble deflection measuring equipment, hydraulic pump and pressure gauge on independent reference beams. Utilizing one or more secondary (backup) measuring systems is highly recommended.

An alignment load (AL) shall be applied to the EDP prior to setting the deflection measuring equipment to zero or a reference position. The AL shall be taken as 10% of the design load (0.1 x DL). After the AL is applied, the test set-up shall be inspected carefully to ensure it is safe to proceed and the deflection gauges set to zero.

Axial compression or tension load tests shall be conducted by loading the EDP stepwise as shown in Appendix B to the extent practical. Pile head deflection is to be recorded at the beginning of each step and after the end of the hold time. The hold time begins when the load equipment reaches the required load step.

Test loads shall be applied until continuous jacking is required to maintain the load step (pile plunging) or until the test load increment equals the specified maximum testing load (2.0 x DL), whichever occurs first. The observation period for this last load increment should be 10 minutes unless indicated otherwise by pile design professional, project geotechnical engineer, or owner's representative. Deflection readings should be recorded at 1, 2, 3, 4, 5 and 10 minutes. This portion of the test is referred to as the "Creep Test" with the purpose of measuring the time-dependent movement (creep) of the EDP. If the total deflection between 1 and 10 minutes exceeds the specified maximum pile head deflection, the test load is typically maintained for an additional 50 minutes and the total deflection is recorded at 20, 30, 40, 50 and 60 minutes.

The applied test load shall be removed in approximately equal decrements per the schedule in Appendix B and holding each load for 1 minute. The final load should be held for 5 minutes.

Recording Test Data

The magnitude of each load is determined from the jack pressure gauge and the load cell area. Each reading taken from the load test can be plotted to form a load-deformation curve. An example of this is shown in Figure 6. The total deflection is recorded after the alignment load and at each load increment.

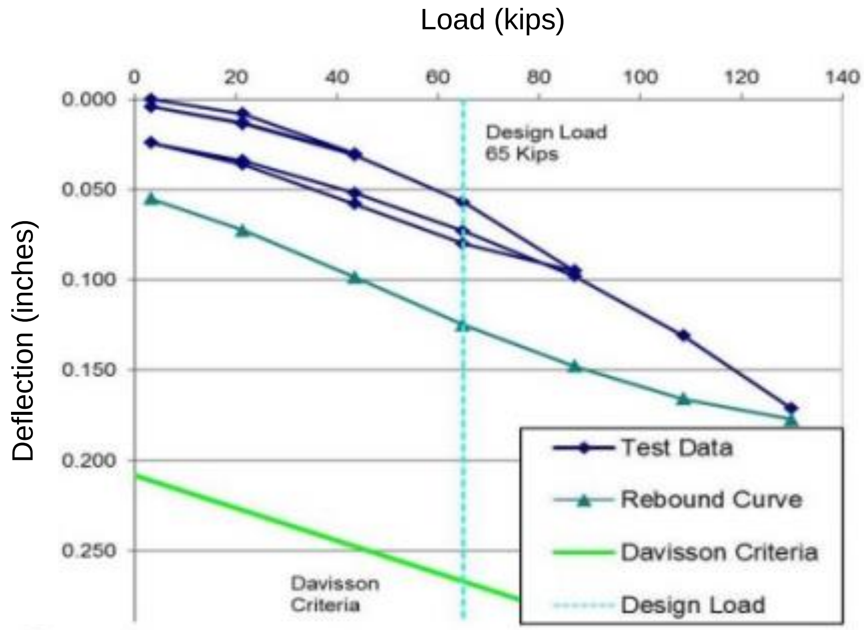


Figure 6: Typical load vs. settlement curve for axial loading and unloading of test pile

Acceptance Criteria for Pile Load Test

Acceptance of the load test results is generally governed by the building code for that jurisdiction and is subject to review by the structural engineer of record. The acceptance criteria must be defined prior to conducting the load test.

It is recommended that both criteria below be met for approval unless indicated otherwise by the pile design professional, project geotechnical engineer, or owner's representative.

1. The test EDP shall sustain the compression and tension design load (1.0 x DL) with no more than 0.5" of total vertical pile head deflection.
2. Failure does not occur at the maximum compression and tension test loads (2.0 x DL). The failure load shall be defined by one of the following definitions, whichever results in the lesser load.

   a. The point at which the movement of the EDP tip exceeds the elastic compression/tension of the pile shaft by 0.08 x B. B is the diameter of the largest driver plate. *(Note that tension loads are limited to the minimum ultimate tensile strength of the coupling joints of the central steel shaft. It is recommended to use the minimum ultimate tensile strengths as published by the pile supplier).*
   b. The point at which the slope of the load versus deflection (at end of increment) curves exceeds 0.0250 inches/kip.

The contractor shall provide the engineer of record with copies of the field test report confirming EDP configuration and construction details within 24 hours of completing the load tests. This written documentation will either confirm the load capacity as required on the working drawings or propose changes based upon the results of the pre-production tests.

References

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ASTM D1143, *Standard Test Method for Piles Under Static Axial Compressive Load.* American Society for Testing and Materials, New York.

ASTM D3689, *Standard Test Method for Individual Piles Under Static Axial Tensile Load.* American Society for Testing and Materials, New York.

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FHWA (2005), *Micropile Design & Construction, Reference Manual.* Federal Highway Administration Publication, Report No. FHWA-NHI-05-039, December 2005

FHWA (2016), *Design and Construction of Driven Pile Foundations – Volume I.* Federal Highway Administration Publication, Report No. FHWA-NHI-16-009, July 2016

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APPENDIX A

Excalibur Grouted Displacement Pile Installation Sequence

1. Attach the hydraulic drive head to the Excalibur lead section and align pile tip at specified pile location.

2. Advance the lead section approximately 12 inches below ground and begin grouting (350 psi maximum). If there is a planned unbonded zone, maintain minimal grout flow until specified start to bonded zone is reached.

3. Record grout take during entire installation of each pile using the Excalibur Grouted Displacement Pile Installation Record. A grout flow meter can be utilized to increase grout volume measurement accuracy.

4. Grout shall be pumped continuously to fill the annulus created by the Excalibur's displacement plate.

5. Sufficient crowd shall be applied to the pile throughout the entire installation process to ensure 6 inches of advancement per revolution.

6. Document installation torque every 1 to 3 feet during installation and at pile termination using the MPS Excalibur Displacement Pile Installation Record provided. Pile capacity is not determined by installation torque and data is used as reference only.

7. Where extensions are required, stop the drive head and remove from lead section. Attach the hydraulic drive head to the Excalibur extension section. Attach the extension section to the lead section with specified hardware or by threading sections together and continue installation. Add extensions as required to reach design depth.

8. If dense soils or obstructions are encountered and the pile will not advance, reverse the pile 24 inches and re-advance. Repeat 3 to 5 times while measuring how much the pile advances each time. Do not exceed maximum specified torque of the shaft. If the pile will not advance, then pre-auguring may be required to reach design depth (Confer with Engineer of Record).

9. If the pile is terminated above the pile cut-off elevation, cut the pile using an appropriate method such as a band saw or torch.

10. Upon completion of the pile installation, ensure that the grout level is brought to the top of pile (inside and outside of the steel pipe shaft).

11. Install steel pile cap or termination.

Excalibur Non-Grouted Displacement Pile Installation Sequence

1. Attach the hydraulic drive head to the Excalibur lead section and align pile tip at specified pile location.

2. Advance the lead section into the ground while maintaining steady torque.

3. Sufficient crowd shall be applied to the pile throughout the entire installation process to ensure 6 inches of advancement per revolution.

4. Document installation torque every 1 to 3 feet during installation and at pile termination using the MPS Excalibur Displacement Pile Installation Record provided. Pile capacity is estimated using installation torque and shaft specific torque factor (K_t).

5. Where extensions are required, stop the drive head and remove from lead section. Attach the hydraulic drive head to the Excalibur extension section. Attach the extension section to the lead section with specified hardware or by threading sections together and continue installation. Add extensions as required to reach design depth.

6. If dense soils or obstructions are encountered and the pile will not advance, reverse the pile 24 inches and re-advance. Repeat 3 to 5 times while measuring how much the pile advances each time. Do not exceed maximum specified torque of the shaft. If the pile will not advance, then pre-auguring may be required to reach design depth (Confer with Engineer of Record).

7. If the pile is terminated above the pile cut-off elevation, cut the pile using an appropriate method such as a band saw or torch.

8. Install steel pile cap or termination.

MPS Excalibur High Capacity Displacement Pile Installation Record

	Installation Contractor		Date
	Project		Start Time
	Pile Number		Finish Time
	Nearest Boring		
Project No.	Location		
Ground Elevation	Observer		
Cutoff Elevation	Pressure:Torque Conversion	ft-lb/psi	

Installation Summary

Depth (ft)	Pressure Out (psi)	Back Pressure (psi)	Pressure Reading (psi)	Torque (ft-lb)	Grout Pump Strokes	Grout Volume (ft^3)	Grout Line Pressure (psi)
1							
2							
3							
4							
5							
6							
7							
8							
9							
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Pile Information	
Design Tip Depth (ft)	
Steel Shaft OD (in)	
Steel Shaft Thickness (in)	
Drive Plate Diameter (in)	
Drilling Information	
Drill Rig	
Drill Head	
Pile Installation	
Pre-drill Depth (ft)	
Stick-up at Completion (ft)	
Embedment Depth (ft)	
Torque at Final Depth (ft-lb)	
Plumbness N/S	
Plumbness E/W	
Grout Information	
Grout Mix	
Average 28 day UCS (psi)	
Pump Stroke to Volume Conversion	
Total Grout Volume (ft^3)	
In-ground Grout Volume (ft^3)	
Average Grouted Diameter (in)	
Installation Review	
Pile Meets Criteria?	Y/N
Per	
Reviewer	
Comments	

Installation Summary								Comments
Depth (ft)	Pressure Out (psi)	Back Pressure (psi)	Pressure Reading (psi)	Torque (ft-lb)	Grout Pump Strokes	Grout Volume (ft^3)	Grout Line Pressure (psi)	
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APPENDIX B

Load Test Schedule			Pile Head Deflection (in)			Notes
Load	Applied Load	Hold Time (minutes)	Record and Plot Total Movement (δ)	Record and Plot Residual Movement (δ_r)	Calculate Elastic Movement ($\delta_t - \delta_r = \delta_e$)	
AL		2.5				
Cycle 1	0.15DL	2.5	δ_1			
	0.30DL	2.5	δ_1			
	0.45DL	2.5	δ_{t1}			
	AL	1		δ_{r1}	$\delta_{t1} - \delta_{r1}$	
Cycle 2	0.15DL	1	δ_2			
	0.45DL	1	δ_2			
	0.60DL	2.5	δ_2			
	0.75DL	2.5	δ_2			
	0.90DL	2.5	δ_2			
	1.00DL	2.5	δ_{t2}			
	AL	1		δ_{r2}	$\delta_{t2} - \delta_{r2}$	
Cycle 3	0.15DL	1	δ_3			
	1.00DL	1	δ_3			
	1.15DL	2.5	δ_3			
	1.30DL		δ_3			
Hold load for at least 10 minutes while recording movement at specified times. If the total movement measured exceeds the specified maximum value then the load hold should be extended to a total of 60 minutes. Zero out movement reading for creep test.						
Cycle 3 cont'd	1.45DL	2.5	δ_{t3}			
	AL	1		δ_{r3}	$\delta_{t3} - \delta_{r3}$	
Cycle 4	0.15DL	1	δ_4			
	1.45DL	1	δ_4			
	1.60DL	1	δ_4			
	1.75DL	2.5	δ_4			
	1.90DL	2.5	δ_4			
	2.00DL	10	δ_4			
	1.50DL	5	δ_4			
	1.00DL	5	δ_4			
	0.50DL	5	δ_{t4}			
	AL	5		δ_{r4}	$\delta_{t4} - \delta_{r4}$	
Remove load and compare results to acceptance criteria						

AL = Alignment Load
DL = Design Load