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Challenges from North to South
Des défis du Nord au Sud

Innovative Deep Foundation Support using Ductile Iron Piles

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ABSTRACT

Working in urban environments presents unique logistical challenges beyond those typically associated with traditional geotechnical analysis and design. This paper describes the construction, design and quality control details including load testing of Ductile Iron Piles - an innovative piling system used in Europe for decades. Project applications and system benefits are also described. The paper presents practical examples of North American projects where the system provided economic, construction and technical advantages.

RÉSUMÉ

Travailler en milieu urbain présente des défis logistiques uniques supérieurs à ceux habituellement associés à l'analyse et à la conception de la géotechnique traditionnelle. Ce document décrit la construction, la conception et les détails de contrôle de la qualité, y compris des tests de chargement de pieux en fonte - un système innovateur utilisé en Europe pendant des décennies. Les applications de projet et les avantages du système sont également décrits. Le document présente aussi des exemples concrets de projets en Amérique du Nord, où le système fournissait des avantages économiques, techniques ainsi qu'en construction.

1 INTRODUCTION

Working in urban environments presents unique logistical challenges beyond those typically associated with traditional geotechnical analysis and design. These challenges often include constrained sites with limited access, vibration concerns for adjacent structures and working from variable grades or in excavations.

Traditional foundation options like driven piles are often considered with high building loads and/or soft soil conditions. However, the high vibration risks associated with driven H-piles or pipe piles often lead project teams to approaches better adapted for the urban challenges, including drilled micropiles, helical anchors, augercast piles or caissons. These solutions provide designers with a range of options, but may be costly and have slow installation rates.

For decades, European engineers and contractors have used specially-manufactured *Ductile Iron Piles* to provide reliable and cost-effective foundation support to help address these issues in urban settings as an alternative to more traditional deep foundation systems. While the system has historically been used only sporadically in a few local North American markets, the economic, technical and construction benefits are now being realized on a more wide-spread basis in the United States and Canada.

2 DUCTILE IRON PILES

2.1 Overview

Pre-fabricated Ductile Iron Piles (DIPs) are small diameter piles (micropiles) manufactured using a centrifugal-casting process to produce the ductile iron pipe sections with high strength and superior impact resistance for drivability. The piles employ a proprietary Plug & Drive bell and spigot connection system that ensures rapid pile connections in the field and easily allows for variable pile lengths without additional equipment or splicing. The connection has been shown to exhibit equal or greater strength than the pile material itself. (Niederwanger, G. and Lehar, H, 2001) Ductile Iron Piles are installed using an excavator-mounted hydraulic hammer fitted with a special drive adapter that advances the pile into the ground using a combination of excavator crowd force and the percussive energy from the hammer. This allows the system to be used in constrained, urban sites with limited clearance where material laydown and access often present practical construction challenges.

Figure 1. Picture of Ductile Iron Pile Installation

2.2 Fabrication and Material Properties

Ductile Iron Piles are comprised of grey cast iron. Ordinary grey or lamellar graphite cast iron is transformed into spheroidal graphite or ductile cast iron by undergoing a sophisticated centrifugal or spin casting process, drastically improving the cast iron's impact resistance, ductility, tensile strength and flexural stiffness. Ductile cast iron is comprised of: 90-95% scrap metal iron, approximately 3.7% carbon, and approximately 2.7% silicon.

The manufacturing process employs a strict quality assurance system that is certified in compliance with standard BS EN ISO 9001. Further, European ONCERT certification (ONR 22567 regulation) and technical approval (ETA-07/0169) provide regular control of the product and prefabrication process.

Table 1 provides details on the engineering properties used for design.

Table 1: Ductile Iron Pile Material Properties

Material Property	MPa [ksi]
Tensile Strength	420 [60.9]
Compressive Strength	900 [130.5]
Yield Strength (0.2% offset)	320 [46.4]
Modulus of Elasticity	170,000 [24,656]

Piles are manufactured in standard 5 meter long modular sections. Pile diameters and thicknesses do vary – allowing for the development of the most efficient design approach. Outside diameters are available in sizes ranging from 98 mm to 170 mm. Thicknesses vary from 7.5 mm to 10.6 mm.

2.3 Construction

Ductile Iron Piles are designed to resist compression, tension and lateral loads. The system is installed to develop resistance through either end-bearing or friction.

End-bearing Ductile Iron Piles are installed by first inserting a flat or pointed driving shoe over the end of the hollow pile. The pile is then driven into the ground using high-frequency impact energy (hydraulic hammer) until the Plug & Drive socket end is nearly at the working grade. The driving resistance (time required to drive each one metre increment) is observed during driving. The spigot end of the second DIP is then inserted into the socket end of the existing pile and the driving process is repeated. This process continues until the pile terminates on refusal or achieves a required driving criteria (typically a rate equal to 25 mm in 50 seconds). If interior grout is being used, the neat cement (cement & water) grout is placed either after the pile achieves the required set or later in the process after multiple piles have been installed. The use of a central threaded reinforcing bar is also used when additional load-carrying capacity is required.

Friction DIPs are installed by first inserting a specially-designed conical end cap over the leading end of the pile. The conical end cap is designed specifically for grouting applications and is larger diameter than the outside pile diameter to facilitate grouting exterior to the pile. The pile is then driven into the ground using high-frequency impact energy (hydraulic hammer) with a specially-designed grout driving shank for the simultaneous pumping of sand-cement grout. The grout fills the interior of the pile and travels out the conical end cap and alongside the DIP. The pressurized exterior grout compacts the adjacent soil and creates the grout/soil interface to provide efficient skin friction along the friction DIP.

The pile is driven and grout is pumped continuously until the Plug & Drive socket end is nearly at the working grade. The driving resistance (time required to drive each meter increment) is observed during driving along with grout volumes. The spigot end of the second DIP is then inserted into the existing pile and the driving / grouting process is repeated. This process continues until the pile extends to a sufficient design depth in the terminating layer to develop a sufficient bond length. The addition of a central threaded reinforcing bar is used to also provide additional tension resistance with the system.

In addition to compression and lateral load resistance, the system can resist tensile loads. This bar can be added to the interior grout for both end bearing or friction DIP installation methods. For larger tensile capacities, the tensile capacity is derived from the resistance afforded by the grouted bond zone in the friction DIP installation method.

Despite being a driven system, the Ductile Iron Pile system results in limited vibration levels as a result of the high frequency impact ramming energy used for installations. This is in comparison with traditional driven piles where high amplitude, low frequency energy creates harmful levels of vibrations. Vibration monitoring performed on numerous DIP sites confirm low vibration magnitudes. Results measured on a site described herein are shown in Figure 2. The figure shows that vibration levels are well below the damage criteria even within less than one metre from a receptor.

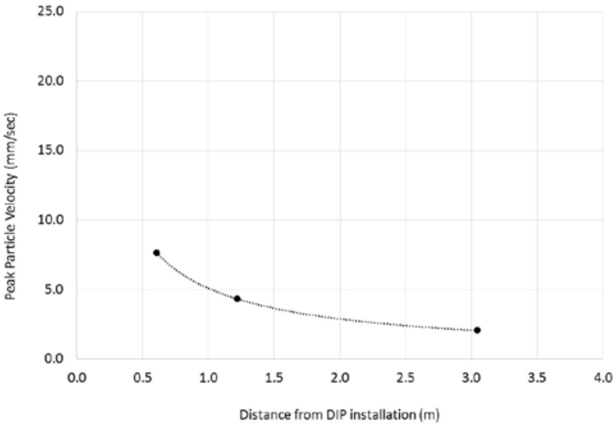

Figure 2. Ground Vibration Monitoring Adjacent to Installations

2.4 Design Approach

Design of the Ductile Iron Piles follows aspects of conventional analyses for deep foundations including driven piles and micropiles. Both structural capacity of the pile components and geotechnical capacity in either end-bearing or friction are evaluated. Depending on the local building codes or project requirements, designs are performed in accordance with Allowable Stress Design (ASD) or Limit States Design (LSD). The design approach based on Limit States Design with a focus on the Ultimate Limit State (ULS), typical for pile design, is presented herein.

2.4.1 Structural Capacity

The applied vertical compression load is resisted by the structural strength of the composite ductile iron pile including the ductile iron pile material, grout and central reinforcing bar, if applicable. Each of the components are considered separately based on the codified values for resistance factors. Therefore, the ULS structural capacity for design is shown in Equation 1:

$$\phi R_n = \phi_s f_{y\text{-}dip} A_{dip} + \phi_c f'_c A_g + \phi_{bar} f_{y\text{-}bar} A_{bar} \qquad [1]$$

where ϕ_s, ϕ_c and ϕ_{bar} are the structural resistance factors for the Ductile Iron Pile material, grout and reinforcing bar, if used, respectively. The remaining terms describe the yield strength of the specific material as well as cross-sectional area corresponding to each of the materials. Reductions in certain material yield strengths may be required to account for strain compatibility between the different components. Structural resistance factors are contained in standards for Canadian Highway Bridge Design Code (CHBDC) published by the Canadian Standards Association (2006). Values for design are ϕ_s = 0.90, ϕ_c = 0.75 and ϕ_{bar} = 0.90 for high-strength bars.

2.4.2 Geotechnical Capacity

The geotechnical capacity depends on the soil conditions and the specific design approach to develop capacity selected for the site – namely friction through a grouted bond zone or end-bearing to a competent bearing stratum.

For frictional elements with capacities derived from a grouted bond zone, the nominal capacity is a function of the perimeter shearing surface and the ultimate soil-grout bond strength as shown in Equation 2.

$$\phi R_u = \phi(\pi D L_b \alpha_{bond}) \qquad [2]$$

where D is the diameter of the exterior grouted zone as developed by the oversized conical grout cap, L_b is the length of the bond zone and α_{bond} is the ultimate bond strength between the grouted pile and the adjacent soil. The displacement installation process of the Ductile Iron Pile enhances the bond strength, particularly in granular soils, as a result of densification during driving. Ultimate bond strengths typically vary from 100 to 300 kPa. Resistance factors (ϕ) from the CHBDC (2006) and Canadian Foundation Engineering Manual (CFEM) (2006) for compression and tension applications are 0.4 and 0.3. Performance of site-specific static load testing allows for the increase in these values to 0.6 and 0.4, respectively.

For end-bearing applications, the pile is driven to refusal or "set" on or into competent material such as bedrock or very dense soil. Decades of experience in Europe documented through load testing shows that acceptable geotechnical end-bearing resistance is achieved when an equivalent drive rate of less than 25 mm of downward displacement in 50 seconds is achieved.

3 RETAIL FACILITY, PITTSFIELD, MA, USA

Designers on a retail facility in Pittsfield, Massachusetts (USA) were challenged with loose soil conditions and construction immediately adjacent to an abutting retail facility. Plans included using *Geopier*® ground improvement for the majority of the building, but required alternate foundation support measures immediately adjacent to the existing building. The following sections describe the project details, soils and solution.

3.1 Project Description

Construction involved redevelopment of a single-story retail space immediately adjacent to an existing single-story retail building. Foundation design loads were 414 to 787 kN and wall loads ranged from 36 kN/m to 219 kN/m.

3.2 Soil Conditions

Soil conditions consisted of up to 1.8 meters of loose to medium dense silty sand fill and loose native silty sand to depths of about 3 meters. One boring encountered a 0.6 meter thick layer of soft peat. Very loose to medium dense silty sand with SPT N-values generally ranging from 2 to 6 blows per 0.3 m were then encountered to the maximum exploration depth of 8.8 metres. Groundwater was encountered at 2.4 to 3 metres below grade. Figure 3 illustrates the soil profile at the site.

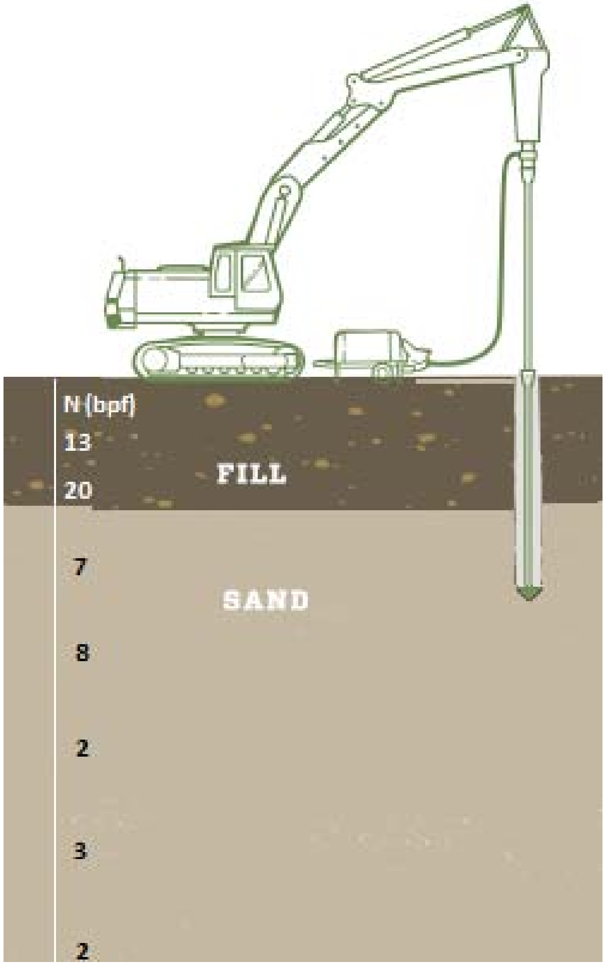

Figure 3. Illustration of Soil Profile and Friction DIP Installation

3.3 Ductile Iron Pile Design Approach

The loose fill and native sand conditions were ideal for a *Geopier* ground improvement solution that was initially proposed to support shallow foundations and control settlement. However, the proximity of the new building immediately adjacent to the existing structure presented issues with access, excessive vibrations and the potential for settlement of the existing structure. Due to access conditions, the project team also considered helical anchors designed in the loose sand with a capacity of 120 kN (ASD). Working with the owner and structural engineer, a Ductile Iron Pile design was proposed using a working capacity of 180 kN (ASD) that reduced the number of piles by 25%. Further, the development of a bond zone in the loose conditions provided greater confidence in achieving capacity as opposed to developing a required torque criteria that is often employed with helical anchors. Both options were competitively bid and the Ductile Iron Piles were selected based on cost and schedule.

3.4 Installation Details

A total of 39 Ductile Iron Piles were installed along the building line adjacent to the existing building. The Series 118/7.5 piles (118 mm outer diameter with 7.5 mm wall thickness) were designed as friction piles using a 220 mm diameter conical grout cap to build a bond zone in the very loose to loose sand. Production pile installation was completed in 3 working days – working adjacent to the existing building. Vibration monitoring performed during installation recorded peak particle velocities of of less than 5 mm/second at immediate distances from installations.

Figure 4. Picture of Installation Adjacent to Building

3.5 Load Testing

Load testing performed on a sacrificial pile extending to a depth of about 9.8 metres in the loose conditions showed movement of less than 4 mm at 355 kN (200%). The test was completed and then cycled up to a load of 534 kN

(300%) and recorded deflections of only 8 mm - a superior response under loading for the friction pile in loose conditions. Permanent (non-recoverable) deflection after loading to 300% was less than 5 mm. The load test was instrumented with telltales at the top of the bond zone and at the bottom of the pile.

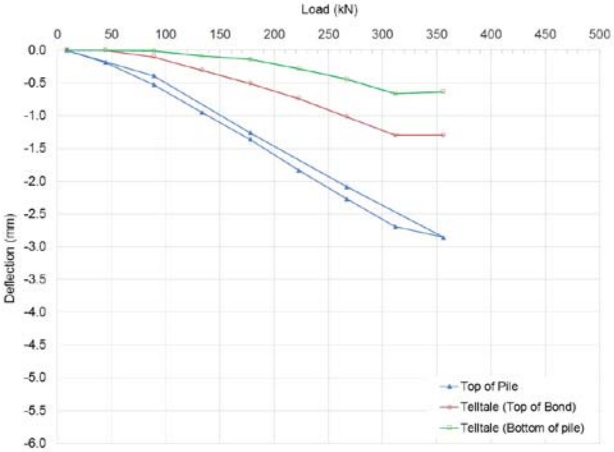

Figure 5. Plot of Load Test Results – Retail Facility

4 5-STORY RESIDENTIAL, BOSTON, MA, USA

Development of residential buildings in downtown Boston, Massachusetts (USA) often requires working on constrained sites where transportation of material to sites and working around the site represents significant logistical challenges. Further, the historic nature of surrounding structures represents a sensitive building environment. The demolition of an existing single-story retail facility and redevelopment of a 5-storey residential building incorporated all of these challenges. In addition to logistic challenges, the project featured problematic soil conditions and sizable building loads with which to contend.

4.1 Project Description

The project involved revitalization of a site in the Fenway District of Boston only three blocks from historic Fenway Park. Construction was planned for a new 5-storey apartment building located immediately surrounded by existing 3- and 4-storey residences.

4.2 Soil Conditions

Soil conditions consisted of up to 2.7 metres of loose to medium dense “urban” sand fill with various amounts of debris consisting of bricks, concrete and other construction materials. The fill was underlain by soft peat and organic clay/silt to 8.5 metres followed by very soft to medium stiff clay extending to a depth of more than 53 meters where bedrock was encountered. SPT N-values in the clay were 3 to 5 blows per 0.3 metres in the upper crust but soon dropped to WOH (weight of hammer) and WOR (weight of rod) until bedrock was encountered.

4.3 Ductile Iron Pile Design Approach

With column loads approaching 2,700 kN, deep foundation support was required at the fill/organic/soft soil site. The project team initially considered driven steel H-piles with 900 kN capacities (ASD). High vibrations coupled with the challenges of transporting long pile sections and the added cost/time for pile splicing led the design team towards a more practical solution for the urban site. Ductile Iron Piles were selected as a more cost-effective and faster alternative to the H-piles and traditional drilled micropiles. The Ductile Iron Pile system provided a 2:1 replacement of the H-piles with a working capacity of 450 kN (ASD).

4.4 Load Testing

Prior to the start of production operations, a Ductile Iron Pile (Series 118/7.5) test pile was installed to terminate on rock at a depth of 53.7 metres. The test pile was loaded using a gravity reaction load test setup, shown in Figure 6, because of the costs associated with deep rock anchors for tension resistance.

Load testing of the end-bearing Ductile Iron Piles showed a deflection of 32 mm at the design load (100%) of 450 kN. The load test was performed to 200% of the design load (900 kN). The response was generally elastic with a deflection at the maximum test load approaching 80 mm. The deflection of the 53.7 metre long test pile met expectations for compression of a long micropile. The results met the project requirements for load-carrying capacity and deflection while also delivering foundation economy.

Figure 6. Picture of Gravity Load Test Setup

For selected piles subject to minor tension loads (less than 20 kN), a 3 meter long #8 (25 mm) threaded reinforcing bar was inserted into the pile to resist minor tensile loads (less than 25 kN). Results of a tension test performed on the uplift pile are shown in Figure 8.

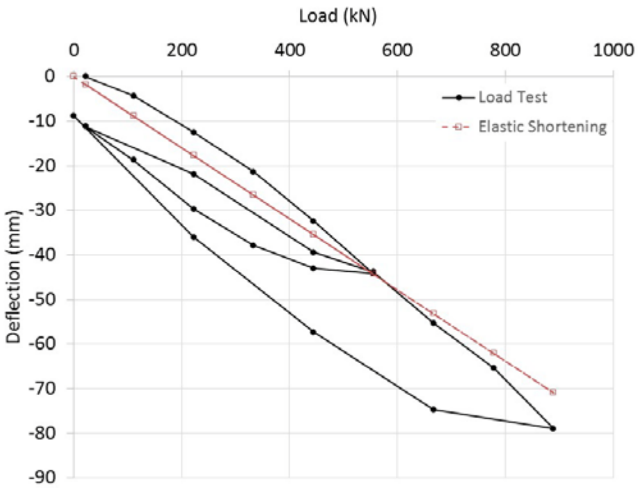

Figure 7. Plot of Compression Load Test Results – Residential Building

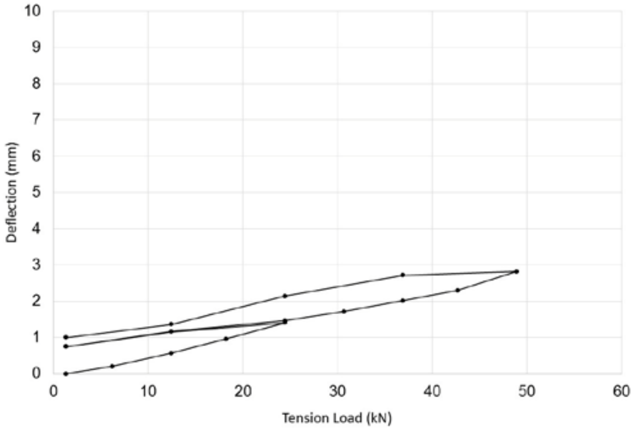

Figure 8. Plot of Tension Load Test Results – Residential Building

4.5 Installation Details

Production pile installation was performed at rates of 300 meters per day or more. Figure 1 shows the installation at the site. A total of 87 piles were installed in just over 2 weeks. As shown in Figure 2, vibration monitoring performed during installation recorded peak particle velocities of only 7.5 mm/second on the ground 0.6 meters away from installations. The vibrations were reduced to 4 mm/second a distance of 1.2 metres away. Measurements on the actual existing building foundations were less than 4 mm/second while installations were within 0.6 meters from the building.

5 CONCLUSIONS

This paper describes the application of a European piling system developing a niche on urban piling projects in North America. The design details are based on codified standard approaches for traditional piles or micropiles. Performance including load testing on two project sites described herein illustrate the features, benefits and successful installation and test results of the Ductile Iron Pile system.

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