DUCTILE IRON PILE FOUNDATION SOLUTION FOR INTERIOR RETROFIT PROJECTS

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ABSTRACT

Urban and industrial construction projects commonly involve interior work within buildings, warehouses and manufacturing facilities. Renovations of these existing structures must address both structural and geotechnical engineering challenges while also balancing the practicality of implementing solutions within site constraints including limited site access, overhead clearance restrictions, vibration tolerances and uninterrupted facility operations. This paper highlights two projects for an international shipping company where mezzanine level additions within active shipping facilities required construction of new foundations. Construction requirements included low vibration levels, as well as rapid and clean installation to limit impacts on the active shipping operations. The selected system also needed to adjust to both variable ground conditions and differing overhead clearances. This paper describes the installation, design and performance of Ductile Iron Piles used to meet the project challenges. The low vibration, driven pile system offered the ability to work within restricted overhead environments while successfully delivering working compression capacities ranging from 45 to 75 tons (41 to 68 tonnes) as well as lateral and tension resistance. The paper also presents the results of site-specific load testing (and pile capacity) for various termination criteria.

Keywords: Ductile Iron Pile, interior, overhead clearance,

INTRODUCTION

Urban and industrial construction projects commonly involve interior work within buildings, warehouses and manufacturing facilities. Renovations of these existing structures must address both structural and geotechnical engineering challenges associated with the new construction. Foundation solutions must also balance the need to achieve design requirements with the practicality to be installed within the particular site constraints including limited site access, overhead clearance restrictions, vibration tolerances and uninterrupted facility operations.

A staple in European construction for over 30 years, Ductile Iron Piles (DIP) are often used on projects to meet the many design and construction challenges, while providing the benefit of cost and time savings compared with other piling systems. The low vibration, driven pile system offers the ability to work within restricted overhead environments while delivering moderate to high capacities. The system was recently used on four separate projects across the Northeast U.S. for an international shipping company where mezzanine level additions were planned within active shipping distribution facilities. The projects involved support for new column foundations subjected to compression, tension and lateral demands. In addition to the technical design requirements, of particular importance to the owner, was the deployment of a foundation system that involved low vibration, rapid construction and clean installation to limit impacts on the active shipping operations. The selected system was also required to adjust to both variable ground conditions as well as differing overhead clearances within the structures. Details of installation, design and testing at two of the facilities are described herein.

DUCTILE IRON PILES

Ductile Iron Piles are a low vibration, driven pile system pictured in Figure 1. The modular, small-diameter piles have been manufactured by Austrian-based Tiroler Rohre GmbH for over three decades and used extensively throughout Europe. With diameters ranging from 3.8 in (98 mm) up to 6.7 in (170 mm) and wall thicknesses of 0.24 in (6 mm) to 0.51 in (13 mm), working structural capacities range from 25 tons (23 tonnes) to more than 100 tons (91 tonnes). Piles are manufactured using a centrifugal-casting process to transform the lamellar graphite cast iron into spheroidal graphite or ductile cast iron to improve strength and impact resistance for durability during driving. The piling material exhibits a design yield stress of 46 ksi (320 MPa) and modulus of elasticity of 24,600 ksi (170,000 MPa) (TRM 2014). Each pile is cast with a bell and spigot to form a Plug-and-Drive connection mechanism. The connection develops strength through a combination of the tapered compression fit as well as a friction (cold) weld that occurs during the high-frequency driving process, thereby eliminating the need for field splicing. The connection also exhibits full moment capacity of the nominal pile section based on the results of bending tests confirming the stiffer load-deflection response of both the bell-spigot and coupler drive connections compared with the nominal straight-line pipe section (DuroTerra 2018). The piling comes in standard 16.4 ft (5 meter) lengths and delivered in compact bundles containing between 8 and 18 pile sections depending on pile diameters. The bundles can be easily transported to congested urban or interior sites and offloaded into limited laydown areas to allow ease of installation on constrained sites.

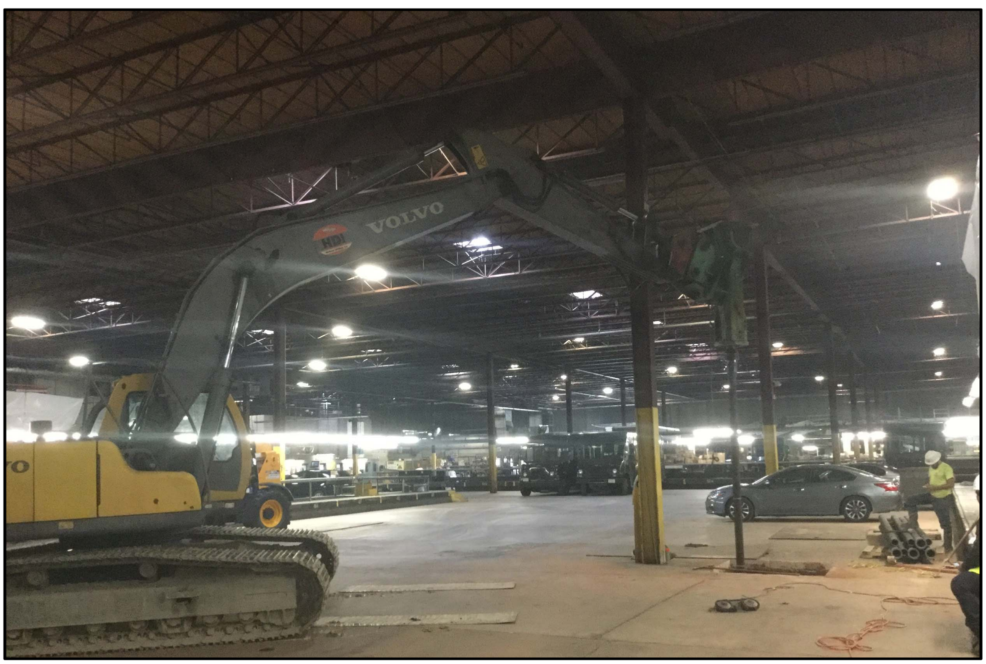

Fig. 1. Ductile Iron Pile Installation at Shipping Facility

Installation

The system is installed using an excavator-mounted, hydraulic breaker hammer. The hydraulic hammer uses a modified drive shank that seats into the pile bell. Using the hammer's percussion energy, the closed-ended pile segment is driven into the ground while monitoring rates of advancement. Using the same excavator, a second pile section is swung into place and inserted into the Plug and Drive (bell and spigot) connection and then driven. This process is repeated until the design length or pile termination ("set") criteria is reached, where the set is a maximum rate of advancement (i.e. 1 inch or less in 50 seconds). The hammer size (energy) is matched with the size of the Ductile Iron Pile and the driving conditions to develop the most efficient installation while not overstressing the pile material. Hammer sizes typically range from 3,000 ft-lb to 7,000 ft-lb class hammers for typical range of pile sizes.

Vibration measurements of the high frequency driving energy recorded on various project sites with multiple pile diameters, all at distances of less than 5 feet (1.5 m) from installation, are shown in Figure 2. Results of the monitoring illustrate that the majority of vibrations are in the high frequency spectrum and exhibit peak particle velocities less than 1 inch/second (25 mm/s). Monitoring also shows high frequency vibrations rapidly decrease with distance from the pile location.

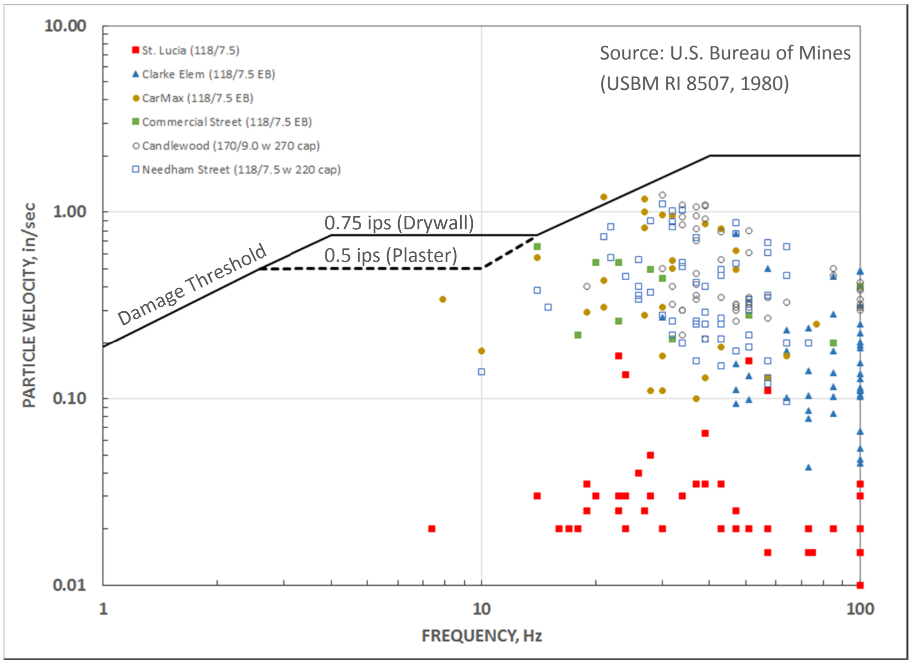

Fig. 2. Vibrations Measurements near Ductile Iron Pile installation

Geotechnical Application

Ductile Iron Piles can develop geotechnical capacity in either end-bearing or in friction depending on the installation technique. End-bearing piles are outfitted with a flat or pointed drive shoe and are driven through problem soils to terminate by achieving set in very dense soil or rock. A common recommended set criterion for end-bearing piles is less than 1 inch of movement in 50 seconds. Soil conditions exhibiting SPT N-values on the order of 50 blows per inch [50 bpi] are often required to achieve typical set thresholds. After achieving set, the remaining pile is cut to elevation and the completed pile is filled with neat cement grout. A center reinforcing bar may be placed into the wet grout, if required by the design. The remaining cut section including the bell is used as a starter pile section to minimize waste.

Friction Ductile Iron Piles are used to generate compression or tension resistance by bonding between the soil and cement grout interface. At the start of driving, an oversized conical grout shoe is placed over the end of the hollow pile. The grout caps are 5.9 in (150 mm) up to 14.6 in (370 mm) in diameter and create an annular space around the pile during driving. The pile is driven into the ground while continuously pumping cement grout through the hollow pile. The grout exits through the grout ports in the conical cap, immediately filling the annular space around the pile exterior during driving. The pile shaft becomes encapsulated in grout, developing a grout-to-ground bond zone. Additional pile sections are driven until the pile extends to the design length within the bond zone. Monitoring of drive rates provides useful information to determine when the pile encounters the design bond zone. After completion of driving, a center reinforcing bar is inserted into the wet grout if required for compression or tension capacity.

SHIPPING FACILITY, HARTFORD, CT

Renovations at an existing shipping facility in Hartford, Connecticut included construction of a new 25,000 sq. ft. (2,323 sq. meter), steel-framed mezzanine level within the existing high-bay warehouse. The existing building was constructed in the 1970s and supported on driven piles (either timber or steel based on original design documents). Typical overhead clearances were on the order of 30 feet (9.1 m), although limited areas were between 20 and 25 feet (6.1 to 7.2 m). Loading conditions at the new column footings were up to 400 kips (181 tonnes) in compression. Footings were also subjected to tension loads of up to 120 kips (54 tonnes) based on pile design requirements. To construct new mezzanine foundations, the existing concrete floor slab would be saw-cut to accommodate the new pile foundations. Following pile installation, new pile caps would be formed and poured. Management of the facility required operations to be moved in and out daily and work zones to be covered overnight. In addition, temporary shutdowns were required in the morning to allow for the daily departure of trucks. These aspects presented substantial logistical challenges to be addressed by the selected foundation system.

Geotechnical Conditions & Recommendations

Subsurface soil conditions described in the Geotechnical Engineering Report prepared by GZA GeoEnvironmental, Inc., (2017) consisted of medium dense to dense granular fill to depths of 3 to 9 feet (0.9 to 2.7 m) followed by very soft to stiff clay, silt and organic silt extending to depths of 16 to 27 feet (4.9 to 8.2 m) below grade. The cohesive layer was underlain by loose sand and silty sand followed by a 2 to 6 foot (0.6 to 1.8 m) thick layer of dense glacial till. Rock depths encountered during explorations ranged from about 26 feet (7.9 m) up to 40 feet (12.2 m) below grade. Groundwater was measured at 4 to 9 feet (1.2 to 2.7 m) below grade.

Project plans and specifications were prepared based on 7-inch (177 mm) diameter drilled micropiles installed through the fill, clay and organic soils and terminating by bonding in glacial till / rock to develop a capacity of 50 tons (45 tonnes) in compression. Alternative foundation options presented by the Geotechnical Engineer also included Ductile Iron Piles and helical piles.

Pile Selection and Design

Selection of the pile type by the project team was based on factors including anticipated pile performance, vibration limitations, duration, cost, cleanliness and field support requirements. As noted in the geotechnical report, helical piles would require a reduction in the working capacity and therefore increase both pile quantities and pile cap sizes and impact the zone of renovation. While drilled micropiles would develop the working capacities, the rate of installation would slow the project schedule and grouting operations would create undesirable spoils management requirements within the existing facility. The project team selected Ductile Iron Piles as a more-rapid and cost-effective alternative to 50 ton (45 tonnes) micropiles. Prior project experience in similar conditions was used as a baseline to confirm acceptable vibration levels and the cleanliness of the operation.

Ductile Iron Piles were designed to terminate on glacial till or rock to resist compression loading in end-bearing. As described in LeDo et al (2016), the structural design is based on a composite strength approach that is similar to micropiles with the pile material ($P_{ironpipe}$), interior grout (P_{grout}) and high-strength center bar (P_{bar})(if used) contributing to the ultimate capacity as described in Equation 1,

$$P_{dip} = u_{dip} F_{y-dip} A_{dip-final} + f'_{c-all} A_{grout} + u_{bar} F_{y-bar} A_{bar} \quad [1]$$

where u_{dip} and u_{bar} are the corresponding allowable stress factors for the pipe and bar, respectively, which range from 0.4 to 0.5 depending on load testing, $F_{y\text{-}dip}$ and $F_{y\text{-}bar}$ are the corresponding material yield strengths, $f'_{c\text{-}all}$ is the allowable grout compressive strength and $A_{dip\text{-}final}$, A_{grout} and A_{bar} are the respective areas of the pipe, interior grout and center bar (if used). As illustrated in Figure 3, a Series 118/7.5 Ductile Iron Pile section (4.65 inches or 118 mm outer diameter with 0.30 inches or 7.5 mm wall thickness) was used along with 4,000 psi (28 MPa) cement grout to achieve a working capacity of 50 tons (45 tonnes). To provide 15 tons (14 tonnes) of allowable tension resistance, all piles were installed with an over-sized grouting shoe to create an annular space around the pile that was filled with cement grout by continuously pumping through the pile and out the grouting shoe during installation. Piles were driven to achieve a rate of set of 1-inch (25 mm) or less in 50 seconds on glacial till or rock but developed an exterior grouted zone within the annular space created while driving the oversized shoe. This grouted zone provided grout-to-ground bonding to achieve sufficient geotechnical capacity for tension resistance. A full-length #8 Williams Grade 75 ksi (525 MPa) center bar was installed in the wet grout to meet the structural tension requirements.

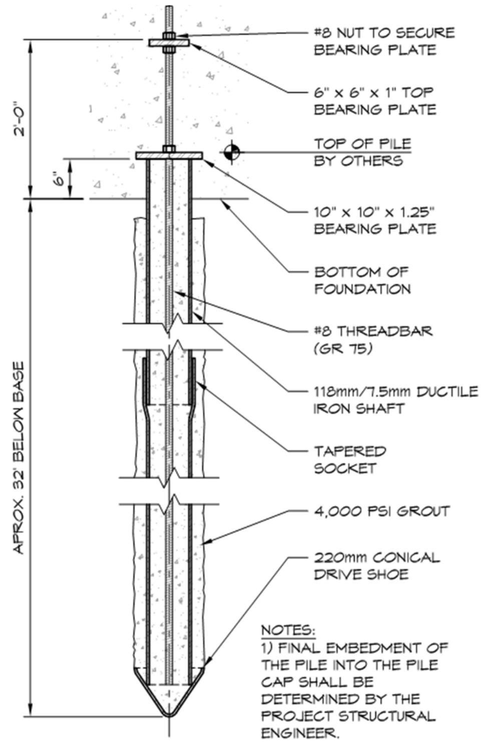

Fig. 3. Ductile Iron Pile Detail

Load Testing and Construction

Pre-production load testing was performed at the start of construction by design/build pile contractor Helical Drilling, Inc. One compression test pile and four tension reaction piles were all installed in a similar manner as the production piles. Piles extended 37 feet (11.3 m) below grade before achieving set. The test was performed in accordance with ASTM D-1143. In addition to monitoring the compression response of the test pile, reaction piles were also monitored to verify the tension load-deflection response. Figure 4 shows the results of the load testing which confirmed the design capacities with less than 0.2 inches (5 mm) of deflection at 100 tons (91 tonnes) in compression and less than 0.25 inches (6 mm) of deflection at 25 tons (23 tonnes) in tension. Following the completion of the test program, installation of the 73 production piles was performed in only 8 working days. Pile lengths averaged 29 feet (8.8 m) due to the variable rock depth. Select locations with limited overhead clearance of 20 feet (6.1 m) required the cutting of piles and use of drive-on couplers similar to the bell-spigot configuration to complete the installation.

AIR HUB SHIPPING FACILITY, PHILADELPHIA, PA

Facility upgrades consisted of doubling the size of an existing mezzanine inside a 1,000,000 square foot (92,903 sq. meter) international shipping logistics warehouse adjacent to the Philadelphia International Airport. Originally constructed in the late 1980's, the 500,000 square foot (46,451 sq. meter) mezzanine expansion was in response to the recent, unprecedented growth in eCommerce.

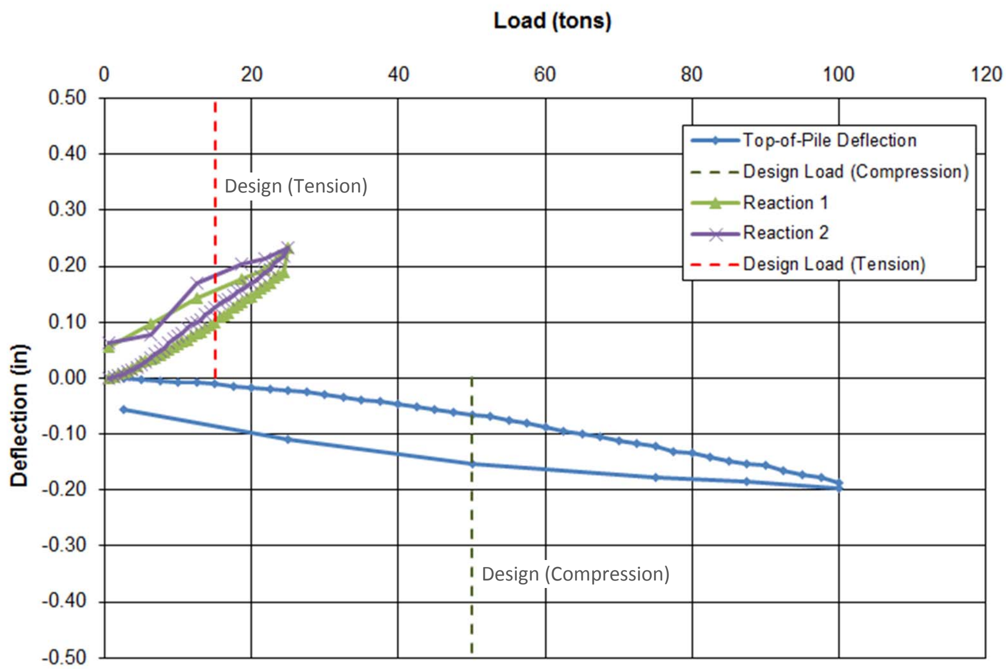

Fig. 4. Results of Compression and Tension Load Testing in Hartford, CT Facility

The existing building, consisting of pre-engineered steel and tilt-up precast concrete wall construction on grade beams, is supported on 60 ton (54 tonne) capacity step tapered piles driven about 75 ft. (23 m) into dense, lower alluvial deposits. The slab is conventional ground-supported construction. The project design team was headed by CVM. New pile-supported column footings were designed to support up to 258 tons (234 tonnes) in compression and lateral loads up to 18 tons (16 tonnes). The new mezzanine columns were located inline and between the existing column supports, which also encompassed the conveyor processing and truck loading platforms. In all, 74 new pile caps supported by a total of 288 piles were designed to support the new mezzanine.

Overhead clearances varied to a maximum of 35 feet (11 m) with areas adjacent to the existing mezzanine limited to 20 feet (6 m). Horizontal clearances were as low as 18 inches (0.5 m). The new mezzanine foundations were earthen formed by precise slab and platform removal with temporary infill prior to pile installation to maintain minimal to no downtime at the facility. Second and third shifts are the primary working hours, therefore construction commenced during modified daytime hours and did not allow for the impact of more than the areas that could be constructed during that shift. This included any sort of piping, hoses, wires, or cables extending outside of the work zone. These tight working constraints and minimal impact requirements on active operations presented construction challenges that the selected piling system needed to be compatible with while achieving the design working load capacity.

Geotechnical Conditions

USDA maps the underlying site soils within the proposed mezzanine retrofit area as made land, gravelly materials and Tidal Marsh deposits, common along the tidally influenced sections of the Delaware River. The Geotechnical Engineering Report prepared by Dynamic Earth, LLC, (2018) describes the history of site development and subsurface conditions.

Three borings were performed which generally encountered fill up to a depth of 10 feet (3 meters) below the warehouse slab. Below the fill, stratified natural alluvial deposits consisting of sand, silt and clay extend up to a depth of about 65 ft (20 m) with N-values averaging 7 blows/foot (bpf). Below these “upper” alluvial deposits were medium dense to very dense "lower" alluvial deposits consisting of sand, gravel and varying amount of silt with N-values from 18 to 79 bpf, averaging 38 bpf. Beneath the alluvial deposits are natural residual soils extending to boring termination depths of 85 to 90 ft (26 to 27 m) with N-values ranging from 13 to 51 bpf, averaging 32 bpf.

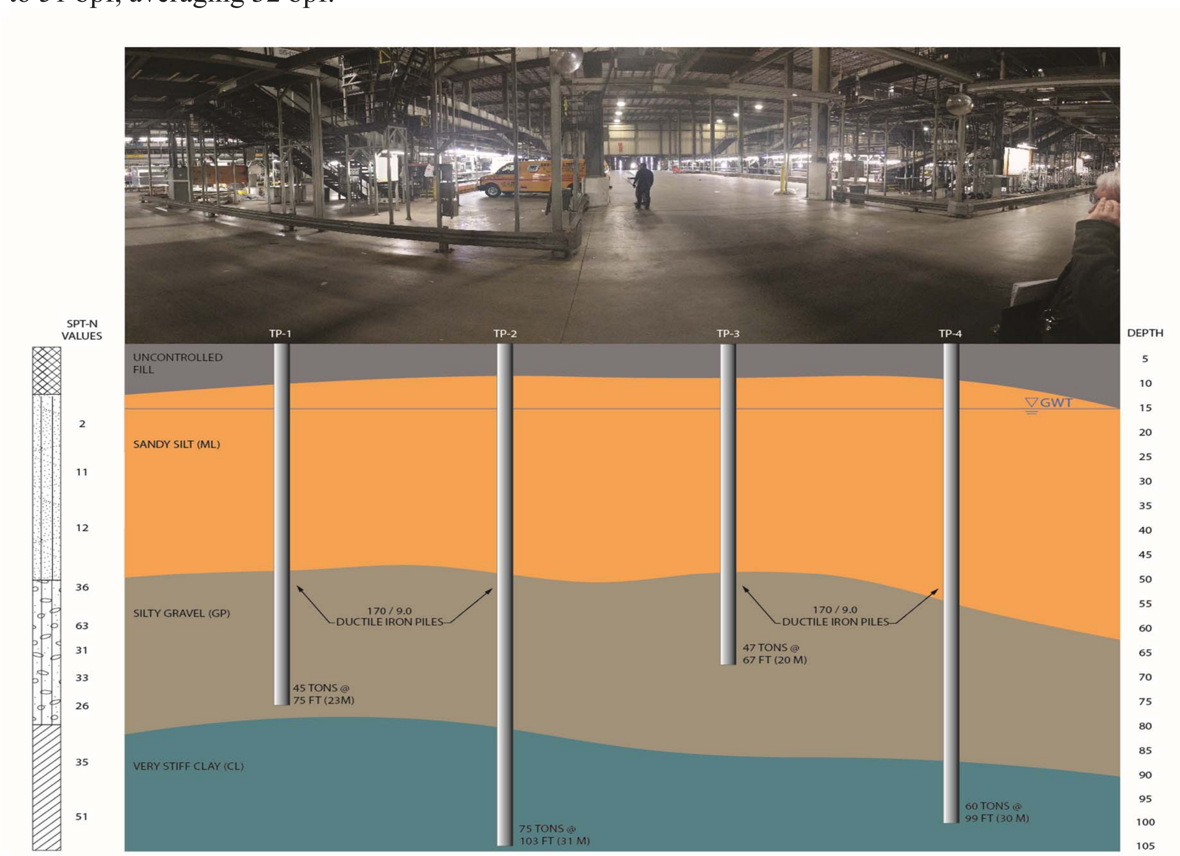

Fig. 5. Test Pile Tip Elevation and Confirmed Allowable Capacity (F.S. =2)

Pile Selection and Design

Based on site logistics, constraints, headroom, spatial limitations, active facility operations, and soil conditions, the project design team selected Series 170/9.0 (6.9 inch or 170 mm OD with 0.35 inch or 9 mm wall thickness) Ductile Iron Piles installed to develop capacity in end-bearing for new column support. End bearing DIPs, which do not require pressure grouting the exterior of the pile, were considered advantageous over grouted friction DIPs, based on site constraints, concerns over grout management within the active facility and on account of previous success driving end bearing DIPs inside the Hartford, CT facility.

Typically installed where rock is within reachable depths to maximize pile structural capacity, little data exists utilizing small-diameter, end-bearing DIPs in looser soils where traditional set rates are not achieved. During the project's Design Development phase, geotechnical design using the Nordlund Method (FHWA 1996) estimated end bearing DIP ultimate capacity of 110 tons (100 tonnes) for 75 ft (23 m) long piles terminating in the lower Alluvial stratum. The design estimated approximately 75% capacity in end bearing and the remaining 25% of capacity in side friction between the pile casing and soil. Post contract award column load modifications required up to 120 tons (109 tonnes) ultimate capacity per pile based on the structural engineers pile lay-out, which consisted of 2-pile to 5-pile caps. It was, therefore, decided to perform a pile load test to 120 tons (109 tonnes) to confirm a 60 ton (54 tonnes) allowable capacity with a factor of safety of 2.0 for a 75 ft. (23 m) long DIP.

The 6.7 inch (170 mm) diameter Series 170/9.0 DIP was filled with 2,000 psi (13.8 MPa) grout giving it a maximum ultimate structural capacity of 166 tons (150 tonnes), meaning the estimated geotechnical capacity would govern the performance since the piles were to bear in soil rather than on rock. A flat end plate was installed at the tip of each pile and cap plate on the top of each pile.

Load Testing and Construction

Design-build contractor, GeoConstructors, Inc., performed test and production pile installation and performed pile load testing. Pile load testing occurred on non-production piles installed outside the southwest entrance to the facility. In all, four load tests were performed on variable length piles, illustrated in Figure 5.

Initially, one static axial load test was performed in accordance with ASTM D1143 to confirm 120 ton (109 tonne) ultimate capacity. The initial test pile (TP-1) was driven 75 feet (23 m) into the lower Alluvial deposits (silty gravel), to a set of 1.9 seconds per inch (0.75 seconds/cm). The target ultimate capacity of 120 tons (109 tonnes) was not achieved and a lesser ultimate capacity of 90 tons (82 tonnes) was confirmed. With the looser conditions and high advancement rate (set) at 75 feet (23 m), the project design team directed the DIP installer to install a second test pile (TP-2) deeper into the very stiff Residual (clay) stratum in an attempt to successfully confirm the 120 ton (109 tonne) ultimate capacity. The second test pile was driven 103 feet (31 m) to a set of 50 seconds per inch (20 seconds/cm). TP-2 was successfully tested to 150 ton (136 tonne) ultimate capacity. While TP-1 results confirmed the ultimate capacity was 25% lower than the target ultimate capacity, TP-2 results were 25% higher.

Not wanting to re-design many of the pile caps that were already being prepped for production work, the project design team decided to have two additional piles installed and tested. TP-3 was driven 67 feet (20 m) into the lower Alluvial deposits to a set of 3.2 seconds per inch (1.3 seconds/cm), and TP-4 was driven 99 feet (30 m) into the very stiff Residual stratum to a set of 7.6 seconds per inch (3 seconds/cm). TP-3 was tested to 94 ton (85 tonne) ultimate capacity, mirroring TP-1 which was also bearing in the lower Alluvial stratum. TP-4, bearing in the Residual stratum similar to TP-2, was tested to 120 ton (109 tonne) ultimate capacity. Figure 6 plots the results of the load tests for each of the test piles. A graph of DIP allowable capacity (incorporating a factor of safety of 2.0) versus set time for these tests is shown in Figure 7.

The load test data was used to optimize pile caps with minimal changes in pile cap size and orientation. Many of the 5-pile caps were reduced to 4-pile caps and 4-pile caps reduced to 3-pile caps by utilizing piles bearing collectively per cap in either the lower Alluvial or the Residual strata to meet the required load demand.

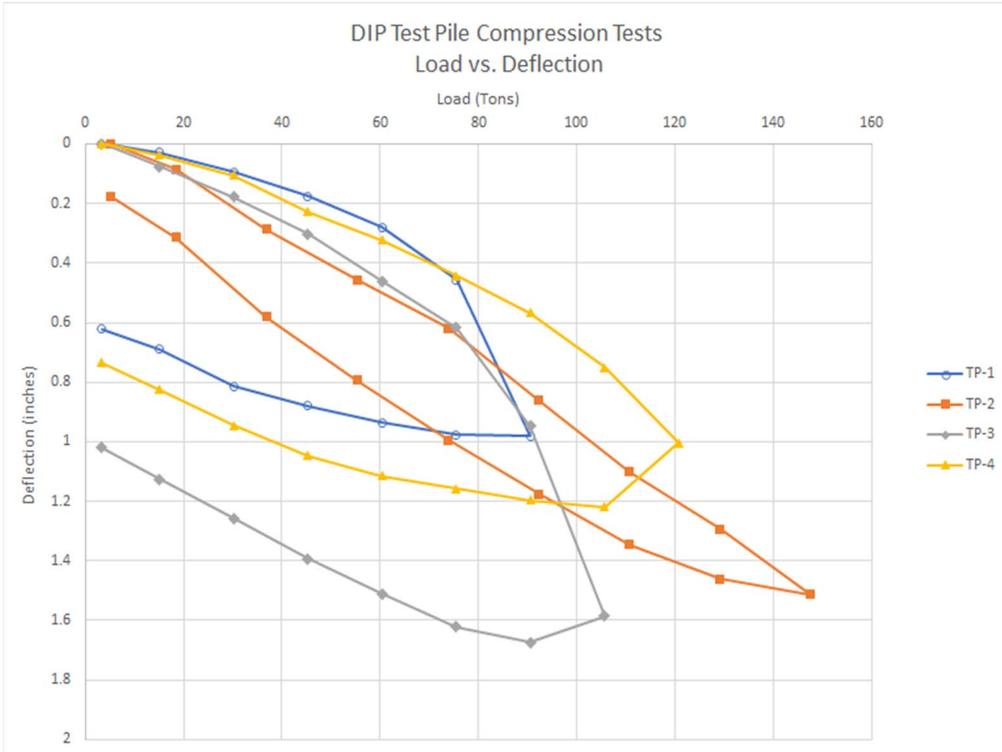

Fig. 6. Results of Compression Load Testing in Philadelphia, PA Facility

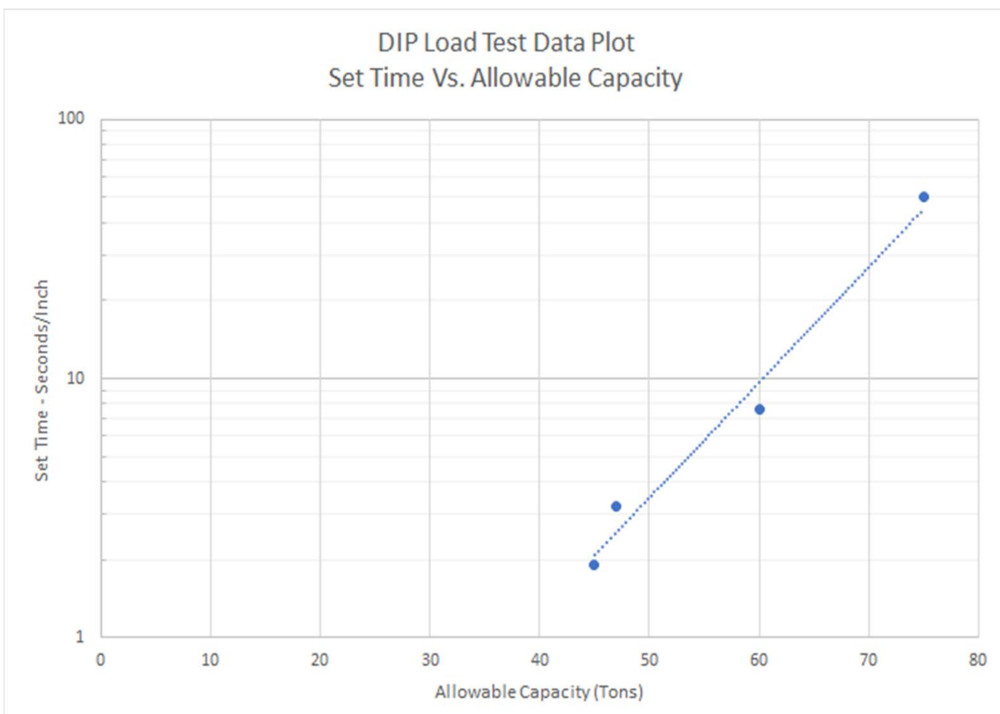

Fig. 7. Test Pile Allowable Capacity vs. Set Time

SUMMARY AND CONCLUSIONS

Ductile Iron Piles are a proven pile solution to support moderate to high loads. Installed with a high frequency hammer mounted on an excavator, they are particularly effective on constrained sites, in areas with low vertical and horizontal clearance and where vibrations are a concern. DIPs can be driven with a closed end plate to develop their capacity in end bearing, typically where rock is reachable to maximize pile structural capacity. They can also be installed by grouting through a conical grouting cap to create a column of grout on the pile exterior and develop load capacity in friction via the grout-soil interface.

Two interior retrofit projects, consisting of mezzanine expansions in shipping facilities in Hartford, CT and Philadelphia, PA, utilized end-bearing DIPs to support new construction in low headroom warehouses. The DIPs were selected over equivalent capacity micropiles based on cost and production and over helical piles by providing greater capacities at reduced cost. In Hartford, CT, DIPs were driven 26 to 40 feet (8 to 12 meters) to rock to develop allowable capacities of 50 tons (45 tonnes) compression, 15 tons (14 tonnes) tension. In Philadelphia, PA, 45 to 75 ton (41 to 68 tonnes) allowable compression capacity DIPs were successfully set in soil, ranging in depths from 67 to 103 feet (20 to 31 meters), with the lower capacities bearing in shallower dense granular soils and the higher capacities in a deeper very stiff clay strata.

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