TECH BRIEF

Structural Design of Ductile Iron Piles in Compression

Ductile Iron Piles (DIPs) support allowable axial compression loads ranging from 25 tons to more than 120 tons. The compression design capacity of DIPs depends on characteristics of the selected pile materials and the prevailing geotechnical conditions. Design capacities are determined by calculating the structural capacity (allowable strength) of the pile material and estimating the geotechnical capacity (soil resistance) and selecting the smaller of these two values. Geotechnical design approaches are described in detail in Tech Brief – Geotechnical Design of Ductile Iron Piles in Compression.

This document describes the design methodology to evaluate the allowable structural capacity of Ductile Iron Piles to resist compression loads. Ductile Iron Pile projects in the United State are most commonly designed based on Allowable Stress Design (ASD). While Load Resistance Factor Design (LRFD) methodologies can be used with Ductile Iron Piles, this document focuses only on ASD approaches.

BACKGROUND

The Ductile Iron Pile system is a low vibration, driven pile system. The system is manufactured in Europe by centrifugal or spin-casting of spheroidal graphite cast iron composed of an iron-carbon-silicon alloy. The material exhibits high impact resistance, ultimate strength and elastic limit. The alloy also retains more typical characteristics of cast iron including high compressive strength, fatigue resistance, and corrosion resistance. Modular pile sections are typically manufactured in 5 meter (16.4 ft) lengths with a Plug & Drive connection mechanism. Each section has a tapered socket with an internal shoulder for full engagement at one end and a tapered spigot at the other end. This system rapidly connects to form a pile of virtually any length without the effort of dedicated field welding or splicing. A picture of the connection is shown in Figure 1.

Figure 1:
Plug and Drive Connection

The modular system uses an excavator-mounted, high-frequency hydraulic hammer fitted with a special drive adapter that rapidly advances the pile into the ground using a combination of excavator crowd force and the percussive (ramming) energy from the hammer.

Ductile Iron Piles are manufactured in three diameters: 98 mm (3.89 in), 118 mm (4.65 in) and 170 mm (6.70 in) with different pile wall thicknesses that range from 6.0 mm (0.24 in) to 13.0 mm (0.51 in). The strength and stiffness properties for design include a yield stress of 320 MPa (46.4 ksi) and an elastic modulus value of 170,000 MPa (24,600 ksi). Additional material properties and dimensions for the different pile sizes documented by the manufacturer (Tiroler Rohre, GmbH) are available in the **Ductile Iron Pile Spec Sheet**.

Structural Design

Ductile Iron Piles behave as a composite pile similar to a micropile and derive their structural capacity through contributions of the ductile iron strength, grout strength (if used) and a center reinforcing bar (if used). Structural capacity calculations including buckling checks are used to determine design capacities. A typical pile section for a dry installation (no exterior grout) designed for compression loading is shown in Figure 2.

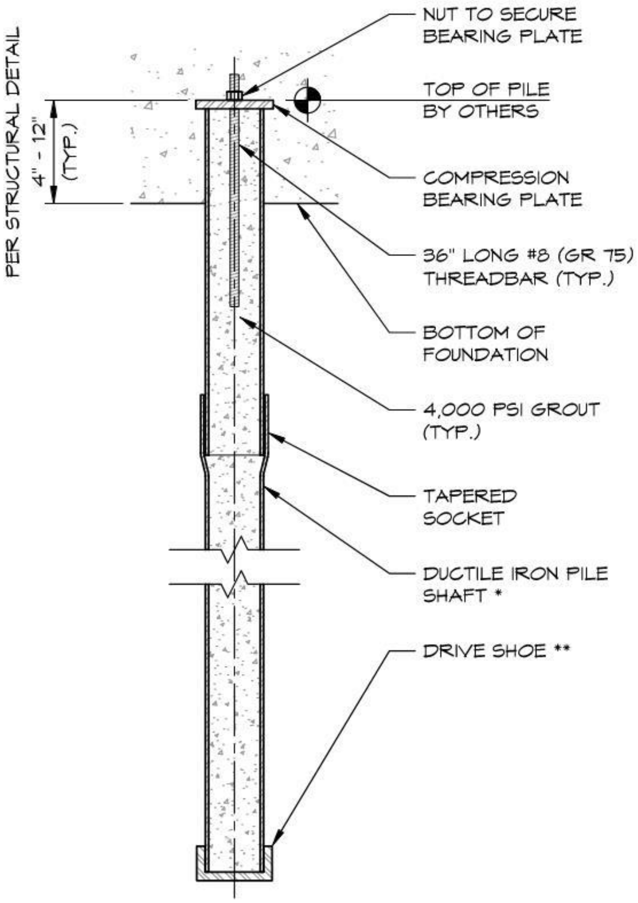

Figure 2: Typical Ductile Iron Pile Section for a Dry Installation (No Exterior Grouted)

Structural Capacity Calculation

A check of the structural capacity requires a comparison of the design working load of the pile against the allowable strength of the pile. The allowable pile strength (P_{dip}) is calculated as shown in Equation 1 for the separate contributions of strength:

$$P_{dip} = P_{ironpipe} + P_{grout} + P_{bar} \quad \text{(Eq. 1)}$$

where $P_{ironpipe}$ is the allowable load resisted by the ductile iron pipe, P_{grout} is the load resisted by the grout and P_{bar} is the load resisted by the center reinforcing bar (if used). When grout and another material are to be used simultaneously to support a load in compression, the maximum strain is limited by the grout. Per ACI, the maximum usable strain at the extreme concrete compression fiber is equal to 0.3 percent (2012). This is the maximum strain that the grout can experience before failure. Based on the material properties of the ductile iron, the stress at 0.3 percent strain is 74 ksi and exceeds the yield stress of the ductile iron for design. Therefore, the yield stress of the ductile iron (46 ksi) is the controlling stress level in the composite capacity calculations and no reduction in grout strength is necessary.

The allowable load for the ductile iron material is equal to the final pile cross-sectional area ($A_{dip\text{-}final}$) multiplied by the yield stress ($F_{y\text{-}di}$) as shown in Equation 2 where an allowable stress factor (μ) of 0.4 to 0.5 is typically used depending on whether load testing is being performed (IBC Table 1810.3.2.6). The final cross-sectional area must consider potential loss for corrosion depending on the installation environment. The loss from corrosion is neglected on the interior pile face when grout is installed within the pile. In the case of a wet installation of an exterior grouted pile, corrosion on the exterior pile face is typically also neglected.

$$P_{ironpipe} = uF_{y-di}A_{dip-final} \qquad \text{(Eq. 2)}$$

Similarly, the allowable load for a center reinforcing bar (when used) is equal to the bar cross-sectional area (A_{bar}) multiplied by the yield stress as shown in Equation 3 where an allowable stress factor (μ) of 0.5 is used (IBC Table 1810.3.2.6). Note that for strain compatibility between the bar and pile, the lower value of the strength of the bar or the pile may be used for compression calculations.

$$P_{bar} = uF_{y-bar}A_{bar} \qquad \text{(Eq. 3)}$$

The contribution of the grout to the load carrying capacity is calculated as the allowable grout compressive strength ($f'_{c\text{-}all}$) multiplied by the grout area (A_{grout}) as shown in Equation 4. The allowable compressive strength is limited to 0.33 of the ultimate compressive strength. Further limitations of the allowable compressive strength may be appropriate based on local building codes (i.e. MA Building Code limits the maximum value to 1,600 psi). Grout is typically a 4,000 to 5,000 psi sanded grout mix although neat cement may be used in some cases.

$$P_{grout} = f'_{c-all}A_{grout} \qquad \text{(Eq. 4)}$$

At a minimum, the grout area refers to the inner diameter of the pile that is almost always grouted. In cases with exterior grouted piles using an oversized drive shoe with a larger exterior grouted portion of the pile, a larger area of grout representing grout exterior to the pile may also be considered.

The sum of the individual strength components are combined to calculate the total allowable compression load resistance of the DIP from a structural perspective. The total allowable load resistance must be greater than the applied loading demand.

Design Example

This design example calculates the allowable structural design of a Series 118/9.0 Ductile Iron Pile installed with a dry Installation process (no exterior grout).

Example assumes:

- Dry installation with interior grout, but no exterior grout
- Grout strength of 4,000 psi
- No corrosion loss
- No high strength center bar is included

Step 1 – Determine Ductile Iron Pile Area for Design

From the DuroTerra Ductile Iron Pile Spec Sheet, Series 118/9.0 piles have the following design properties:

- Diameter = 118 mm (4.65 in)
- Wall thickness = 9 mm (0.35 in)
- Yield Stress = 320 MPa (46.4 ksi)

The contribution of structural capacity for the pile derived from the Ductile Iron Pile material itself is determined based on the cross-sectional area of the ductile iron pipe (A_{DIP}) which is a function of the pile outer diameter (d_{outer}) and wall thickness.

$$A_{DIP} = \frac{\pi}{4}\left(d_{outer}^2 - d_{inner}^2\right)$$

$$A_{DIP} = \frac{\pi}{4}\left((4.65\ in)^2 - (3.95\ in)^2\right) = 4.73\ in^2$$

Note this calculation excludes corrosion loss on the exterior and the interior of the pile. For dry installation applications using grout only on the interior of the pile (no exterior grout), it is typical to include some level of corrosion loss to account for corrosion potential on the exterior of the pile. The presence of grout on the interior of the pile would generally be considered adequate protection to minimize corrosion on the pile interior. The assumed corrosion loss on the exterior would reduce the dimensions of the outer diameter and thereby reduce the long-term structural capacity. Corrosion rates depend on many variables and should be selected based on project-specific conditions. Estimates of corrosion loss for various ground conditions can be found in various industry references. The DuroTerra Tech Brief – Corrosion Resistance provides further discussion about corrosion on Ductile Iron Piles and includes industry references for corrosion loss rates.

Step 2 – Determine Grout Area for Design

Based on a dry installation application (no exterior grout), the contribution of the structural capacity from the grout comes from the interior grout only. In this case, the area (A_{grout}) is calculated based on the inner diameter of the pile (d_{inner}).

$$A_{grout} = \frac{\pi}{4}\left(d_{inner}^2\right)$$

$$A_{grout} = \frac{\pi}{4}\left((3.95\ in)^2\right) = 12.25\ in^2$$

> *Note that high strength center bars may be used on the interior of the Ductile Iron Pile to provide enhanced structural capacity and/or tension resistance. In the event that a high strength center bar is included in the design, the final grout area needs to be reduced by the area of the high strength centerbar.*

Step 3 – Determine Area of Center Bar for Design (if used)

No centerbar is incorporated in this example. However, as an example, if a #8 centerbar is used, the dimensions are provided by the manufacturer or calculated as the following:

$$A_{bar} = \frac{\pi}{4}(d_{bar}^2)$$

$$A_{grout} = \frac{\pi}{4}((1\ in)^2) = 0.785\ in^2$$

Step 4 – Calculate the Allowable Capacity

Equations 1 thru 4 (above) provide the approach for calculating the composite structural capacity of the Ductile Iron Pile by combining the individual strengths of the ductile iron material, grout and center bar (if used). The determination of the allowable stress values is based on selection of reasonable allowable stress factors considering applicable codes, project-specific design requirements and load testing (if applicable). The allowable structural capacity for this pile section excluding contribution of a centerbar (in the example) is the following:

$$P_{DIP} = \mu_{DIP}A_{DIP}f_{y-DIP} + \mu_{grout}f_c'A_{grout} + \mu_{bar}A_{bar}f_{y-bar}$$

$$P_{DIP} = (0.5)(4.73\ in^2)(46.4\ ksi) + (0.33)(4\ ksi)(12.25\ in^2) = 125.9\ kips$$

Buckling Check

While not typically a controlling design consideration, buckling of the ductile iron pile in very weak soil is an appropriate check to verify adequate design capacity. The analysis compares the critical buckling load for an axially-loaded pile to the maximum axial stress of the pile. (Sabatini et al 2005) The approach involves estimating the limiting lateral reaction soil modulus for buckling ($E_{s,limiting}$) based on the pile moment of inertia (I), final pile area following corrosion loss (A), modulus of elasticity (E) and ductile iron yield stress ($F_{y\text{-}di}$) as shown in Equation 5 and comparing this value with the soil lateral reaction modulus value ($E_{s,soil}$) estimated using Table 1. (Sabatini et al 2005) Adequate resistance to buckling is afforded provided a factor of safety exceeding 2.0 results.

It is often conservative to utilize an elastic modulus (E_{comp}) using only the elastic modulus of the DIP material only (neglecting the composite response of the grout and center bar if used). In the event that the buckling analysis suggests an inadequate factor of safety against buckling, a more robust analysis using the composite properties of the ductile iron pipe, grout, and centerbar (if used) can be performed.

$$E_{s,\text{limiting}} = \frac{1}{\left[\left(\frac{4I}{A_{di}^{2}}\right)\left(\frac{E_{comp}}{F_{y-di}^{2}}\right)\right]} \qquad \text{(Eq. 5)}$$

Table 1: Elastic Constants of Various Soils Based on Soil Type (Sabatini et al 2005)

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 – 48,000 (600 – 1,000)*
Dense	48,000 – 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)

*Corrected typo in original reference

CONCLUSIONS

Ductile Iron Piles (DIPs) are routinely designed to support allowable axial compression loads ranging from 25 tons to more than 120 tons. The design methodology features a composite design approach that considers the individual allowable strengths and areas of each of the individual components (ductile iron pipe, grout and centerbar). This Tech Brief describes the material properties, design methodology using allowable stress design and provides an example calculation.

REFERENCES

International Code Council, Inc. (2018). International Building Code 2018. Section 1810 – Deep Foundations. Country Club Hills, IL.

Sabatini, P.J., Tanyu, B., Armour, T., Groneck, P., Keeley, J. (2005). Micropile Design and Construction. FHWA-NHI-05-039, Reference Manual for NHI Course 132078. U.S. Department of Transportation, Federal Highway Administration.

Tiroler Rohre Gmbh (TRM). (2014). “Piling Systems for Deep Foundations.” October, 2014.