DUROTERRA

Bending and Lateral Resistance of Ductile Iron Piles

Ductile Iron Piles are a modular, driven pile system characterized by an innovative Plug and Drive connection mechanism. The axial compression behavior of the Ductile Iron Pile system is well documented in the industry literature. Tension resistance is further described in the DuroTerra Tech Brief (**Tension Tech Brief)**. Ductile Iron Pile designers often must design the system to resist bending and/or lateral forces as well. This document provides a summary of design methodology and considers the available research to describe the bending and lateral behavior of Ductile Iron Piles. In response to questions pertaining to the bending resistance of the segmental Ductile Iron Piles, this document provides details of research and testing performed by Ductile Iron Pile manufacturer (Tiroler Rohre, GmbH) and DuroTerra, LLC that verifies the integrity of the connection. In addition, this document also presents details on the lateral design and performance of the system.

Background

As background, the Ductile Iron Pile system (Figure 1) is a low vibration, driven pile system utilizing modular high strength ductile iron piles manufactured in Austria using a centrifugal- or spun-cast method of fabrication. Piles have a Plug & Drive manufactured connection using 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 any length without a dedicated field welding or splicing effort.

Figure 1: Ductile Iron Pile Installation

The modular system uses an excavator-mounted, high-frequency hydraulic hammer fitted with a special drive adapter (or shank) that rapidly advances the pile into the ground using a combination of excavator crowd force and the percussive (ramming) energy from the hammer. Piles develop capacity through either end-bearing on rock or very dense soil (e.g. glacial till) or through friction when an oversized grout shoe is driven while continuously pumping cement grout to form a grouted bond zone in competent soil.

Piles are available in multiple diameters ranging from 98 mm (3.9 in.) to 170 mm (6.7 in.) and wall thicknesses ranging from 6 mm (0.24 in.) to 13 mm (0.51 in.) allowing for the most efficient and cost-effective designs. For friction piles, grout shoes range in diameter from 150 mm (5.9 in.) to 370 mm (14.6 in.). The range in sizes provide piles with working capacities ranging from less than 25 tons to greater than 120 tons.

Installation

Ductile Iron Piles are installed using either a dry method (non-grouted exterior) or a wet method (exterior grouted). Figure 2 (Ductile Iron Pile for compression/tension) provides pile details for the different methods.

For the dry method, a drive shoe is placed on the end of the first modular pile section. The modular pile section is driven in the ground. The tapered end of the next pile section is inserted into the bell of the first section and the pile is advanced further. This process is repeated until the pile reaches the design termination depth. For tension resistance, a center threadbar designed to resist the full tensile demand is inserted into the pile.

For the wet installation method (exterior-grouted), piles are installed by using an oversized grout shoe at the pile tip that creates an annular space around the pile while driving. Cement grout is continuously pumped through the center of the pile to fill the annular space while advancing the pile. Once the grouted pile reaches the design depth, a high-strength center bar is immediately lowered into the wet grout if tension resistance is required.

For either installation method, once the pile installation is complete, it is cut to the appropriate elevation. A bearing plate (and tension plate if required) are attached to a center threadbar. The Ductile Iron Pile, center bar and bearing/tension plates are encapsulated in the concrete foundation. More information on the installation process can be found in the **DuroTerra brochure**.

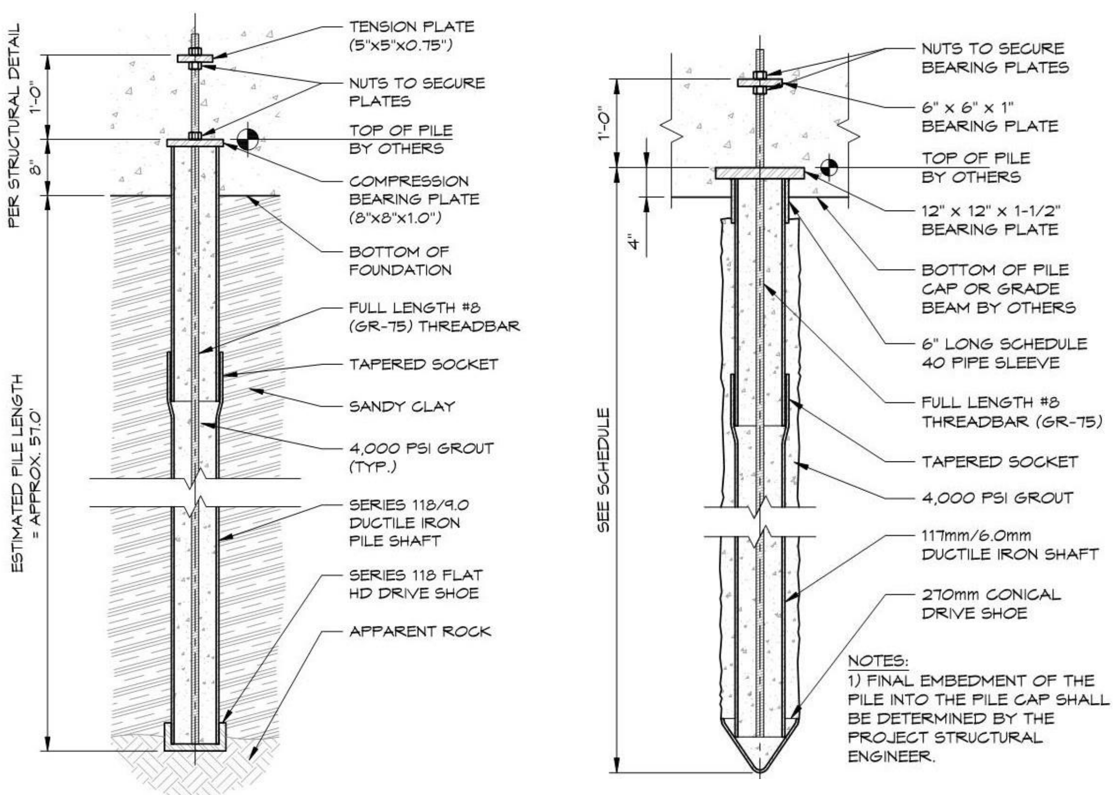
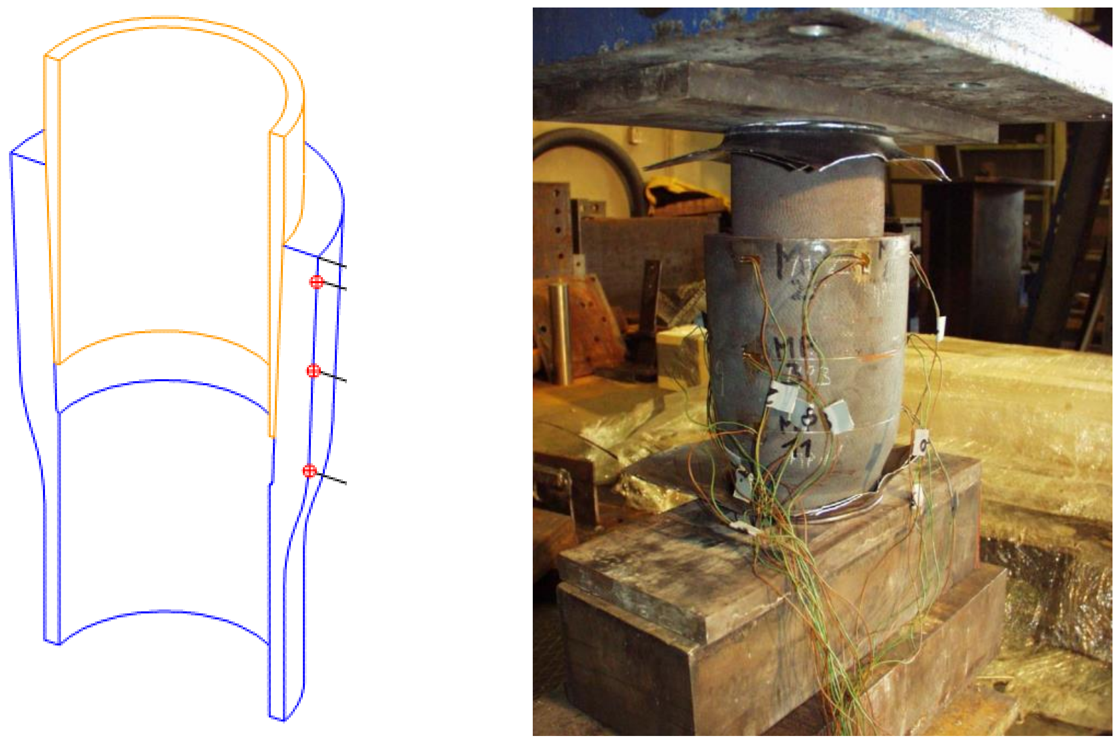


Figure 2: Examples of Ductile Iron Pile Details – a) Non-grouted (Exterior) and b) Grouted (Exterior)

Bell-Spigot Connection

One advantage of the Ductile Iron Pile system is that installation to depths of 150 feet or more can be accomplished rapidly due to the unique bell-spigot connection mechanism. The piles are manufactured with a thickened, reinforced bell section and a tapered end section. The joint is engineered to accept the tapered pile end and develop a connection through two mechanisms: 1) significant hoop stresses (confinement) that develop as the tapered end is driven into the interior of the bell and 2) a friction (cold) weld that occurs during the driving process between the ductile iron bell-spigot interface.



Figures 3a, b: Cross-section of Bell-Spigot Pile Socket and Laboratory Test Setup (Niederwanger and Lehar, 2001)

The performance of the Plug & Drive connection has been verified through a variety of different research efforts including laboratory tests, field tests and numerical analyses. Researchers at the Leopold-Franzens University Innsbruck (University of Innsbruck) as well as the Vienna University of Technology have evaluated the pile socket and concluded through numerical modeling and laboratory testing (Figures 3a,b) that the region around the pile socket does not constitute a weak point with respect to the load carrying capacity of the pile. The primary driver in the structural pile capacity is the straight-shaft section of the pile itself due to the smaller dimensions and cross-sectional area of pile material. The integrity of this joint is further strengthened with the addition of interior grouting which improves the stiffness.

Other forms of verification of the integrity of the pile socket have come from tension tests of piles without a continuous center bar. When used as a structural design member, tension capacity in the pile is most commonly developed by installing a center bar in the interior of the pile to sufficient depth to engage the side friction (or bonding) available along the pile. However, tension load tests have been performed on piles without full length center bars, for the purposes of isolating and evaluating the tensile performance of the pile socket cold-weld. Test loads of over 30 kips have been applied without failure, suggesting that the integrity of the pile socket cold-weld remains intact under tension loads. (Design note – standard practice remains to use a high strength center bar to develop appreciable Ductile Iron Pile tension capacity).

Lastly, GRL Engineers, Inc. performed pile dynamic analysis (PDA) testing on instrumented piles to verify the pile capacity. As part of the monitoring, engineers measured the dynamic response of the pile during the impacts from the high frequency percussion hammer. While the energy per individual blow of the hammer was not sufficient to verify the ultimate capacity of the pile, interesting results were still generated. At the start of driving, readings were reflective of a discontinuous pile (similar in nature to a broken pile) due to the modular pile sections. As the percussive drive energy was applied to the pile, continued monitoring revealed continuous pile behavior after the Plug and Drive connection had fused (Ryberg 2021). This monitoring provided further confirmation of the cold-welding connection that is generated during installation.

As it relates to the actual bending performance of the connection, bending testing has also been performed both in the United States and in Austria to compare the bending resistance between the pile socket and the straight-shaft pile material. Figure 4 pictures the test setup used for one round of testing. Tests were performed by loading the horizontal pile in either 3- or 4-point bending tests (Figure 5). Tests were performed on a control section (straight shaft) as well as the pile socket (bell-spigot) and coupled sections for various pile sizes. Note that the piles were not grouted and therefore the testing reflects a conservative evaluation of the bending resistance which is strengthened and stiffened with the presence of interior grout. A set of test results are shown in Figure 6 for a Series 118/7.5 pile section (118 mm outer diameter and 7.5 mm wall thickness). The test results follow the same pattern as other tests where the critical bending resistance is characterized by the straight shaft properties. The design of the pile socket including the depth of insertion and the significantly larger cross-section area forms the basis for the improved pile socket performance. From a design perspective, the pile bending behavior is modeled based on the straight shaft properties as the limiting factor and knowing that bending performance of the bell-spigot joint will exceed the engineering properties of the straight shaft section.

Figure 4: Ductile Iron Pile Bending Test Setup (U.S.)

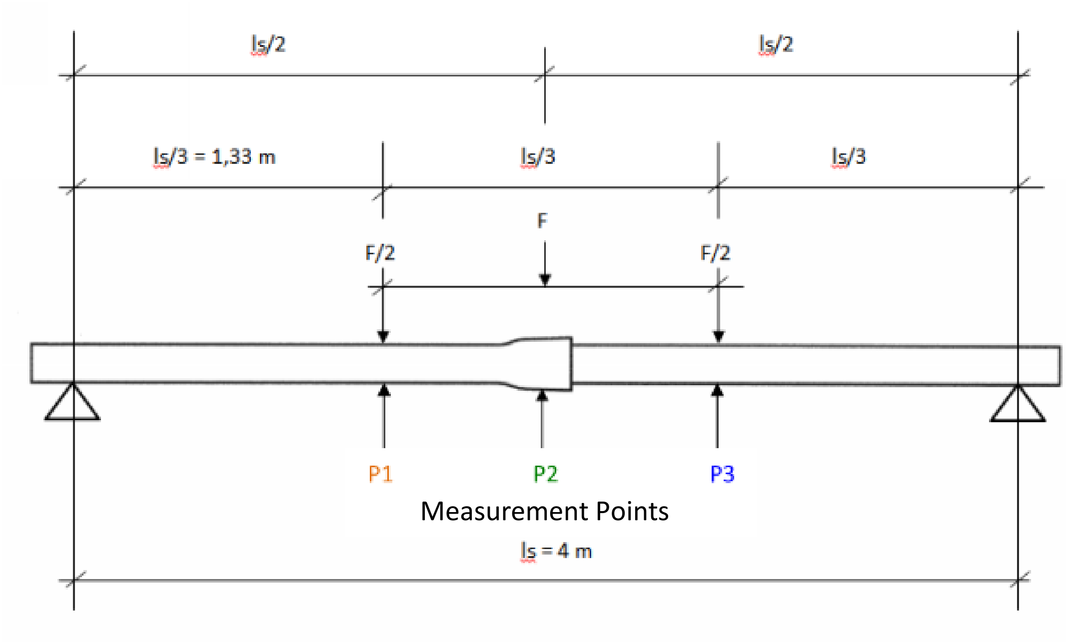


Figure 5: Schematic of Ductile Iron Pile Bending Test Setup (Austria)

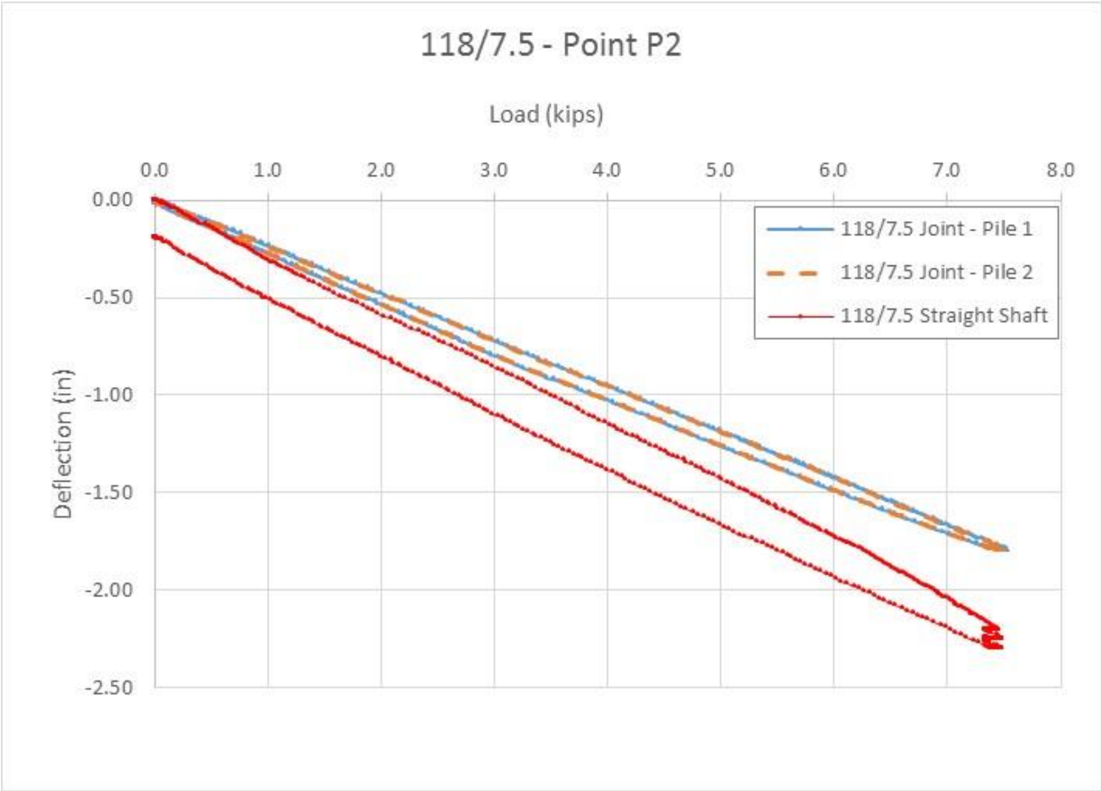


Figure 6: Ductile Iron Pile Bending Test Results

Lateral Resistance

Ductile Iron Piles are commonly used to resist lateral loads applied to pile caps. The lateral analysis for a Ductile Iron Pile is performed similar to other pile systems by evaluating the response of the pile under applied lateral loads and/or bending moments within a particular soil model. These analyses consider the properties of the pile including pile strength, stiffness, and geometry as well as the soil properties to model the soil-structure interaction. The lateral analyses are often performed using computer software to model individual piles (i.e. ENSOFT LPILE) or groups of piles (i.e. ENSOFT GROUP). Piles are modeled as free head, fixed head, or a partially fixed condition. Although modular sections are used, Ductile Iron Piles are modeled as continuous elements based on testing (referenced above) using the straight shaft dimensions.

The lateral analyses are often performed to evaluate the lateral deflection and resulting bending moments under various lateral loads. It is common for the load resulting in 1 inch of lateral deflection to represent the ultimate lateral load and the allowable lateral load for design is determined by dividing the ultimate load by 2 (factor of safety of 2.0). However, project specific loading and performance requirements should be considered when selecting appropriate design values.

In addition to lateral analyses to confirm the capacity of the Ductile Iron Pile, a combined bending analysis should be performed for piles subjected to a combination of axial compression loads and lateral loads. Guidance for the combined bending analysis is available in the literature (Sabatini 2005) and is based on the following approach in Equation 1:

$$\frac{P_c}{P_{c-allowable}} + \frac{M_{max}}{M_{allowable}} \leq 1.0 \qquad \text{Eq. 1}$$

where P_c is the maximum axial compression load, $P_{c\text{-}allowable}$ is the allowable axial compression value, M_{max} is the maximum moment resulting from the applied lateral loads/moments and $M_{allowable}$ is the allowable bending moment for the pile section. The latter two values are most often obtained from the lateral analysis output. The $P_{c\text{-}allowable}$ value is calculated based on a composite strength analysis using the following approach described in Equation 2:

$$P_{c-allowable} = \mu_{grout} f_c' A_{grout} + \mu_{DIP} F_{y-DIP} A_{DIP} + \mu_{bar} F_{y-bar} A_{bar} \qquad \text{Eq. 2}$$

where μ are allowable stress factors selected from appropriate buildings codes, f_c' is the compressive strength of the grout, $F_{y\text{-}DIP}$ *and* $F_{y\text{-}bar}$ are the respective yield strengths of the DIP material and center bar (if used) and A_{grout}, A_{DIP}, A_{bar}, are respective areas of the grout, Ductile Iron Pile material and center bar (if used). Mechanical properties used in the lateral analysis of Ductile Iron Piles are provided in Table 1.

Table 1: Mechanical Properties of Ductile Iron Piles

Material Property	ksi [MPa]
Yield Strength (0.2% offset)	46.4 [320]
Modulus of Elasticity	24,656 [70,000]

Lateral Performance

Full-scale lateral load tests have been performed on Ductile Iron Piles installed using both the dry installation (non-grouted exterior) method as well as the wet (exterior grouted) installation method to evaluate the response of the pile under lateral loads. Figure 7 provides an illustration of four (4) Series 118/7.5 piles installed with a 220 mm diameter grout shoe with varying depths of the Plug and Drive connection. The figure also shows the results of the lateral load versus deflection response of each of the piles. This testing was performed on a site with approximately 20 feet of loose debris fill underlain by medium dense sand and glacial till below 20 feet. The results show deflections on the order of 0.5 inches at lateral loads of 7 to 10 kips. Increased lateral loads of 9 to 15 kips resulted in deflections of 1 inch. Maximum loads of 15 to 20 kips were applied during the testing and produced deflections on the order of 2 inches. In addition, the results show that the depth of the Plug and Drive connection had no impact on the resulting lateral deflection. For instance, the tests with the greatest deflection occurred in Test Pile 1 and Test Pile 4 which had both the shallowest and the deepest connection of the piles tested.

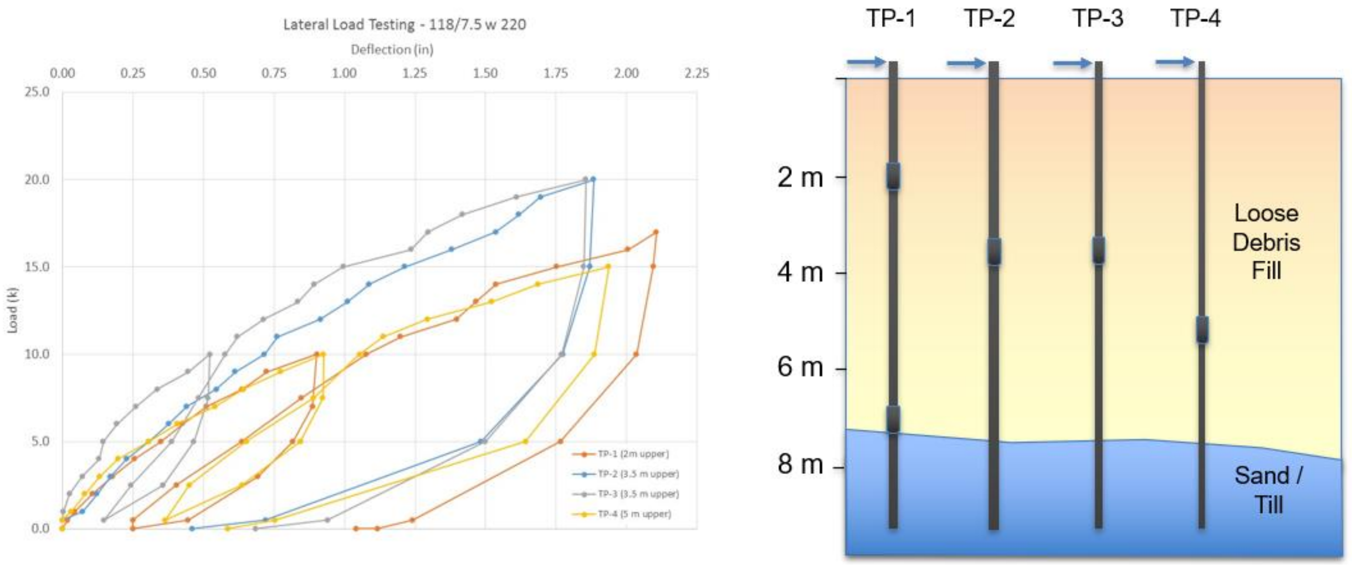


Figure 7: Full-scale Lateral Load Test Results on Series 118/7.5 with 220 mm Grout Shoe

Full-scale testing was also performed on a Series 170/9.0 pile installed with a dry installation approach (non-grouted exterior) on a site with 5 feet of loose to medium dense sand fill underlain by very soft marine clay and very loose marine sand to depths of about 35 feet followed by dense sand and stiff clay. The results of the test are shown in Figure 8. The test pile lateral deflection at the design load of 12.6 kips was 0.28 inches. At the maximum test load of 25.2 kips, a deflection of 1.04 inches was measured. This test was performed by reacting against two (2) other Series 170/9.0 piles. The deflection responses for the reaction piles were also measured and shown in Figure 8. Results of the reaction piles were generally similar to the test pile response. All piles showed acceptable deformations at the design loads of 12.6 kips and a maximum test load of 25.2 kips.

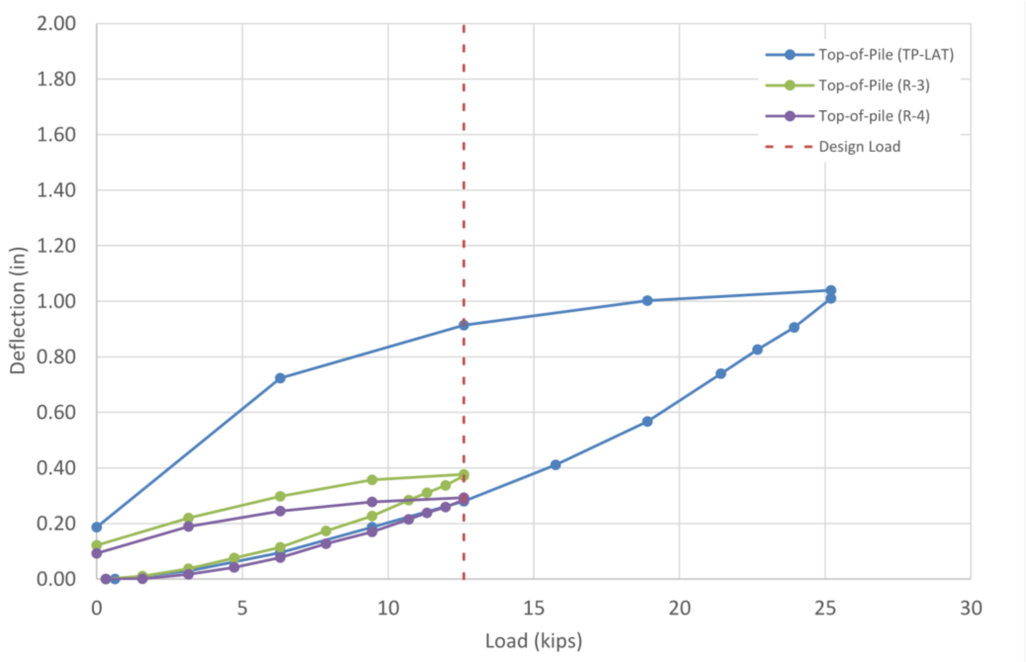


Figure 8: Full-scale Lateral Load Test Results including Reaction Piles on Series 170/9.0

Conclusions

Ductile Iron Piles are routinely used for support of foundations loaded in compression. Ductile Iron Piles may also be used to resist lateral loads applied to the piles. This Tech Brief describes the installation of the pile system and looks closely at the performance of the Plug and Drive connection to resist bending as well as the overall lateral resistance offered by the pile system. A discussion of the lateral analysis method is presented. Full-scale field test results are also presented for various pile sizes and illustrate the acceptable lateral performance offered by the Ductile Iron Pile system.

References:

Niederwanger, G. and Lehar H. (2001). “Bearing Behavior of Spigot-and-Socket Joints with Optimized Socket Geometry.” University of Innsbruck. Innsbruck, Austria.

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. US. Dept. of Transportation, Federal Highway Administration.

Ryberg, A. (2021). “A Trusted Test Method Meets a Newer Pile: Usage of Dynamic Load testing on Ductile Iron Pipe.” Presented at SuperPile ’21. Deep Foundations Institute. Philadelphia, PA. June 25, 2021.