Evaluation of Alternative Abutment Piling for Low-Volume Road Bridges

Final Report
September 2019

BRIDGE ENGINEERING CENTER

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Highway Research Board
(IHRB Project TR-718)
Iowa Department of Transportation
(InTrans Project 17-600)

About BEC

The mission of the Bridge Engineering Center (BEC) is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges.

About InTrans

The mission of the Institute for Transportation (InTrans) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, reliability, and sustainability while improving the learning environment of students, faculty, and staff in transportation-related fields.

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
IHRB Project TR-718		

4. Title	5. Report Date
Evaluation of Alternative Abutment Piling for Low-Volume Road Bridges	September 2019
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Behrouz Shafei (orcid.org/0000-0001-5677-6324), Brent Phares (orcid.org/0000-0001-5894-4774), Bora Cetin (orcid.org/0000-0003-0415-7139), and Kofi Oppong (orcid.org/0000-0003-1506-1474)	InTrans Project 17-600
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	**11. Contract or Grant No.**
12. Sponsoring Organization Name and Address	**13. Type of Report and Period Covered**
Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way Ames, Iowa 50010	Draft Final Report
	14. Sponsoring Agency Code
	IHRB Project TR-718

15. Supplementary Notes

Visit www.intrans.iastate.edu for color pdfs of this and other research reports.

16. Abstract

Alternatives to driving H-piles are being utilized by a number of states and private industry. Helical/screw pilings are used, and the load bearings are listed as 5 to 50 tons per piling. Micropiles are also used with bearing capacities of 4 to 101+ tons typical per piling. Either of these two options can offer a cost-effective and/or quick construction alternative to driving H-piles.

In addition to helical pilings and micropiles, other regularly used alternative piling systems include grouted helical pilings, ductile iron pilings, drilled displacement pilings, and geopier foundations. A study of their cost-effectiveness and application was the first/main objective of this project.

There is also a need to utilize safe, cost-effective pile driving systems to reconstruct or repair bridges, especially those for low-volume roads. Vibratory pile driving is a method to accomplish this goal.

There is limited data available for tests on the strength of alternative piles or vibratory-driven piles. The second objective of this project was to study the strength and bearing resistance of alternative piles as well as pilings driven with vibratory equipment. This project documented design guidance, construction methods, and acceptance criteria for using alternative abutment piling systems for local roads.

This study included a survey of county engineers in Iowa and of industry engineers in many states.

7. Key Words	18. Distribution Statement
alternative abutment piling—bridge pile construction—drilled displacement piles—ductile iron piles—geopier foundations—helical piles—micropiles	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	64	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

EVALUATION OF ALTERNATIVE ABUTMENT PILING FOR LOW-VOLUME ROAD BRIDGES

Draft Final Report
September 2019

Principal Investigator
Behrouz Shafei, Structural Engineer
Bridge Engineering Center, Iowa State University

Co-Principal Investigators
Bora Cetin, Assistant Professor
Civil, Construction, and Environmental Engineering, Iowa State University

Brent Phares, Research Associate Professor
Bridge Engineering Center, Iowa State University

Research Assistant
Kofi Oppong

Authors
Behrouz Shafei, Brent Phares, Bora Cetin, and Kofi Oppong

Sponsored by
Iowa Highway Research Board
and Iowa Department of Transportation
(IHRB Project TR-718)

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Second Revised Research Management Agreement
with the Institute for Transportation
(InTrans Project 17-600)

A report from
Bridge Engineering Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
www.instrans.iastate.edu

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors would like to thank the Iowa Department of Transportation (DOT) and Iowa Highway Research Board (IHRB) for sponsoring this project. The authors would also like to thank the technical advisory committee (TAC) for their time and effort working on this project.

EXECUTIVE SUMMARY

Currently used alternative abutment piling systems were identified through a literature review and discussed in this study. These alternative piling systems included micropiles, helical screw piles, grouted helical piles, ductile iron piles, drilled displacement piles, and geopier foundations. The discussion on these systems in this report includes their description, typical bearing resistances, advantages, limitations, and a local road bridge construction project in which each has been used.

Design guidance, construction methods, and acceptance criteria for helical piles and vibratory-driven piles were included in this study. These involve using several methods to predict the drivability and bearing resistance of a pile to be installed, and, then, using other methods to confirm the bearing resistance of the pile after installation.

The popularity of the alternative systems and vibratory pile driving was investigated through a survey that was sent to two groups of respondents. The first group consisted of county engineers in Iowa, and the second group consisted of selected industry engineers in many states. Among the 99 counties contacted in Iowa, 73 responded. Among the 40 selected companies contacted, 24 responded. Follow-up phone calls were made and email messages were sent to some of the companies.

The survey showed that most of the counties in Iowa have not endeavored to use alternative abutment piling systems, even though staff might be aware of the systems. The survey also showed that all of the alternative abutment piling systems included in this study, as well as vibratory pile driving, have been used successfully on many projects throughout the US and have the potential to be considered for low-volume roads in Iowa.

CHAPTER 1:INTRODUCTION

Bridge abutment foundations are built to provide structural integrity to the abutment and the rest of the bridge structure. Without these foundations, many abutments would have insufficient bearing resistance and would more than likely fail under normal service loads. A proper abutment foundation can transfer the required loads to deeper and more competent soils.

Micropiles, helical pilings, and other alternative abutment piling systems currently used for construction were explored for this study. Alternative abutment piling systems are piling systems that were assumed to have been developed in recent years and are frequently used in bridge abutment construction. Alternative abutment piling systems also have some advantages over conventional abutment piling systems, such as H-piles.

Some alternative systems have better bearing resistance, are easier and quicker to install, or are more cost-effective solutions for projects with difficult soils. In some rare cases, an alternative system could be the only feasible solution for a project.

As a result of the potential advantages of alternative abutment piling systems, this study compiled frequently used alternative abutment piling systems that can be used by the counties in Iowa. The alternatives are discussed and information on their strengths, difficulties, and typical bearing resistance are provided.

A detailed review of the state of the practice and a complementary survey were conducted. The alternative piling systems identified and documented were micropiles, helical piles, grouted helical piles, ductile iron piles, drilled displacement piles, and geopier foundations.

The survey following the literature review was designed to obtain the perspective of engineers, within and outside the state of Iowa, on alternative piling systems. The first survey was sent to all 99 Iowa counties. Among the 99 counties contacted, 73 responded. The second survey was sent to 40 selected piling construction or drilling companies, most of which are outside the state. Among the 40 companies contacted, 24 responded. Follow-up phone calls were made and email messages were sent to some of the companies.

Several pile installation methods were considered, including the use of an impact hammer, vibratory hammer, or drilling equipment. In addition to identifying alternative abutment piling systems, methods of estimating the drivability and bearing capacity of vibratory-driven pilings were investigated.

Vibratory pile driving is a fast and cost-effective method of installing piles, but often comes with a drawback. This drawback is the fact that the bearing capacity of a vibratory-driven pile is usually only a fraction of the bearing capacity of an impact-driven or drilled pile. Vibratory pile driving is usually more suited to sandy and gravelly soils than to clayey soils.

There are several methods of estimating and confirming the bearing capacity of vibratory-driven piles, and these methods range from empirical equations to physical testing. The methods provide varying bearing capacity values. The current methods of determining the drivability and bearing capacity of vibratory-driven pilings were identified and discussed for the benefit of county engineers in Iowa who wish to find more accurate bearing capacity estimates for their yet-to-be-installed and installed vibratory-driven pilings.

CHAPTER 2: STATE OF THE PRACTICE

A review of the state of the practice was conducted to identify the advantages, limitations, ultimate bearing resistance, and project cost of various alternative piling systems commonly used for bridge abutment construction. A brief discussion is presented on conventional piling systems followed by discussions on alternative piling systems.

For this study, conventional piling systems are systems that have been used for several decades. The alternative systems are the systems that have been developed in recent years with the promise of wide application.

2.1 Conventional Piling Systems

Piling systems are usually classified based on the method of construction. Conventional pilings include driven piles, drilled shafts, caissons, mandrel-driven thin shells filled with concrete, auger-cast piles, pressure-injected footings, and anchors (Coduto 2001).

- Driven piles are constructed by prefabricating slender members and driving them into the ground using an impact hammer or a vibratory equipment. The most common driven piles are timber piles, steel H-piles, and concrete piles.

- Drilled shafts are constructed by drilling a cylindrical hole into the ground, inserting reinforcing steel, and filling the hole with concrete. Drilled shafts are sometimes referred to as caissons. However, caissons are more known to be constructed by driving a relatively thick steel casing into the ground, drilling out the soil inside the steel casing, and then filling the hole with concrete. Sometimes steel reinforcement is placed inside the steel casing before it is filled with concrete, and then the steel casing is removed.

- Mandrel-driven thin shells filled with concrete are constructed by driving thin corrugated steel shells or casings into the ground using a mandrel, and then filling the shells with concrete. The mandrel is like a plug that can be inserted and removed from the hollow steel casing.

- Auger-cast piles are constructed by drilling a slender cylindrical hole into the ground using a hollow-stem auger, and then pumping grout into the hole through the auger while it is slowly retracted.

- Pressure-injected footings are constructed by using cast-in-place concrete that is rammed into the soil using a drop hammer.

- Anchors include several types of deep foundations that are specifically designed to resist uplift loads.

A statewide study conducted in Iowa found that the most common foundation types for low-volume road bridges in Iowa were H-piles, timber piles, and reinforced concrete piles (Klaiber et al. 2004a). Low-volume roads are roads with an annual daily traffic (ADT) of about 100 or fewer vehicles per day (VPD) (AASHTO 2016). In the same study, the most commonly used piling systems for highway bridges were steel H-piles, drilled shafts, and concrete-driven piles.

Another similar study was conducted nationwide by the National Cooperative Highway Research Program (NCHRP) on deep foundations and the study found that the two most common foundation types used for off-system bridges were steel H-piles and timber piles (Klaiber et al. 2004b). The study also showed that spread footings and concrete piles were used but less frequently for off-system bridges. An off-system bridge is any bridge or road that is not on the National Highway System from the standpoint of federal aid.

From these statewide and nationwide studies, the most commonly used foundation systems for both highway and off-system road bridges include spread footings, timber piles, steel H-piles, drilled shafts, and concrete-driven piles. All of these piling systems fall under the category of conventional systems.

2.2 Alternative Piling Systems

Alternative piling systems have been developed, mainly because, in some situations, they offer some advantages over conventional piling systems. This is not to imply that conventional piling systems can never be the better option to use for a specific project. However, problem solving becomes easier when there are more feasible solutions to choose from. Following is information on these commonly used alternative abutment piling systems for bridge construction:

- Micropiles
- Helical piles
- Grouted helical piles
- Ductile iron piles
- Drilled displacement piles
- Geopier foundations

2.2.1 Micropiles

Description: A micropile is a deep foundation system consisting of a small diameter (12 in. or less) structural element that is constructed by boring a hole in the soil and filling it with steel reinforcement and either gravity-flow or pressurized cementitious grout (Klaiber et al. 2004a). The steel reinforcement typically consists of either steel bars and/or a tubular drill casing left in place for the upper length of the micropile shaft. A practical total length limit for most projects may be on the order of 100 ft.

Depending on the soil conditions and pile size, a micropile can have a bearing capacity as high as 101+ tons (Rabeler et al. 2000). A bearing capacity in excess of 45 tons is typical from load testing (Sabatini 2005). These relatively large capacities are developed from the frictional forces between the grout and the surrounding soil. The bearing capacity of a micropile can be increased by embedding the pile into dense soil or rock (see Table 1) or by using enlarged bases.

Table 1. Range of micropile design capacities

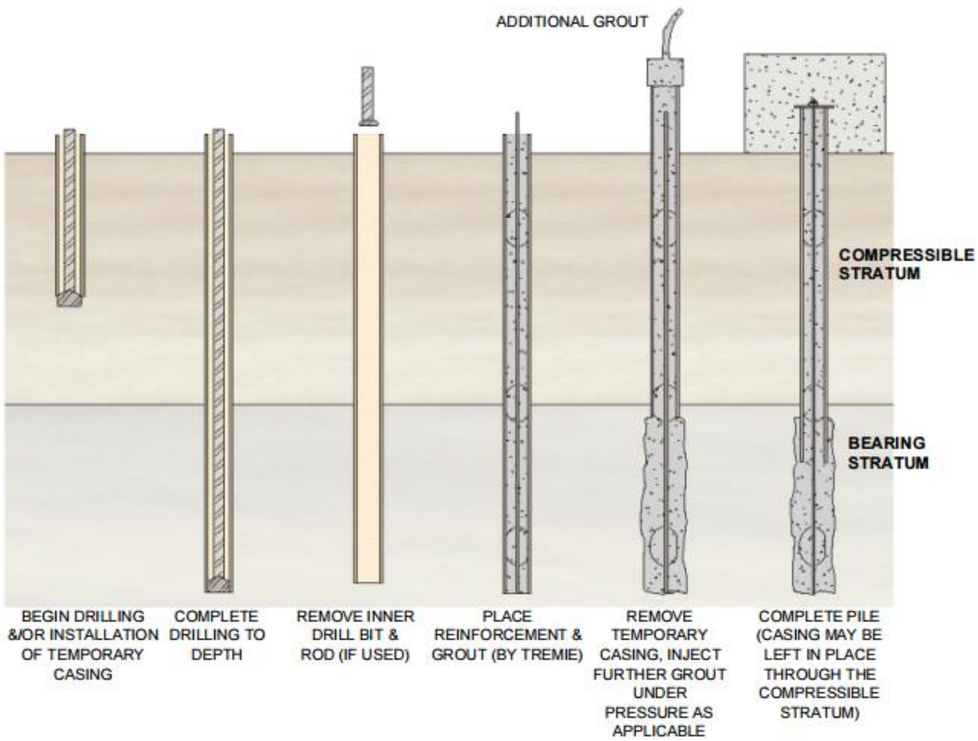
Bearing Stratum	Typical Design Capacities, ton
Stiff to hard clay	4 to 10
Medium to dense sand	10 to 34
Very dense sand/till	20 to 79
Weathered to competent rock	51 to 101+

Source: Rabeler et al. 2000

Buckling of micropiles needs to be considered because of their slenderness. The buckling strength of micropiles can be enhanced by using a steel casing or by increasing the thickness. Table 1 shows typical micropile design capacities for various bearing stratums and has been suggested to offer reasonable preliminary design values when micropiles are installed within the bearing stratum (Rabeler et al. 2000).

The Montana Department of Transportation (DOT) conducted a survey on the use of micropiles in nine neighboring western state transportation agencies: Idaho, Nebraska, North Dakota, Oregon, South Dakota, Utah, Washington, Wyoming, and the Federal Highway Administration (FHWA) Western Federal Lands Division (Perkins 2015). The results concluded that the use of micropiles in each territory depended on the availability of qualified contractors.

For the agencies that responded, the greatest use of micropiles was for new bridge foundations, followed by projects involving retrofitting existing bridge foundations. Responses indicated that micropiles have been used exclusively on projects for which other conventional deep foundation systems would not work. The obtained responses supported the notion that micropiles are particularly suited for difficult ground conditions (presence of cobbles and boulders, intermediate geomaterials) and sites with restricted work areas having limited space and/or remote access. The general construction sequence for micropiles using a drill casing is shown in Figure 1.



Sabatini et al. 2005

Figure 1. Micropile construction sequence

Advantages: The equipment used to install micropiles is relatively small and can be mobilized in low headroom conditions. Micropiles usually require about 10 to 12 ft of headroom; however, micropiles have been successfully installed with 6 ft headroom as well (Aktan and Attanayake 2015).

Micropiles can be installed in difficult ground conditions; that is, in the presence of cobbles, boulders, remnants of old foundations, and in intermediate geomaterials. Installation of micropiles causes minimal noise and vibration. Micropiles can be used for underpinning existing bridge abutments. Micropiles can be used where all other piling systems cannot be used. Micropiles can be used if the surface soil is subject to scour.

Limitations: The small diameters of micropiles limit their lateral load and flexural capacities. The lateral load and flexural capacities can, however, be increased by the use of battered micropiles or by replacing the bar reinforcement with structural steel tubing on the upper length of the micropile shaft (Sabatini et al. 2005).

Micropiles require special techniques for installation, including various drilling techniques, reinforcement types, grout mixtures, and grout placement procedures. If a micropile is not properly designed for the site conditions, or if the contractor does not have sufficient expertise with installing micropiles, the structural and bearing capacity of the micropile can be compromised (Sabatini et al. 2005). Micropiles are sometimes considered to be the most expensive alternative because of the amount of expertise needed for construction.

Case Study: Bridge No. B-0158 on Ensor Road over Third Mine Branch near Stablersville in northern Baltimore County, Maryland, was replaced in 2016 at a cost of $1,065,282 (Baltimore 2013). The 90+ year old two-lane, two-span concrete bridge was completely removed and replaced with a two-lane, single-span prestressed concrete slab bridge. The project required the drilling of 8 in. micropiles, cast-in-place footings, abutments, and wingwalls, and included hot-mix asphalt approach roadways and guardrails. Nineteen micropiles were installed at each abutment.

The original bridge was considered to be structurally deficient with a sufficiency rating of 42% and had a restricted load posting. The new bridge is 32 ft long with a 22 ft clear roadway (BRTB 2016). The new bridge has an ADT of 75. The micropiles were installed 38 ft into the ground, which included embedding the micropiles into 7 ft of solid rock. The pile installation was conducted using RevDrill tools. Each micropile was installed on a 3/1 batter and load tested to 136 tons. Figures 2 and 3 show the installation of the micropiles at one of the bridge abutments.

Figure 2. Setup for installing micropiles on Ensor Road bridge over Third Mine Branch

Figure 3. Micropiles being installed on Ensor Road bridge over Third Mine Branch

2.2.2 Helical Piles

Description: Helical piles consist of a series of helix-shaped, circular plates that are attached to a slender steel shaft. The steel shaft could be circular or rectangular. The helices, which are typically fixed to a lead shaft section of up to 10 ft in length, can all have a common diameter, or the helices may increase in diameter with distance above the tip of the pile. The piles are installed by rotating the shaft using a hydraulic torque unit. The helices screw downward into the soil, thereby pulling the shaft into the ground.

Clemence and Lutenegger (2014) conducted a state of the practice survey for helical piles in Canada. The study showed that helical piles were used most often in fill, soft clays, and hard/stiff clays. The study showed that helical piles were most often used for foundations of new construction and for repair of existing foundations.

The survey indicated that the majority of respondents (75%) used either the individual plate method or the cylindrical shear method to calculate bearing capacity, and 64% use torque correlation. This shows that some of the correspondents use more than one method when performing estimations on bearing resistance. For design guidance, the three bearing resistance estimation methods for helical screw piles can be found in the following references: Foundation Supportworks 2014, Hoyt and Clemence 1989, and Perko 2009.

A study conducted on the load capacity of helical piles found that helical piles can develop significant resistance to axial compressive loads up to 281 tons and tensile loads up to 225 tons (Sakr 2010). The helical piles investigated by Sakr (2010) and Sakr (2011) are larger than the average helical piles used for construction (see Figure 4).

Sakr 2010

Figure 4. Large helical pile installation

Another study conducted on helical piles showed that helical piles can work well in cohesive soil (Elkasabgy and El Naggar 2014).

The Helical Anchors *Engineering Design Manual* (2014) can be looked at for information on design guidance, construction methods, and acceptance criteria. It is a short, easy-to-read, and straight-to-the-point manual that provides essential instructions for helical pile design and installation.

The design manual provides two methods for determining the bearing resistance of helical piles. The first method involves predicting bearing capacity using the general equation for deep foundation piling. The second method involves predicting bearing capacity using a torque-versus-bearing-resistance correlation.

The design manual recommends that the bearing resistance be verified for helical piles on critical projects by employing load testing. Lastly, the design manual has examples of helical pile design in both cohesive and non-cohesive soils.

Advantages: Helical piles provide cost-effective solutions to supporting bridge abutments over poor soil conditions. They can be installed in limited access areas like existing buildings or sensitive environments. Installation requires smaller equipment compared to driven H-piles. Helical piles can be installed much faster than other deep foundation systems. Helical piles require no curing time. They are ideal for projects where noise and vibrations are construction considerations, especially for sites located within heavily populated areas. Helical piles produce little to no vibration during installation. This decreases possible damage to existing structures from soil movement. Installation creates no deep open-hole excavation that needs inspection. There are very little to no spoils to remove or remediate. Figures 4 and 5 show helical piles.

CHANCE 2012, © 2012 Hubbell Incorporated

Figure 5. Installation of a helical pile

Limitations: Unlike micropiles, helical piles might be difficult to install in soils with cobbles, boulders, or remnants of old foundations.

Case Study: Due to the construction of a new "Light Rail System" by New Jersey (NJ) Transit, Interstate Storage & Pipeline had to create an alternate route to their pump house in Riverside, New Jersey (CHANCE 2007). A pre-fabricated bridge was designed and constructed on this alternate route. Due to underground gas lines, overhead power lines, fiber optics, and NJ Transit restrictions, helical screw piles were used for the foundation design. A traditional footing was unable to be utilized due to the restrictions of the site, including the steep slope of the embankments.

The bridge was prefabricated in two 8 ft wide sections, each measuring 39 ft long. The bridge was designed for HS-25 loading due to the type of vehicles that would be using the bridge. Each abutment foundation was constructed using a steel cap beam supported by five 3.5 in. diameter helical piles designed and installed for a minimum of 25 tons each. The reinforced concrete deck was 7 in. thick.

The entire construction portion of the project was completed within 60 days for a total cost of $270,000 for the entire project, including all engineering fees. Figures 6 and 7 show the bridge built using helical screw piles.

CHANCE 2007

Figure 6. Construction of a one-lane bridge built with helical piles as the abutment foundation

CHANCE 2007

Figure 7. The completed one-lane bridge built with helical piles as the abutment foundation

2.2.3 Grouted Helical Piles

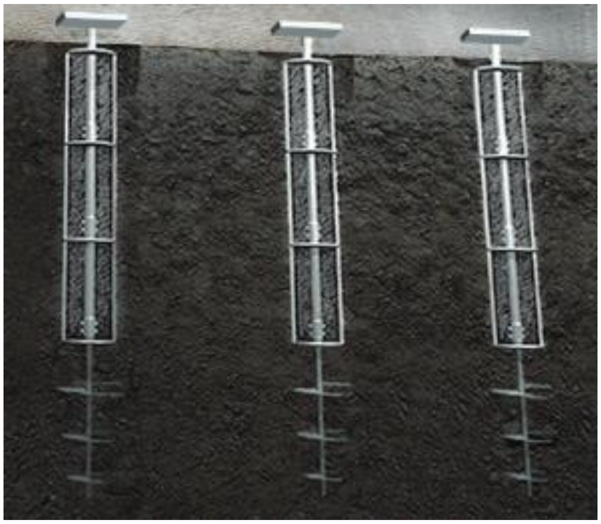
Description: Grouted helical piles are helical piles that have in situ grouting around their shafts. The grouting is meant to increase the bearing resistance and buckling resistance. To install grouted helical piles, a hole is first dug into the ground about 1.0 ft to 2.0 ft deep. The hole is usually a little wider than the diameter of the helices on the screw pile. The hole could be circular or rectangular. Next, the helical pile is screwed into the ground until the last screw just enters the ground. Then, a metal plate with two paddles underneath the plate (also called a displacement plate) is installed on the shaft of the screw pile, so that, when installation continues and the metal plate and paddles are pulled down, the earth is forced away from the shaft creating a void. The hole is then filled with grout so that, as the piles are being screwed into the ground, the void created by the displacement plate is filled with the grout. Installation continues until the pile is embedded in a competent stratum.

Grouted helical piles are also known as helical pulldown micropiles, because of the column of grout that is “pulled down” around the anchor shaft into the voids created by the displacement plate during installation.

Advantages: Grouted helical piles can be used where soft soil overlies a more competent stratum. The grouted column could significantly increase the shaft’s resistance to buckling. The grout provides additional corrosion protection to the anchor shaft in aggressive soils. A polyvinyl chloride (PVC) sleeve can be incorporated around the pile to add even more corrosion protection and also to mitigate the effects of downdrag. The grouted shaft also increases the stiffness of the column and bearing capacity of the foundation such that the side friction capacity is just as significant as the end-bearing capacity.

Grouted helical piles require little to no removal of spoils. They are easier to install than conventional piling systems. They can be installed in low headroom areas and do not need heavy equipment for installation. Installation is quicker than conventional piling methods. The installation method is the same as that for helical screw piles, except for the addition of the displacement plate and grout.

Limitations: The use of grout and displacement plates incurs additional costs. For example, a 30 ft pile could cause an increment of 10% in additional costs (Vickars and Clemence 2000). The use of grout increases installation time because of curing time. There is the potential for negative skin friction developing along the pile shaft. Figure 8 shows three installed grouted helical piles.



CHANCE 2013, © 2013 Hubbell Incorporated

Figure 8. Grouted helical piles

Case Study: South Jersey Helical Piers performed an emergency replacement of the Route 559 bridge at Weymouth Road over Deep Run in Hamilton township, Atlantic County, New Jersey. The bridge was a temporary 60 ft bridge to carry Route 559 traffic. The old Route 559 bridge was closed after Tropical Storm Irene passed over the area in 2011. The old bridge was determined to be damaged beyond repair after a county inspection.

The temporary bridge was built in-shop, and then taken apart and transported to the field. After grouted helical piles were installed as the abutment foundation, the bridge was reconstructed on top of the foundation. An average of 13 grouted helical piles were installed per day over the duration of the project. Fifty grouted helical piles were installed and the diameter of the grout column was 5 in. (Danbro Distributors 2012). Figure 9 shows the installation of the grouted helical piles for the emergency bridge replacement.

Danbro Distributors 2012, © Copyright 2019

Figure 9. Installation of CHANCE helical pulldown piles for Route 559 emergency bridge replacement

2.2.4 Ductile Iron Piles

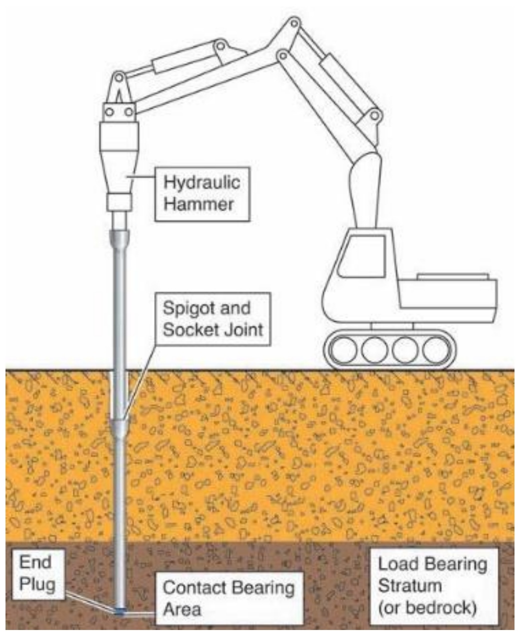
Description: Ductile iron piles are manufactured by Tiroler Rohre GmbH (TRM) in Austria. The pipe material is a centrifugally cast ductile iron that has excellent tenacity, ductility, strength, and corrosion resistance properties. Ductile iron piles employ a "plug and drive" connection system consisting of a tapered socket at one end and a tapered spigot at the other end. This allows the individual pile sections to be connected together to form a pile shaft of any length without the use of special tools. The connection is formed by elastic deformation of the ductile iron and by cold welding the friction surfaces.

After installing one ductile iron pile, the surplus at the uppermost pipe section is cut with a standard pipe cutting saw. The surplus is then fitted with its own driving shoe for use as the first section for the next pile, thereby minimizing waste. Friction-bearing piles are grouted simultaneously with driving, both through the interior of the pile and along the exterior annulus to provide both the required frictional resistance and excellent protection against corrosion (Schmidt and Dobras 2009).

Ductile iron piles are manufactured in standard lengths of about 16.4 ft. The piles are available in multiple diameters and wall thicknesses.

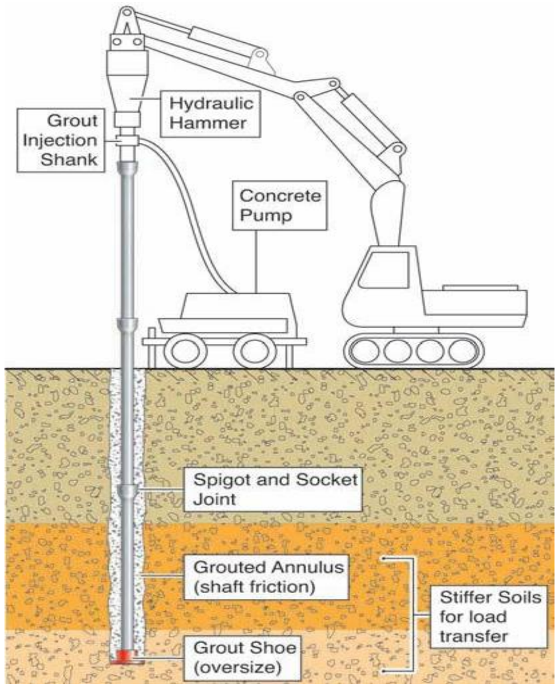
Ductile iron piles have been used for garages, residential apartments, and commercial office buildings. They have been used in several states including Connecticut, Maryland, Massachusetts, New Hampshire, New Mexico, New York, North Carolina, Rhode Island, Vermont, and Virginia.

Advantages: The spigot and socket joint exhibits high-compressive strength and resistance to bending. The connection eliminates the need for threads, couplers, pins, keys, and welding on the job site. Ductile iron piles have low mobilization cost and rapid installation times up to 1,300 ft per day utilizing lightweight and easily maneuverable equipment. The piles are robust (high-impact resistant) and have high corrosion resistance. They have high capacity to match steel H-piles. Battered installations help with lateral resistance. Figures 10, 11, and 12 are drawings of ductile iron piles.



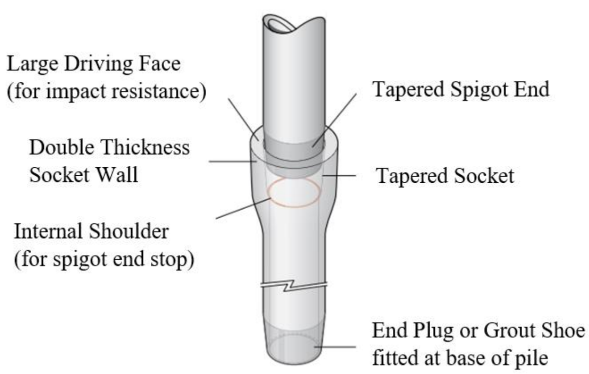
DYWIDAG-Systems International

Figure 10. Typical end-bearing ductile iron pile installation



DYWIDAG-Systems International

Figure 11. Typical skin-friction ductile iron pile installation



DYWIDAG-Systems International

Figure 12. Spigot and socket joint

Limitations: Even though ductile cast iron has superior corrosion resistance compared to steel, it is still made of a material that can rust in the long term.

Case Study: Construction of a new CarMax facility in Westborough, Massachusetts, included a new dealership building as well as multiple parking lots. A bridge was constructed close to the facility using end-bearing ductile iron piles as the abutment foundation. The 52 ft long, single-span bridge was required to cross a small stream/wetland and provide access to a second parking area at the rear of the facility. Vertical and lateral loads on the 6.5 ft wide bridge abutments were 13.3 ton/ft and 1.6 ton/ft, respectively. The soil profile at the bridge abutments consisted of loose to medium dense sand up to 28 ft, followed by medium dense glacial till to about 35 ft.

Groundwater was encountered at depths of about 5.0 ft to 6.0 ft below grade at the time of drilling.

The abutment foundation was initially designed for steel H-piles, but the design was later revised in favor of ductile iron piles. Two rows of piles were designed within the 6.5 ft wide abutment footings. The front row of piles was designed with a batter to provide the lateral resistance. The ductile iron pile system was selected based on cost, speed of installation, and ease of access to the site. The pile was designed to develop capacity in the end bearing on the glacial till.

A pre-production load test was performed at the site. The test pile was installed to terminate on rock at a depth of 36 ft. The pile exhibited a nearly linear load-deflection response with 0.31 in. of deflection at 36 tons (100% design load) and 0.62 in. of deflection at 72 tons (200% design load). Net deflection when unloaded was 0.13 in.

Installation of the 32 piles occurred over a three-day period in winter construction conditions. The piles were easily installed while working from variable grades. The mobile excavator and modular nature of the piles also made for quick installations on the opposite abutment across the small stream (DuroTerra n.d.). Figure 13 shows the ductile iron pile installation at the site bridge.

DuroTerra n.d.

Figure 13. Installation of CarMax facility site bridge

2.2.5 Drilled Displacement Piles

Description: A special class of auger piles was created as a result of advances in auger piling technology. These are commonly known as drilled displacement (DD) piles (Brown and Drew 2000, Prezzi and Basu 2005). DD piles consist of cast-in-place grout with a central threaded bar and are constructed with a hollow steel displacement tool.

DD piling techniques laterally displace and compact the soil during installation, unlike continuous flight auger (CFA) piling, which excavates the soil (Yang et al. 2010). As a result, the displacement construction process generates little to no excess spoils, so it is particularly advantageous in areas where soil removal may be costly, like on sites with contaminated soils.

Displacement piles can function as end-bearing or side-friction elements. They can be constructed with an expanded base to achieve higher geotechnical capacities, similar to pressure-injected footings (Helical Drilling Inc. n.d.).

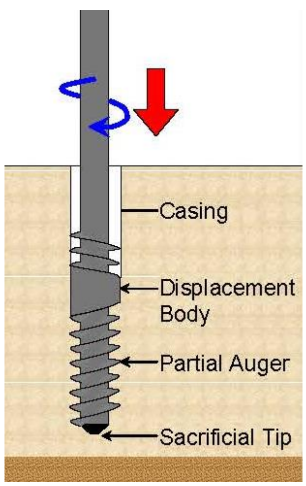
Typical DD piles are 12 in. to 18 in. in diameter, although 24 in. DD piles have been installed. Piles of lengths up to 100 ft have been installed to date. Several types of DD piles are the Atlas pile, DeWaal pile, Fundex pile, Olivier pile, Omega pile, pressure-grouted displacement (PGD) pile, and SVV (STRABAG Vollverdrängungsbohrpfahl) pile. Table 2 shows calculated capacities for a drilled displacement pile, a full-displacement pile, and a non-displacement pile tested at a Georgia Institute of Technology test site.

Table 2. Calculated capacities per pile using the soil profile of the Georgia Institute of Technology test site

	Total Capacity, ton		
	Method		
Pile Types	**A**	**B**	**C**
Drilled displacement pile	94	159	119
Full-displacement pile		127	
Non-displacement pile		45	

Source: Basu et al. 2010

The load bearing resistance of DD piles lies within the bearing capacities of full-displacement piles and non-displacement piles. Figure 14 shows an illustration of a DD pile drilling tool.



Basu and Prezzi 2009

Figure 14. DD pile drilling tool

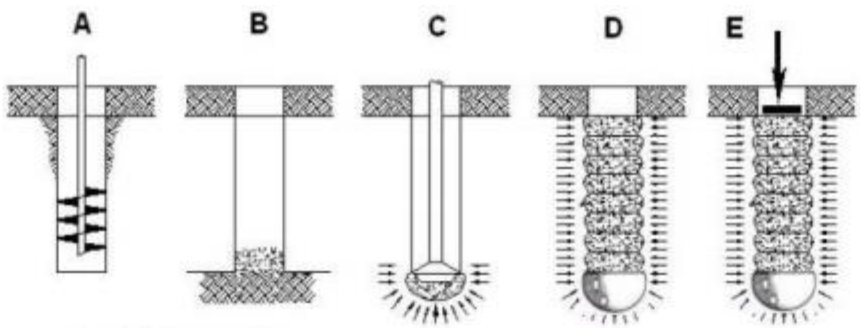
Advantages: DD piles are an environmentally friendly alternative piling system. Installations can be done at a fast rate, with minimal vibration, noise, and spoil. DD piles have high bearing resistances due to lateral displacement of the soil surrounding the pile. They are associated with savings that result when they are installed in the right soil conditions.

Limitations: DD pile platforms and tooling can potentially be more expensive than conventional piling equipment. They are more likely to be used on mega-projects.

Case Study: Could not find an example of this system used on a local road.

2.2.6 Geopier Foundations

Description: Geopier foundations, or rammed aggregate piers, are a type of specially compacted aggregate columns that can be used to vertically reinforce a soil profile in poor soil conditions. Geopier foundations are constructed using a unique technique that imparts lateral stress on the surrounding soil, which increases the vertical bearing capacity and reduces the magnitude of total settlement (Fox et al. 2004). Concrete can be used instead of aggregate, in which case the name changes to geoconcrete foundation. Figure 15 provides a depiction of geopier foundation construction.



A. Make cavity, B. Place stone at bottom of cavity, C. Ram stone to form bottom bulb, D. Densify stone in lifts to form undulated shaft, E. Preload top of geopier

Fox et al. 2004

Figure 15. Geopier construction

Advantages: Geopier foundations are being used to control foundation settlement and to stabilize soil slopes. Geopier foundations are an effective and cost-competitive alternative in certain challenging situations.

Limitations: A drill rig is needed for installation in addition to an impact or a vibratory hammer.

Case Study: The 11th Street Bridges in Washington, DC, were constructed using a geoconcrete foundation. The project replaced two bridges built in the 1960s with three new bridges that separate local and freeway traffic. Foundation soils below the abutments of the bridges consisted of 25 ft to 50 ft of low blow count organic silts and clays underlain by dense gravels.

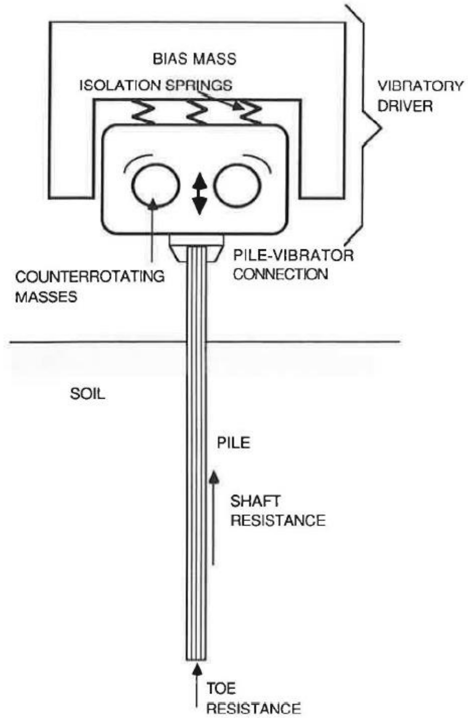
The original design for the project called for the use of wick drains and mechanically stabilized earth (MSE) wire wall surcharging, which would have resulted in 10 to 45 in. of settlement. In addition, the consolidation settlement would have taken many months to complete.

An alternative approach was provided using geoconcrete foundations with piers that had capacities on the order of 175 tons and were spaced at 7 to 9 ft. A single stage wall was built and the timeframe for MSE wall installation was dramatically reduced. Settlement was limited to less than 3 in. Statnamic testing was used to confirm the capacities of the 35 ft to 50 ft deep geoconcrete elements supporting MSE walls up to 45 ft tall (GeoStructures, Inc. n.d.).

2.3 Methods of Estimating Drivability and Bearing Capacity of Vibratory-Driven Piles

Vibratory-driven piles are usually driven into the ground with ease, especially in sandy soils. Installation of piles with vibratory hammers has the advantage of producing little to no pile damage, reduced noise pollution, and reduced installation time in granular soils. A 60 to 70 ft long pile can be installed in 5 minutes or less with vibration; whereas, a similar pile driven by an impact hammer may require 15 to 30 minutes to install (O'Neill et al. 1990).

It has also been recorded in studies that the bearing resistance of vibratory-driven piles in clayey soils is usually only a fraction of the bearing resistance of impact-driven piles. A study published in 2014 on vibratory-driven piles reported that both the end-bearing and side friction capacity values decreased by about 50% when compared to similar piles that had been impact-driven in alluvium soil (Lamiman and Robinson 2014). A drawing of a typical vibratory driver and pile is shown in Figure 16.



O’Neill et al. 1990

Figure 16. Typical vibratory driver and pile

Under favorable conditions, driving with a vibratory hammer is indeed a more economical pile installation solution compared to impact-driven piles. There is the question, however, about which methods can adequately predict the drivability and bearing resistance of vibratory-driven piles to be installed, and methods that can confirm the bearing resistance of vibratory-driven piles once installed.

2.3.1 Predicting the Drivability and Bearing Capacity of Piles to be Installed

The drivability of a pile deals with what equipment will be required to drive a given pile to a given depth. There is also the concern that vibratory-driven piles might cause excessive vibrations on nearby structures. In predicting drivability and bearing resistance before installation, a number of attempts have been made that involve using simple or complex equations.

The simple equations are mostly empirical and include Jonker’s force method, Bernhard’s power method, Davisson’s power method, the SNiP formula, Schmid’s method, Feng and Deschamps’s equation, the Case method, and O’Neil’s power transfer expressions. The more complex equations used are wave equations, and these are usually in the form of software like the GRL Wave Equation Analysis Program (GRLWEAP).

2.3.1.1 Jonker's Force Method

Jonker (1987) proposed a method to predict the drivability and bearing resistance of piles to be driven with a vibratory hammer. The equations assume that the pile will core and not plug while it is being driven into the ground. Jonker used the term SRV, meaning soil resistance during vibratory driving. Jonker explained that soils subjected to vibrations temporarily change their internal strength resulting in a far lower resistance for a penetrating element when compared to the same element being driven into the soil by impact.

Similar to pile drivability predictions for impact hammers, Jonker's SRV value was estimated from the static bearing resistance of a pile. The static bearing resistance of a pile for an unplugging pile behavior is expressed by:

$$Q_t = F_o + F_i + Q_w \quad \textbf{(1)}$$

where:

Q_t = total bearing capacity
F_o = total outer skin friction
F_i = total inner skin friction (for pipe piles)
Q_w = end bearing

If β-factors are introduced to define the ratio between the vibratory and static resistance, the overall driving resistance can be expressed as:

$$SRV_t = \beta_o F_o + \beta_i F_i + \beta_t Q_w \quad \textbf{(2)}$$

Few experiments were conducted with Jonker's equation and the range of values obtained for the β-factors are as follows:

β_o = 0.05 – 0.3
β_i = 0.05 – 0.3
β_t = 0.6 - 0.7

For penetration (drivability),

$$SRV_t \leq F_d + W_p + W_h \quad \textbf{(3)}$$

And for extraction,

$$SRV_t \leq F_d + F_s - W_p - W_h \quad \textbf{(4)}$$

where:

F_d = dynamic force
W_p = weight of pile
W_h = weight of hammer
F_s = surcharge force

2.3.1.2 Bernhard's Power Method

Bernhard performed model pile studies and came up with a power formula that is as follows (Feng and Deschamps 2000):

$$R_u = \frac{\Pi^{max} PL}{V_p^{ave} p} \qquad \textbf{(5)}$$

where:

R_u = ultimate bearing resistance
Π^{max} = maximum vibrator efficiency factor with suggested value of 0.1
P = input power
L = length of the pile
V_p^{ave} = averaged penetration velocity
p = total penetration

2.3.1.3 Davisson's Power Method

Davisson's equation is as follows (Feng and Deschamps 2000):

$$R_u = \frac{550\ H_p}{(r_p + S_L f)}\ (in\text{-}lb) \qquad \textbf{(6)}$$

where:

R_u = ultimate bearing resistance
H_p = horsepower delivered to pile
r_p = final rate of pile penetration, in ft/sec
s_L = loss factor which can be assumed as 0.03 ft/cycle
f = frequency, in cps

2.3.1.4 Schmid's Method

Schmid came up with an equation to determine the bearing capacity of vibratory-driven piles. The equation is as follows (Feng and Deschamps 2000):

$$R_u = \frac{(B+E+Q)T}{\alpha T_c} \quad \textbf{(7)}$$

where:

R_u = ultimate bearing capacity
B = bias weight
E = weight of the vibrator
Q = weight of the pile
T = period of vibration
α = a coefficient that normally should be between 0.5 and 1.0, typically 0.67.
T_c = contact time between the soil and the pile tip

2.3.1.5 The SNiP Formula

SNiP (II-B.5-67): This empirical formula was used in the Soviet Union (O'Neill 1990):

$$R_u = \lambda\left(\frac{25.5\,N}{A_o n} + Q\right) \quad \textbf{(8)}$$

where:

R_u = ultimate bearing capacity
λ = a coefficient considering the influence of vibration driving on the soil properties (usually λ = 5 is assumed)
N = power used to drive the pile in kW
A_o = vibrational amplitude of the pile in cm
n = rotational frequency of eccentric vibrator in Hz
Q = total weight of driver, bias weight and pile in kN

2.3.1.6 Feng and Deschamps's Equation

Feng and Deschamps (2000) came up with an empirical relationship to predict the ultimate bearing resistance of vibratory-driven piles based on hammer, pile, and penetration characteristics. The variables are all readily available from the hammer data and from driving records, except for the over-consolidation ratio (OCR). The speed of light is used to normalize the equation and maintain consistent units. The equation is as follows:

$$R_u = \frac{3.6\ (F_c + 11 \cdot W_B)}{(1 + 1.8 \times 10^{10} \cdot \frac{v_p}{c} \sqrt{OCR}\ )} \cdot \frac{L_E}{L} \tag{9}$$

where:

R_u = ultimate bearing capacity
F_c = centrifugal force
W_B = bias weight
v_p = penetration velocity at end of driving
c = speed of light = 1.8×10^{10} m/min (5.91×10^{10} ft/min)
OCR = over-consolidation ratio
L_E = embedded length
L = pile length

2.3.1.7 The Case Method

The Case method for vibratory-driven piles was developed by Rausche (2002). For elastic piles:

$$R_u(t) = \frac{1}{2}(F1 + Z \cdot v1)(1 - J_c) + \frac{1}{2}(F2 + Z \cdot v2)(1 + J_c) \tag{10}$$

where:

$F1$ = force at time t
$F2$ = force at time $t + 2L/c$
$v1$ = velocity at time t
$v2$ = velocity at time t + 2L/c
Z = pile impedance (EA/c)
J_c = dimensionless damping factor
L = pile length
c = wave speed in pile material $\left(\sqrt{E/\rho}\right)$
E = Young's modulus of pile material
A = cross sectional area of pile material

For a rigid body, the time $2L/c$ reduces to zero, and, thus $F1 = F2 = F(t)$ and $v1 = v2 = v(t)$ and the formula becomes:

$$R(t) = F(t) + M \cdot a(t) - J_v \cdot v(t) \tag{11}$$

Equation 11 is adequate for low frequency hammers. For higher frequencies, near the hammer-pile system's resonance level, the Case method equation for elastic piles would be more reasonable. Formula 10 approaches 11 as the pile length approaches zero and the pile becomes a rigid body of mass *M*, with acceleration *a(t)*. The damping factor, J_v, is equivalent to the product of *Z* and J_c.

2.3.1.8 O'Neil's Power Transfer Expressions

O'Neill et al. (1990) developed an equation to determine the ultimate bearing capacity of vibratory-driven piles. The equation assumes a rigid body of the pile, and it is as follows:

$$R_u = \frac{0.005\, P_h}{r_{pt}[\beta_1(\sigma_h')\beta_2(D_r)\beta_3(d_{10})]} \quad \textbf{(12)}$$

where:

R_u = ultimate bearing capacity
P_h = average power delivered to the pile head during the final one-diameter of penetration = $P_t[0.25 + 0.063\, a_h(\text{g})]$
r_{pt} = average rate of penetration during the final one-diameter of penetration
$\beta_1(\sigma_h')$ = empirical parameter for soil vertical effective stress = - 0.486 + 0.0743σ_h' for 10psi ≤ $\sigma_h' \leq$ 20 psi
$\beta_2(D_r)$ = empirical parameter for soil relative density = 1.96D_r – 1.11 for 0.65 ≤ $D_r \leq$ 0.90
$\beta_3(d_{10})$ = empirical parameter for the 10-percent soil particle size = 1.228 – 0.19d_{10} for 0.2 mm ≤ $d_{10} \leq$ 1.2 mm
P_t = theoretical power of the hammer = $f\left(4W_b + \frac{8\pi^2 f^2 f_n^2 me}{(f_n^2 - f^2)}\right)\frac{mef^2}{M(f_n^2 - f^2)}$
m = combined mass of all rotating, unbalanced weights
M = mass of the vibrator, excluding bias mass
e = eccentricity of the rotating weights
f_n = natural frequency of the vibrator mass-isolation spring system = $(k/M)^{0.5}$
f = frequency of the system
k = combined spring constant of the isolation springs
a_h(g) = absolute peak acceleration = $\alpha_1(D_r)\ \alpha_2(d_{10})\left(r_{pt}^{\alpha_3(\sigma_h')}\right)$, where r_{pt} = in./sec
$\alpha_1(D_r)$ = -2.186 + 3.54D_r for 0.65 ≤ $D_r \leq$ 0.90
$\alpha_2(d_{10})$ = 8.99 + 2.76d_{10} for 0.2 mm ≤ $d_{10} \leq$ 1.2 mm
$\alpha_3(\sigma_h')$ = 1.71 – 0.081σ_h' for 10psi ≤ $\sigma_h' \leq$ 20 psi
D_r = 0.007 $\frac{(q_{cnc})0.5}{0.33\sigma_v'}$ (developed my Schmertmann, can use other relative density equations)
q_{cnc} = cone tip resistance in kgf/cm^2 for normally consolidated sand = $\frac{q_c}{\{1+0.75\ [\ (OCR)^{0.42} - 1]\}}$
σ_v' = vertical effective stress
q_c = cone tip resistance in kgf/cm^2 for overconsolidated sand
K_o = 0.43 $(\text{OCR}^{0.57})$
$\sigma_h' = K_o \sigma_v'$

O'Neill et al. (1990) also developed a procedure to determine the drivability of a pile to be installed. The procedure is a back calculation of the required bearing resistance. The procedure is as follows:

1. A target static pile capacity is determined from the following equation:

$$R_u = N_\sigma \sigma'_o A_t + \sum_{i=1}^{N} \beta' i \sigma'_{hi} A_{si} \quad \textbf{(13)}$$

where:

σ'_o = the mean effective stress in the soil at the pile toe
A_t = the area of the toe
i = an index for pile segments (e.g., top half and bottom half) for shaft resistance computations
A_{si} = the peripheral area of segment *i*
σ'_{hi} = the lateral effective stress in the soil in situ at the elevation of the mid-depth of segment *i*
N_σ = a bearing capacity parameter = 181.1D_r + 11.36d_{10}(mm) – 76.1
β' = a shaft resistance parameter = 2.50D_r – 0.076d_{10}(mm) – 0.85

Other appropriate methods for estimating static capacity can be substituted for the method described above. Once the static capacity of the pile has been established, the following steps are employed:

2. A target value of terminal penetration velocity r_{pt} is selected. It is suggested that a value of 0.1 in./sec represents refusal.

3. The power required at the pile head, P_h, to produce the selected value of terminal penetration velocity is then computed. The equation is shown again below:

$$R_u = \frac{0.005\, P_h}{r_{pt}[\beta_1(\sigma'_h)\beta_2(D_r)\beta_3(d_{10})]}$$

4. The peak absolute value of pile head acceleration, a_h(g), that would result from the above choices is estimated. The equation is shown again below:

$$a_h(\mathrm{g}) = \alpha_1(D_r)\ \alpha_2(d_{10}) \left(r_{pt}^{\alpha_3(\sigma'_h)}\right)$$

5. Finally, the power required for the vibrator is computed from the equation below:

$$P_h = P_t[0.25 + 0.063\ a_h(\mathrm{g})]$$

2.3.1.9 Wave Equation Methods

The wave equation program, GRLWEAP, includes a quick vibratory drivability analysis capability. The program not only provides a large hammer database, but also a comprehensive set of soil parameter recommendations. Obviously, such recommendations cannot compete with and do not replace actual experience from local case studies. However, such a wave equation analysis could be a good starting point.

For bearing resistance, GRLWEAP produces a bearing graph, which is a plot showing the relation between the static resistance to driving (SRD) and driving resistance per unit of time. Comparing these to impact-driven piles, the SRD would be the bearing resistance, and the driving resistance per unit of time would be the blow count. For drivability, the analysis is practically a sequence of bearing graph calculations for increasing depths of penetration. This process requires an accurate assessment of the following for realistic assessment of the SRD:

- Long term static resistance (LSTR), which may be calculated by geotechnical methods
- Factor for gain/loss (fgl), which in the case of soil setup is less than 1.0 and may be thought of as the inverse of the soil setup factor
- A relaxation factor

2.3.2 Confirming the Bearing Capacity of an Installed Pile

After vibratory-driven piles are installed, there is the need to confirm the bearing capacity of the installed piles. In confirming the bearing capacity, several methods are used, and descriptions of three of them follow.

With the first method, a pile is installed by driving it to about half the required installation depth using a vibratory hammer. Then, the other half of the installation is completed using an impact hammer (Mosher 1990). The bearing resistance of the pile can be confirmed using methods for impact-driven piles. This way, there is a good balance between installation speed and the bearing resistance desired.

With the second method, a pile is fully installed using a vibratory hammer; then, a restrike test is performed on it one day after installation to confirm the bearing capacity of the installed pile (O’Neill et al. 1990, Rausche 2012).

With the third method, a pile is instrumented before installation. During installation, force and velocity data are measured using a pile driving analyzer (PDA) and information from this PDA is fed into the signal matching software called the Case Pile Wave Analysis Program (CAPWAP) to determine stresses at each depth along the pile, and the SRD.

CHAPTER 3:SURVEYS

After a comprehensive review of the state of the practice, a survey questionnaire was prepared to obtain first-hand information on alternative piling systems and vibratory-driven piles. The survey questionnaire was divided into two parts to obtain a more organized questionnaire. The first part of the survey had questions on alternative piling systems and the second part had questions on vibratory-driven piles.

The survey questionnaire was sent out to county engineers in all 99 Iowa counties. A separate survey questionnaire was also sent out to 40 foundation engineering companies, most of which are outside of Iowa. It was estimated that the survey would take about 10 to 15 minutes to complete. The survey questionnaire is included in the Appendix.

3.1 Iowa County Engineers

County engineers in all 99 Iowa counties were invited to participate in the survey. Out of these, 73 counties responded. The response to "How familiar are you with micropiles?" is shown in Figure 17.

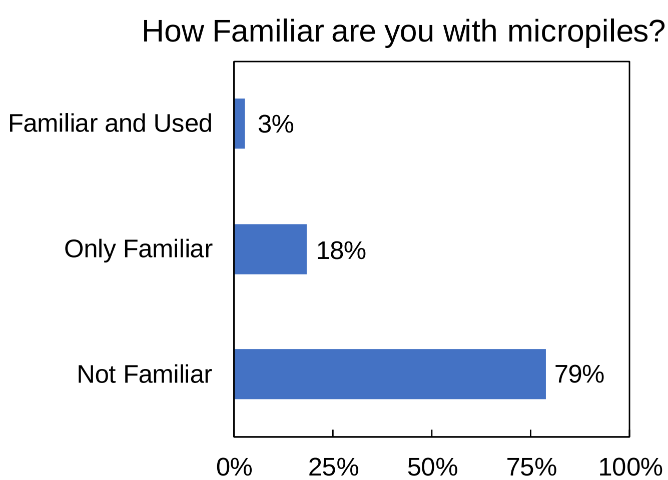


Figure 17. How familiar are you with micropiles?

Of the 71 respondents to this question, 3% were familiar with and had used micropiles in their work sometime in the past, 18% were familiar with micropiles but had never used them in their work, and an overwhelming 79% were not familiar with micropiles at all. The results showed there is very little use of micropiles by county engineers in Iowa.

The advantages listed for using micropiles included ease of construction and use of less expensive materials. This system can provide additional bearing resistance to existing structures, does not need a crane to install, can be used in uncertain sub-surface conditions, can help in soil with low strength conditions, can be installed in low clearance or well restricted areas, can help with slope stabilization, has less of an issue with drilling and hitting rocks, and can be the most cost-effective alternative in situations involving low clearance or difficult soil construction conditions.

Difficulties listed for using micropiles included unfamiliarity with the technique, finding experienced contractors to design and/or install, may not be useful in Iowa's scour-prone streams, more variability with micropiles, especially compared to getting bearing on bedrock, and may not be cost-effective for smaller projects.

The response to "How familiar are you with helical screw piles?" is shown in Figure 18.

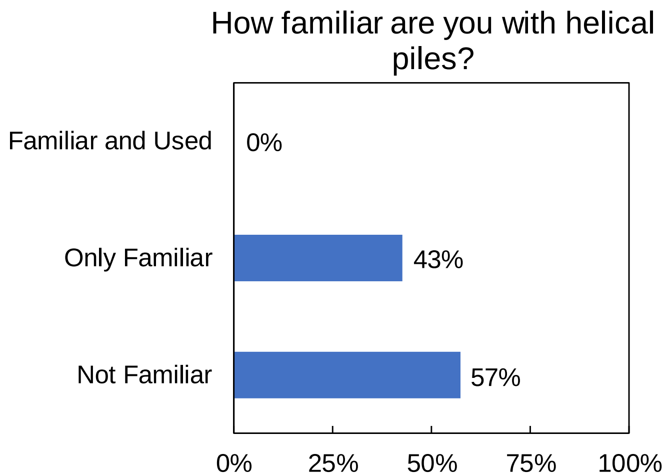


Figure 18. How familiar are you with helical screw piles?

Of 68 respondents to this question, 0% were familiar with and had used helical screw piles in their work sometime in the past, 43% were familiar with helical screw piles but had never used them in their work, and 57% were not familiar with helical screw piles at all. The results showed that helical screw piles have hardly ever been used by county engineers in Iowa. It is also evident from the results that about half of Iowa county engineers have some knowledge about helical screw piles, and the other half do not.

Advantages listed for using helical screw piles included reduced vibration and noise for sensitive areas. This system can be used under an existing bridge with low headroom as supplemental piles, can help with bearing in poorer soils, can use relatively small equipment fitted with a special driver for installation, has an easier and faster installation, does not have to go extremely deep into the ground in some cases, does not need a dragline, does not need a crane or excavator, can be immediately loaded after installation, and no waiting needed for concrete and grout to harden.

Difficulties cited for using helical screw piles included special driver may not be locally available for installation, contractors may not be locally available to perform installations, still needs decent soil to get good bearing resistance, difficult to install in rocky or old riprap soil conditions, estimating bearing resistance is not straightforward, might not provide enough lateral loading resistance, not sure about pricing, local agency lack of familiarity and usage, and pile slenderness.

The response to “How familiar are you with grouted helical piles?” is shown in Figure 19.

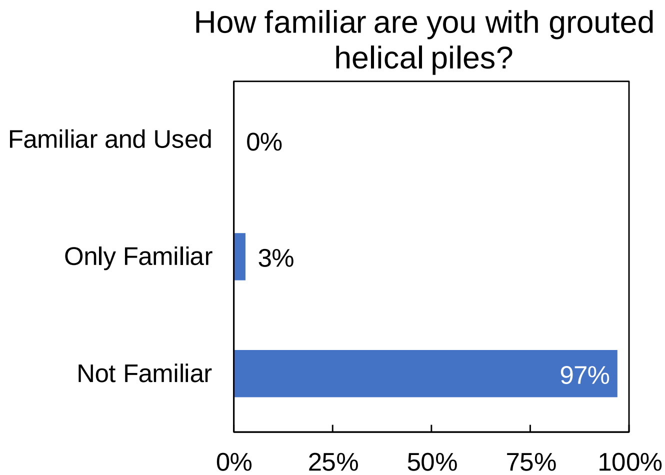


Figure 19. How familiar are you with grouted helical piles?

Of 67 respondents to this question, 0% were familiar with and had used grouted helical piles in their work sometime in the past, 3% were familiar with grouted helical piles but had never used them in their work, and a resounding 97% were not familiar with grouted helical piles at all. The results showed that grouted helical piles are hardly known by Iowa county engineers.

Advantages listed for using grouted helical piles included it is economical, it needs smaller equipment for installation, it is vibration-free, and it improves the soil around the pile.

Difficulties cited included it is difficult to install in rocky soils, there are limitations of grout use in certain areas like wetlands, there is a lack of experienced contractors in Iowa, a special driving head is needed for installation, and pump field quality control is needed.

The response to “How familiar are you with ductile iron piles?” is shown in Figure 20.

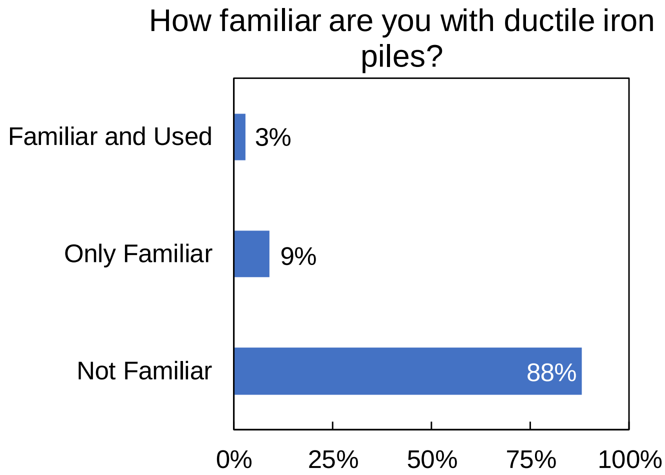


Figure 20. How familiar are you with ductile iron piles?

Of 67 respondents to this question, 3% were familiar with and had used ductile iron piles in their work sometime in the past, 9% were familiar with ductile iron piles but had never used them in their work, and 88% were not familiar with ductile iron piles at all. The results showed that only a few Iowa county engineers have knowledge about ductile iron piles or have used them in their work sometime in the past.

Advantages cited by the county engineers for ductile iron piles included low cost, high load bearing resistance, availability of experienced contractors, can be easily added on to, can use if rocks or boulders are encountered, makes for a quick installation, can be used in limited access applications, and minimal vibration concerns.

Difficulties cited included unfamiliarity of many engineers in Iowa, noise due to splicing, larger dragline and driving equipment needed, and more applicable to building applications.

The response to “How familiar are you with drilled displacement piles?” is shown in Figure 21.

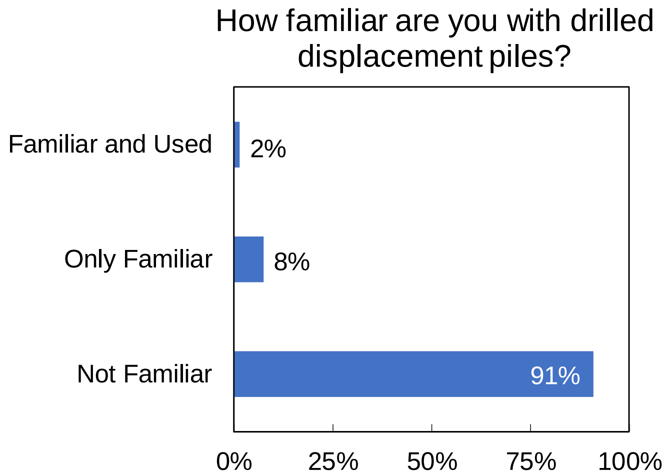


Figure 21. How familiar are you with drilled displacement piles?

Of 66 respondents to this question, 2% were familiar with and had used drilled displacement piles in their work sometime in the past, 8% were familiar with drilled displacement piles but had never used them in their work, and 91% were not familiar with drilled displacement piles at all. The results showed that only a few Iowa county engineers have knowledge about drilled displacement piles or have used them in their work sometime in the past.

Advantages cited by the county engineers for drilled displacement piles included higher bearing resistance for same depth and pile diameter compared to conventional drilled shafts, quick installation, quiet and vibration-free, and improves soil in and around pile.

Difficulties cited included unique and expensive equipment required, which limits their use in smaller projects and rural areas, could be costly, and large and heavy equipment needed for installation.

The response to "How familiar are you with geopier foundations?" is shown in Figure 22.

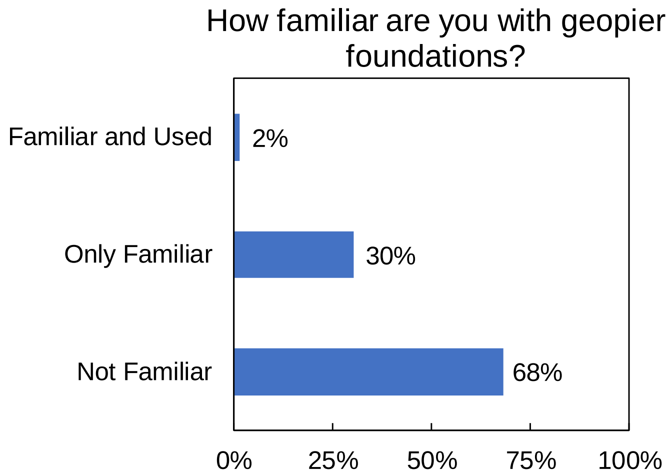


Figure 22. How familiar are you with geopier foundations?

Of 66 respondents to this question, 2% were familiar with and had used geopier foundations in their work sometime in the past, 30% were familiar with geopier foundations but had never used them in their work, and 68% were not familiar with geopier foundations at all. The results showed that only a few Iowa county engineers have used geopier foundations in their work sometime in the past, a considerable number of them know about the system but have never used it in their work, and the majority of county engineers have no knowledge about the system.

Advantages cited by Iowa county engineers for geopier foundations included: can increase the stability of poor slopes and embankments, can be done with some locally available aggregates, a good soil stabilization method for reinforcing weak soils, could be economical, quick to install if site is advantageous for equipment, easy to install, good for spread footings, good for approach road stabilization, and provides settlement drainage.

Difficulties listed for using geopier foundations included it is proprietary and could be expensive in some situations, not usable in scour-prone streams under bridge abutments, there are limited contractors in Iowa, works best with bedrock at or near the surface in order to be stable, not sure how deep these can go and what bearing can be achieved, need to drill a hole, soft and wet conditions could make it difficult, needs protection against scour, and how to design such a system is not well known.

The response to “Are there other abutment piling systems you are familiar with but are not listed in the survey?” is shown in Figure 23.

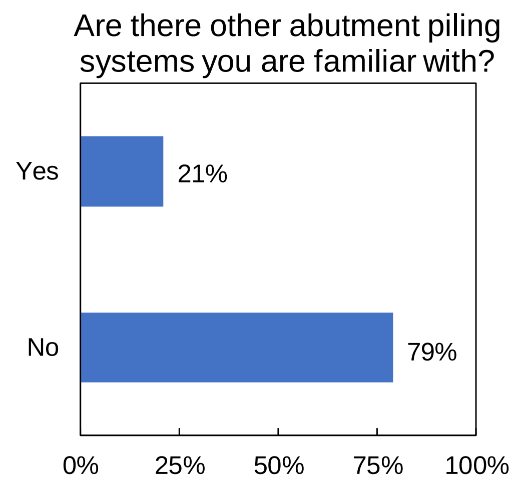


Figure 23. Are there other abutment piling systems you are familiar with?

Of 62 respondents to this question, 21% answered "Yes" and 79% answered "No." Those who responded "Yes" listed the following as other abutment piling systems they are familiar with: geosynthetic reinforced soil-integrated bridge system (GRS-IBS), standard H-piles, timber piles, sheet piles, vibratory-driven piles, and structural pile from oil industry.

The response to "Are you familiar with vibratory-driven piles?" is shown in Figure 24.

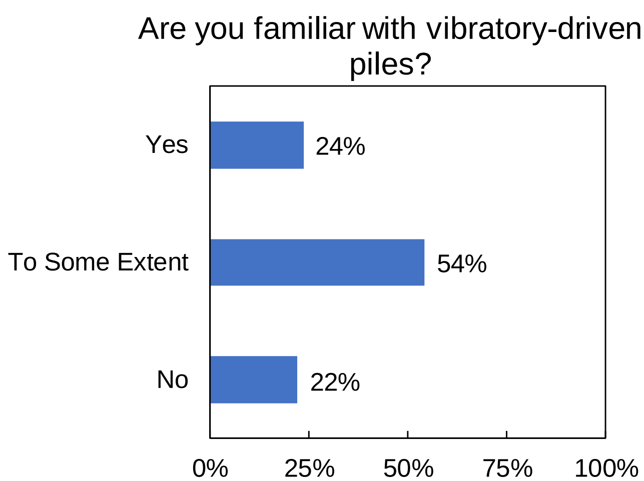


Figure 24. Are you familiar with vibratory-driven piles?

Of 59 respondents to this question, 24% answered "Yes," 54% answered "To some extent," and 22% answered "No."

The response to "Does your jurisdiction perform calculations to determine the drivability and/or bearing capacity of vibratory-driven piles?" is shown in Figure 25.

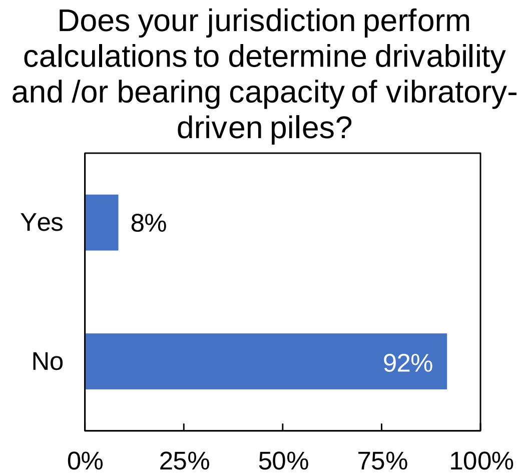


Figure 25. Does your jurisdiction perform calculations to determine the drivability and/or bearing capacity of vibratory-driven piles?

Of 59 respondents to this question, 8% answered "Yes" and 92% answered "No." The 8% of respondents that answered "Yes" were asked follow-up questions.

The first follow-up question was "Does your jurisdiction use GRLWEAP to determine the drivability and/or bearing capacity of vibratory-driven piles?"

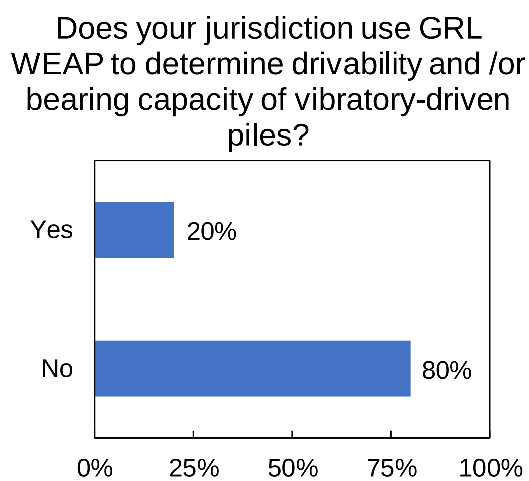


Figure 26. Does your jurisdiction use GRLWEAP to determine the drivability and/or bearing capacity of vibratory-driven piles?

In response to this question, 20% of the 8% said "Yes" and 80% of the 8% said "No."

The second follow-up question was "Does your jurisdiction use PDA to determine the drivability and/or bearing capacity of vibratory-driven piles?"

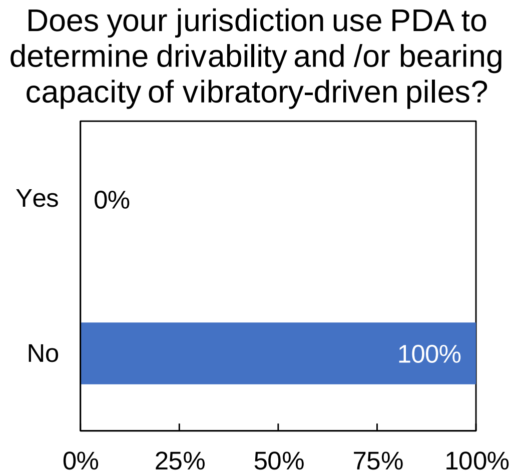


Figure 27. Does your jurisdiction use PDA to determine the drivability and/or bearing capacity of vibratory-driven piles?

In response to this question, 0% of the 8% said "Yes" and 100% of the 8% said "No."

The third follow-up question was "Does your jurisdiction use CAPWAP to determine the drivability and/or bearing capacity of vibratory-driven piles?"

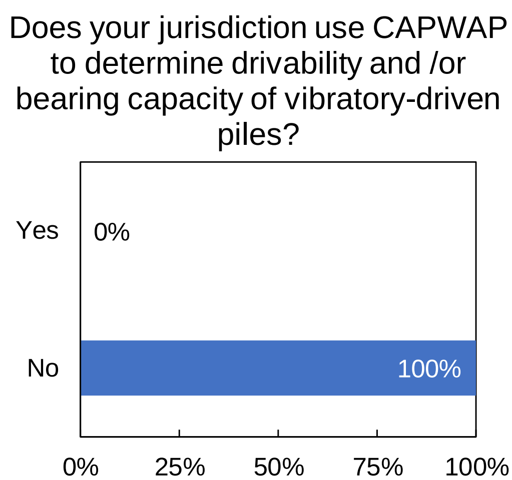


Figure 28. Does your jurisdiction use CAPWAP to determine the drivability and/or bearing capacity of vibratory-driven piles?

In response to this question, 0% of the 8% said "Yes" and 100% of the 8% said "No."

The 8% of respondents that answered "Yes" to the question of "Does your jurisdiction perform calculations to determine the drivability and/or bearing capacity of vibratory-driven piles?" were asked to list any other technology/software used by their jurisdiction to determine the drivability and/or bearing resistance of vibratory-driven piles. The only respondent who answered the question stated that their jurisdiction used the ENR formula based on gravity hammer average penetration. This is a restrike test which involves tapping the pile with a hammer to estimate bearing resistance.

The last question of the survey was, "How does your jurisdiction confirm the bearing capacity of an installed vibratory-driven pile? This question was meant for respondents who answered "No" to "Does your jurisdiction perform calculations to determine the drivability and/or bearing capacity of vibratory-driven piles?"

In response to this question, many respondents said their county does not perform vibratory-driven pile installations. Other respondents stated methods their county used. One respondent said, "We do not do full-depth vibratory-driven piles for bearing capacity." This is to say that the respondent's county performs vibratory installation of piles to only about halfway of the required installation depth; then, an impact hammer is used to complete the pile installation. A few stated that their county uses the ENR formula by using a gravity hammer on pilings after they have been installed with a vibratory hammer. A few other variations included load calculations from a consultant if needed, drive to refusal, use Calhoun-Burns to establish wave equation, and use of other equations or charts.

3.2 Engineering Companies Mainly Outside Iowa

Engineering companies mainly outside of Iowa were also contacted to participate in the survey. Of the 40 companies contacted, feedback was obtained from 24 of them. Contact was made through email and phone calls. Following is the feedback from these respondents.

3.2.1 Rembco Geotechnical Contractors, Inc.

Rembco has used micropiles many times for bridge construction. They have no experience with helical piles, grouted helical piles, ductile iron piles, drilled displacement piles, or geopier foundations. They have, however, heard about all these alternative piling systems that they are not familiar with. Rembco has no experience with vibratory-driven piles but has colleagues who they call on when they need H-piles or steel sheets driven.

They have only heard about PDA and CAPWAP, but have never used them before. In their opinion, the best way to evaluate drivability for a vibratory-driven pile is to ask a pile-driving contractor to review some boring logs and give their opinion. They believe that real drivability and bearing resistance estimations should come from an experienced contractor rather than equations in the literature.

They do not drive piles; they only drill and grout. Rembco said that their micropiles can be installed quickly in virtually any type of ground using highly adaptable mobile drilling equipment. These micropiles have working capacities of up to 250 tons and they offer an economical alternative to larger diameter drilled shaft foundations. These economic advantages are especially realized when working in difficult ground conditions, karst geology, or restricted access situations.

3.2.2 American Deep Foundations, Inc.

American Deep Foundations completed a project in Savannah, Georgia, where they vibrated 12×53 H-piles to a depth of 48 ft, and, then, verified the capacity by PDA testing. They utilized a D12-42 diesel hammer to verify a 75 ton working capacity. H-piles were left to sit 24 hours after installation before PDA testing. The piles vibrated into the ground with very little resistance and achieved a large amount of pile freeze in 24 hours.

3.2.3 Berkel & Company Contractors, Inc.

Berkel is familiar with micropiles, helical piles, and drilled displacement piles. Their micropiles are commonly constructed with steel casing and/or a threaded bar and high-strength cement grout. The capacities of their micropiles vary depending on the micropile size and subsurface conditions. Their micropiles are usually the most expensive deep foundation option, so they are usually reserved for instances where natural or man-made obstructions reside in the ground, in limited access or low-headroom conditions, or in karst geology where rock surfaces are erratic and large voids are present. Their micropiles resist compression, uplift, and lateral loads and can be used to support bridge abutment foundations.

Berkel's helical piles are usually used for light buildings and have a maximum capacity of about 164 tons. Berkel Construction has not used helical piles for bridges yet.

3.2.4 Case Foundation

Case Foundation does not install any of the deep foundation types listed in the survey. However, as a part of the Keller Group, some of their sister companies install every other deep foundation type. For example, one of their sister companies (Cyntech) specializes in helical screw piles. Case foundation does not install vibratory-driven piles but some of their sister companies do. In their opinion, the best way to evaluate vibratory-driven piles is by using GRLWEAP. They believe the analysis of vibratory-driven piles is complex, but that this program will give professionals a proper estimate of the drivability and bearing capacity of vibratory-driven piles.

3.2.5 Midwest Drilled Foundations & Engineering, Inc.

Midwest Drilled Foundations is familiar with micropiles and has used them in construction. They stated that some advantages of micropiles include low head-room requirements, ability to bypass obstructions, and can utilize greater skin friction in soil-grout bond. Some difficulties of micropiles that they mentioned include the difficulty in achieving high capacities per pile, and that they often require close access with the rig to each micropile location.

Midwest Drilled Foundations is familiar with helical piles and has used them in construction. Their stated advantages for helical piles include quick installation, more cost-dependent on material than labor, small to mid-sized equipment required, can read capacity during installation, and low headroom capabilities. Their stated difficulties for helical piles include hard to achieve high loads and cannot easily bypass obstructions such as cobbles, boulders, and old foundations.

They are also familiar with grouted helical piles, but have not used them in construction. Their stated advantages for grouted-helical piles include: can achieve greater capacity than regular helical piles, sometimes have greater capacities than micropiles, and offer added lateral stability/rigidity. Some stated difficulties of grouted-helical piles include: difficult to bypass obstructions and ensuring grout cover along the entire length of the pile.

Midwest Drilled Foundations is not familiar with ductile iron piles or drilled displacement piles. They are, however, familiar with and have used geopier foundations. Some stated advantages of geopier foundations include: low-cost intermediate foundation solution, applicable for most soil types that require improvement, can be installed relatively quickly, eliminate the need to remove and replace large volumes of soil, and can be used in lieu of surcharging a site, which saves considerable time and money. A difficulty of using geopier foundations is that they cannot achieve relatively high bearing pressures.

Midwest Drilled Foundations has heard about vibratory-driven piles, but does not utilize them in their work.

3.2.6 PierTech Systems, LLC.

PierTech Systems is familiar with micropiles but has not used them in their work. They are familiar with and have used helical screw piles and grouted helical piles. They stated that with helical screw piles, the round shaft works best in compression and the square shaft works best in tension. They confirmed that helical screw piles and grouted helical piles are suitable for new bridge abutment foundations. The largest piles can have a maximum load resistance of 500 tons.

They just completed a bridge construction in Wisconsin that required the addition of helical screw piles to increase the load capacity of the abutments. Each H-pile was designed to resist a compression load of 25 kips.

PierTech Systems is not familiar with vibratory-driven piles.

3.2.7 Atlas Foundation Company

Atlas Foundation is familiar with and has used micropiles in their work. Some stated advantages of micropiles include: used to stabilize existing bridges and can be installed in difficult ground conditions, such as rock. Some stated difficulties include: installation process is complex and needs specialized contractors to install.

Atlas Foundation is familiar with and has used helical screw piles and grouted helical piles. They confirmed that these piles can be used in the construction of new bridge abutments.

They are familiar with drilled displacement piles, but have not used them in their work. They are not familiar with ductile iron piles or geopier foundations. They are not very familiar with vibratory-driven piles.

3.2.8 Scherzinger Drilling

Scherzinger Drilling is familiar with micropiles, but only deals with the drilling side on projects. A stated advantage of micropiles is that they can be used in restricted areas where the use of larger piling systems may not work.

They are not familiar with helical screw piles, grouted helical piles, ductile iron piles, drilled displacement piles, or geopier foundations. They are also not familiar with vibratory-driven piles.

3.2.9 Hayes Drilling, Inc.

Hayes Drilling is familiar with and has used micropiles in their work. Their micropiles have been used for bridge abutment construction. Some stated advantages of micropiles include: can be used in projects with limited access areas and can be used in difficult soils.

Hayes Drilling is not familiar with helical screw piles, grouted helical piles, ductile iron piles, or geopier foundations.

They are familiar with drilled displacement piles but have not used them in their work. A stated advantage of drilled displacement piles was that they result in a better bearing capacity, although they could be a more expensive option.

Hayes Drilling is familiar with and has used vibratory-driven piles. Most of their vibratory-driven piles, however, involve driving a steel casing into the ground for a drilled shaft or caisson. As a result, they do not determine the drivability or bearing capacity of their vibratory-driven piles.

3.2.10 Structural Anchor Supply

Structural Anchor Supply is not familiar with micropiles. They are familiar with helical screw piles and grouted helical piles and have used them in their work. They are a supply company and not a construction company. A stated advantage of both helical screw piles and grouted helical piles is that they can be used in low headroom areas.

Structural Anchor Supply is not familiar with ductile iron piles, drilled displacement piles, geopier foundations, or vibratory-driven piles.

3.2.11 Midwest Diversified Technologies, Inc./now Intech Anchoring Systems

Midwest Diversified Technologies was familiar with and had used micropiles in their work. They stated that micropiles are primarily used in areas of low clearance, restricted access, and in collapsing soil types. Their micropiles are installed without pre-drilling holes. Other stated advantages of micropiles included: can be installed relatively quickly and has a high load resistance when compared to other piling options.

Midwest Diversified Technologies was familiar with and had used helical screw piles and grouted helical piles in their work. They confirmed that helical screw piles and grouted helical piles can be used for bridge abutment construction. Some advantages of both systems include: can be constructed relatively quickly, bearing capacity is predictable and measurable, heavy equipment is not required, have lower costs of installation, can be installed in limited access areas, and limited excavation is required during installation. Each anchor is rated up to 50 tons. Their helical screw piles are available in round or square shafts.

Midwest Diversified Technologies was not familiar with ductile iron piles, drilled displacement piles, geopier foundations, or vibratory-driven piles.

3.2.12 Ground Improvement Engineering

Ground Improvement Engineering is not familiar with micropiles, helical screw piles, ductile iron piles, or drilled displacement piles. They are familiar with and have used geopier foundations in their work. Some stated advantages include: reliable, cost-effective, offers a clean and rapid installation, has excellent settlement control, and can be used to improve difficult soils for construction. One difficulty of geopier foundations is that they need a vibratory hammer for installation.

Ground Improvement Engineering is not familiar with vibratory-driven piles.

3.2.13 D.J. Scheffler & Nye

D.J. Scheffler & Nye is familiar with and has used micropiles. One stated advantage of micropiles is that they can support significant foundation loads. The rebar in micropiles is anchored and protected by high-strength concrete instead of normal-strength concrete. The strength of micropiles stems from its high frictional adherence to the native soil.

D.J. Scheffler & Nye is not familiar with helical screw piles, grouted helical piles, ductile iron piles, drilled displacement piles, geopier foundations, or vibratory-driven piles.

3.2.14 Midwest Foundations Company

Midwest Foundations is not familiar with micropiles, helical screw piles, ductile iron piles, or geopier foundations. One advantage stated for geopier foundations is that they provide high bearing resistance.

Midwest Foundations is familiar with drilled displacement piles, but have not used them in their work.

They are familiar with and have used vibratory-driven piles. They use vibratory hammers to drive steel casing down to bedrock. They do not estimate the drivability or bearing capacity of vibratory-driven piles.

3.2.15 Weber-Balke Foundation Co., Inc.

Weber-Balke Foundation is not familiar with micropiles, helical screw piles, ductile iron piles, or geopier foundations. They are familiar with and have used displacement piles. They are familiar with vibratory-driven piles installed as casings for caissons. They do not perform drivability or bearing capacity estimations for their vibratory driven casings.

3.2.16 Anderson Drilling Inc.

Anderson Drilling is familiar with and has used micropiles in their work. Stated advantages for micropiles include: excellent solution for high axial and lateral loads and cost-effective. Anderson Drilling is familiar with and has used drilled displacement piles.

3.2.17 Schnabel Foundation Company

Schnabel Foundation Company is familiar with and has used micropiles. Some stated advantages of micropiles include: can be installed with relatively small drilling equipment, are a cost-effective solution in difficult subsurface conditions and in low overhead conditions, and can be used where there are natural or man-made obstructions since the drill systems developed for these smaller diameter holes are able to penetrate cobbles, boulders, and other obstructions better than conventional drilled or driven pile systems. Schnabel Foundation Company has successfully installed and tested micropiles in compression to over 600 tons.

They are not familiar with helical screw piles, grouted helical piles, ductile iron piles, drilled displacement piles, or geopier foundations.

3.2.18 HJ Foundation Company

HJ Foundation is not familiar with micropiles, helical screw piles, grouted helical piles, ductile iron piles, or geopier foundations. They are familiar with and have used drilled displacement piles in their work. Their drilled displacement piles are usually specified where the project owner has a desire to keep the piling spoils in the ground.

HJ Foundation is familiar with vibratory-driven sheet piles only, and, as such, they do not determine the drivability or bearing capacity of their vibratory-driven piles.

3.2.19 McKinney Drilling Company

McKinney Drilling is not familiar with micropiles, ductile iron pies, drilled displacement piles, or geopier foundations. They are familiar with helical screw piles and grouted helical piles.

3.2.20 Hayward Baker, Inc.

Hayward Baker is familiar with micropiles. Their micropiles have bearing resistance up to a maximum of 500 tons. Stated advantages include: can be used in restricted access areas and can be used in low headroom conditions.

Hayward Baker is familiar with helical screw piles and grouted helical piles and has used these systems in their work. Helical screw piles and grouted helical piles are quick to install and easy to transport. A detailed understanding of the subsurface conditions is necessary to properly interpret the torque conversion.

3.2.21 Taylor Ridge Drilled Foundations, Inc.

Taylor Ridge Drilled Foundations is not familiar with micropiles, ductile iron piles, drilled displacement piles, or geopier foundations. They are familiar with helical screw piles and grouted helical piles. They confirmed that helical screw piles and grouted helical piles are being used for bridge abutment foundations. The stated advantages of both helical piles include: easy to install, little to no vibration, loads can be immediately applied upon installation, little to no disturbance at the jobsite, and installed torque correlates to bearing resistance.

Taylor Ridge Drilled Foundations is not familiar with vibratory-driven piles.

3.2.22 MB Drilling Foundations

MB Drilling Foundations is familiar with and has used micropiles. They are familiar with vibratory-driven piles for temporary or permanent steel casing and, do not perform drivability or bearing resistance calculations.

MB Drilling Foundations is not familiar with helical screw piles, grouted helical piles, ductile iron piles, drilled displacement piles, or geopier foundations.

3.2.23 Kulchin Drilling Foundation Company

Kulchin Drilling Foundation Company is familiar with micropiles. They are not familiar with helical screw piles, grouted helical piles, ductile iron piles, drilled displacement piles, or geopier foundations. They are familiar with vibratory-driven piles, but have not used them in their work. As a result, they do not determine the drivability and bearing capacity of vibratory-driven piles.

3.2.24 GeoStabilization International

GeoStabilization International is familiar with and has used micropiles. Some advantages stated for micropiles include: can be used in difficult access areas, can be installed up to a depth of 160 ft, and installation is quick.

They are not familiar with helical screw piles, grouted helical piles, ductile iron pies, drilled displacement piles, or geopier foundations.

CHAPTER 4: CONCLUSIONS

Currently used alternative abutment piling systems were identified and investigated in this project. These systems included micropiles, helical piles, grouted helical piles, ductile iron piles, drilled displacement piles, and geopier foundations. The investigations of these systems covered their descriptions, typical bearing resistances, advantages, limitations, and a local road bridge construction project in which each has been used.

In terms of project costs, the advantages and limitations of the alternative abutment piling systems indicate that micropiles and drilled displacement piles can be the most expensive alternatives. This is usually true when any of the other alternative abutment piling systems are also feasible solutions for the project. The total cost of a 39 ft long bridge using helical piles as the foundation was $270,000. The total cost of a 32 ft long bridge using micropiles as the foundation was $1,065,282.

The total project cost for grouted helical piles, ductile iron piles, drilled displacement piles, and geopier foundations were not successfully obtained. However, from the information given in the literature review and survey, it is interpreted that the project cost for grouted helical piles, ductile iron piles, drilled displacement piles, and geopier foundations falls within the range for helical piles and micropiles ($270,000 to $1,065,282).

Design guidance and acceptance criteria for vibratory-driven piles were also studied in this project. This involved the study of methods used to predict the drivability and bearing resistance of a pile to be vibratory-driven, and of methods used to confirm the bearing resistance of the pile after installation.

The popularity of the alternative systems and vibratory-driven piles was investigated in the form of two surveys that targeted Iowa county engineers and engineers from the companies that are active in the design and construction of piling systems.

The survey results showed that most of the counties in Iowa have not endeavored to use alternative abutment piling systems, even though they might be aware of the systems. The survey also showed that all the abutment piling systems studied, as well as vibratory-driven piles, have been successfully used for many projects in the US. This highlights the importance of further investigating alternative abutment piling systems to reduce the cost and improve the quality and ease of construction of low-volume road bridges in Iowa.

REFERENCES

AASHTO. 2016. *AASHTO LRFD Bridge Design Specifications*. 7th Edition. American Association of State Highway Transportation Officials, Washington, DC.

Aktan, H. and U. Attanayake. 2015. *Research on Evaluation and Standardization of Accelerated Bridge Construction Techniques: Part I.* MDOT RC-1618A. Michigan Department of Transportation, Lansing, MI. http://utcdb.fiu.edu/RC-1618A_Part-I_507043_7.pdf.

Basu, P. and M. Prezzi. 2009. *Design and Applications of Drilled Displacement (Screw) Piles*. Geotechnical Engineering, School of Civil Engineering, Purdue University, West Lafayette, IN. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2626&context=jtrp.

Basu, P., M. Prezzi, and D. Basu. 2010. Drilled Displacement Piles – Current Practice and Design. *DFI Journal*, Vol. 4, No. 1, pp. 3–20. http://www.dfi.org/eupdate/DFJAug2010Vol4No1-Final.pdf.

Baltimore. 2013. *The Baltimore Region's Annual Listing of Obligated Projects for FY 2016*. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=6&cad=rja&uact=8&ved=2ahUKEwiakuKst6bkAhVQvKwKHWz2Bi4QFjAFegQIBBAC&url=http%3A%2F%2Fbrtb.dtstiptool.com%2FDocument%2FShow%2F8126&usg=AOvVaw1LoUsAwfSEsM192YzouxBW.

Brown, D. and C. Drew. 2000. Axial Capacity of Augured Displacement Piles at Auburn University. Geo-Denver 2000: New Technological and Design Developments in Deep Foundations, August 5–8, Denver, CO, *Geotechnical Special Publication*, No. 100, pp. 397–403.

BRTB. 2016. *Baltimore Region Transportation Improvement Program 2016–2019*. Baltimore Regional Transportation Board, MD.

CHANCE. 2007. *Helical Pile Foundation Report: A Case History*. CHANCE Civil Construction, Hubbell Power Systems Inc., Centralia, MO. http://www.vickars.com/pdf/01-0703.pdf.

CHANCE. 2012. *CHANCE® Helical Pile Foundation System*. CHANCE Civil Construction, Centralia, MO. https://www.foundationtechnologies.com/files/documents/CHANCE___Helical_Piles_Brochure.pdf.

CHANCE. 2013. *Helical Pulldown® Micropile: Deep Foundation Solutions*. CHANCE Civil Construction, Centralia, MO. https://www.foundationtechnologies.com/files/documents/CHANCE___Helical_Pulldown_Micropile_Brochure.pdf.

Clemence, S. P. and A. J. Lutenegger. 2014. Industry Survey of State of Practice for Helical Piles and Tiebacks. *DFI Journal*, Vol. 9, No. 1, pp. 21–41.

Coduto, D. P. 2001. *Foundation Design: Principles and Practices*. Second Edition. Prentice Hall. Upper Saddle River, NJ.

Danbro Distributors. 2012. Case History - Route 559 Emergency Bridge Replacement. https://www.danbro.com/portfolio/route-559-emergency-bridge-replacement/ and https://www.danbro.com/portfolio/route-559-emergency-bridge-replacement/route-559-emergency-bridge-replacement-2/

Deep Excavation LLC. Micropiles with 3/1 Batter Constructed with RevDrill Tools and Load Test to 272 kips. http://www.deepexcavation.com/en/micropile-construction-case-history.

DuroTerra. n.d. *CarMax Dealership Site Bridge*. Brochure. http://duroterra.com/wp-content/uploads/2016/03/DT_CS_017.1-DuroTerra-Case-Study-CarMax-Dealership-Site-Bridge-End-Bearing-DIPs.pdf.

DYWIDAG. *DYWIDAG Driven Ductile Iron Pile*. DYWIDAG-Systems International. http://www.dywidag-norge.no/wp-content/uploads/2014/11/DSI-DYWIDAG_Geotechnics_Ductile_Iron_Pile_eu_02.pdf.

Elkasabgy, M. and M. H. El Naggar. 2014. Axial Compressive Response of Large-Capacity Helical and Driven Steel Piles in Cohesive Soil. *Canadian Geotechnical Journal*. Vol. 52, No. 2, pp. 224–243.

Feng, Z. and R. J. Deschamps. 2000. A Study of the Factors Influencing the Penetration and Capacity of Vibratory Driven Piles. *Soil and Foundations*, Vol. 40, No. 3, pp. 43–54.

Foundation Supportworks. 2014. *Technical Manual*. Foundation Supportworks, Inc. Omaha, NE. https://commercial.foundationsupportworks.com/core/images/universal/fsi-tech-10-16/files/assets/common/downloads/publication.pdf.

Fox, N. S., L. R. Weppler, and R. Scherback. 2004. Geopier Soil Reinforcement System – Case Histories of High Bearing Capacity Footing Support and Floor Slab Support. Fifth International Conference on Case Histories in Geotechnical Engineering, April 13–17, New York, NY. https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=2301&context=icchge.

GeoStructures, Inc. n.d. Case Studies: 11th Street Bridges. http://www.geostructures.com/case_study/11th-street-bridges.

Helical Anchors. 2014. *Engineering Design Manual*. Helical Anchors, Inc., Minneapolis, MN. http://www.helicalanchorsinc.com/wp-content/uploads/2015/06/Helical-Anchor-Inc-Engineering-Manual-Rev-02.pdf.

Helical Drilling Inc. n.d. Deep Foundations/Piles: Displacement Piles. https://helicaldrilling.com/expertise/deep-foundations-piles/#displacementpiles.

Hoyt, R. M. and S. P. Clemence. 1989. Uplift Capacity of Helical Anchors in Soil. Twelfth International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil, August, 13–18, Vol. 2, pp. 1019–1022

Jonker, G. 1987. Vibratory Pile Driving Hammers for Oil Installation and Soil Improvement Projects. Nineteenth Annual Offshore Technology Conference, Dallas, TX, pp. 549–560.

Klaiber, F. W., D. J. White, T. J. Wipf, B. M. Phares, and V. W. Robbins. 2004a. *Development of Abutment Design Standards for Local Bridge Designs, Volume 1 of 3: Development of Design Methodology*. Iowa State University, Department of Civil and Construction Engineering, Ames, IA.

Klaiber F. W., T. J. Wipf, and F. M. Russo. 2004b. *NCHRP Synthesis 327: Cost-Effective Practices for Off-System and Local Interest Bridges*. National Cooperative Highway Research Program, Washington, DC.

Lamiman, E. C. and B. Robinson. 2014. Bearing Capacity Reduction of Vibratory Installed Large Diameter Pipe Piles. Geo-Concgress 2014: From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering, February 23–26. Atlanta, GA.

Mosher, R. L. 1990. Axial Capacity of Vibratory-Driven Piles versus Impact-Driven Piles. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1277, pp. 128–135.

NeSmith, Jr., W. M. 2015. Recent Developments in ACIP and DD Piling. Proceedings of the 2015 Minnesota Geotechnical Society Annual Conference, February 20, Minneapolis, MN. https://www.berkelandcompany.com/images/berkel/categories/TechResources/technical-papers/2015%20Recent%20Developments%20in%20ACIP%20and%20DD%20Piling%20NeSmith.pdf.

O'Neill, M. W., C. Vipulanandan, and D. O. Wong. 1990. Evaluation of Bearing Capacity of Vibro-Driven Piles from Laboratory Experiments. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1277, pp. 112–119.

Perkins, S. 2015. *Survey of Micropile Use in Neighboring Western States*. Montana State University, Department of Civil Engineering, Bozeman, MT.

Perko, H. A. 2009. *Helical Piles: A Practical Guide to Design and Installation*. John Wiley & Sons, Inc., Hoboken, NJ.

Prezzi, M. and P. Basu. 2005. Overview of Construction and Design of Auger Cast-in-Place and Drilled Displacement Piles. 30th Annual Conference on Deep Foundations, Chicago, IL. pp. 497–512.

Rabeler, R. C., T. H. Bedenis, and M. J. Thelen. 2000. High Capacity Drilled Cast-In-Place Piles. Geo-Denver 2000: New Technological and Design Developments in Deep Foundations, August 5–8, Denver, CO, *Geotechnical Special Publication*, No. 100, pp. 125–139.

Rausche, F. 2002. Modeling of Vibratory Pile Driving. TransVib2002 International Conference on Vibratory Driving and Soil Compaction, September 8–10, Louvain-la-Neuve, Belgium. https://www.pile.com/wp-content/uploads/2017/03/vibratoryPile.pdf.

Rausche, F. 2012. Driveability and Dynamic Capacity Estimation for Vibratory Driven Piles. *Pile Driver*, Vol. Q1, pp. 81–88. https://www.pile.com/wp-content/uploads/2017/03/PD_Q1_2012_pg81-88.pdf.

Sabatini, P. J., B. Tanyu, T. Armour, P. Groneck, and J. Keeley. 2005. *Micropile Design and Construction Reference Manual*. FHWA-NHI-05-039. Federal Highway Administration, Washington, DC. https://www.earth-engineers.com/earthengineers/pdfs/FHWA%20Micropile%20Design%20and%20Construction%20%282005%20version%29.pdf.

Sakr, M. 2010. High Capacity Helical Piles – A New Dimension for Bridge Foundations. 8th International Conference on Short and Medium Span Bridges, August 3–6, Niagara Falls, Canada. https://helicalpileworld.com/High%20Capacity%20Helical%20Piles%20-%20A%20New%20Dimension%20for%20Bridge%20Foundations%20by%20Dr.%20Mohammed%20Sakr.pdf.

Sakr, M. 2011. Installation and Performance Characteristics of High Capacity Helical Piles in Cohesionless Soils. *DFI Journal*, Vol. 5, No. 1, pp. 39–57. https://helicalpileworld.com/Dr.%20Sakr%20-%20Installation%20and%20Performance%20Characteristics%20of%20High%20Capacity%20Helical%20Piles%20in%20Cohesionless%20Soils.pdf.

Schmidt, F. and T. N. Dobras. 2009. Driven Ductile Iron Pipe Piles Design, Installation and Performance. International Foundation Congress and Expo 2009: Contemporary Topics in Deep Foundations, March 15–19. Orlando, FL. https://ascelibrary.org/doi/pdf/10.1061/41021%28335%2937. pp. 295–302

Vickars, R. A. and S. P. Clemence. 2000. Performance of Helical Piles with Grouted Shafts. Geo-Denver 2000: New Technological and Design Developments in Deep Foundations, August 5–8, Denver, Co, *Geotechnical Special Publication*, No. 100, pp. 327–341. https://ascelibrary.org/doi/pdf/10.1061/40511%28288%2923.

Yang, Z. X., R. J. Jardine, B. T. Zhu, P. Foray, and C. H. C. Tsuha. 2010. Sand Grain Crushing and Interface Shearing During Displacement Pile Installation in Sand. *Geotechnique*, Vol. 60, No. 6, pp. 469–482. https://spiral.imperial.ac.uk/bitstream/10044/1/14126/2/Geotechnique_60_6_2010.pdf.

APPENDIX: QUESTIONNAIRE

Part 1

1. First name:
2. Last name:
3. Affiliation:
4. Email:
5. Phone:
6. How familiar are you with micropiles?
   i. List the main advantages of micropiles.
   ii. List the main difficulties of using micropiles.
7. How familiar are you with helical screw piles?
   i. List the main advantages of helical screw piles.
   ii. List the main difficulties of using helical screw piles.
8. How familiar are you with grouted helical screw piles?
   i. List the main advantages of grouted helical screw piles.
   ii. List the main difficulties of using grouted helical screw piles.
9. How familiar are you with ductile iron piles?
   i. List the main advantages of ductile iron piles.
   ii. List the main difficulties of using ductile iron piles.
10. How familiar are you with drilled displacement piles?
    i. List the main advantages of drilled displacement piles.
    ii. List the main difficulties of using drilled displacement piles.
11. How familiar are you with geopier foundations?
    i. List the main advantages of geopier foundations.
    ii. List the main difficulties of using geopier foundations.
12. Are there any other abutment piling system(s) you are familiar with, but are not stated in this survey?
    i. List the piling systems that you would like to add.
    ii. List the main advantages and difficulties of them.

Part 2

13. Are you familiar with vibratory-driven piles?
14. Does your jurisdiction perform calculations to determine drivability and/or bearing capacity of vibratory-driven piles?
15. Does your jurisdiction use GRL Wave Equation Analysis Program (GRL WEAP) to determine the drivability and/or bearing capacity of vibratory-driven piles?
    i. List the main questions/difficulties of using GRL WEAP?
16. Does your jurisdiction use Pile Driving Analyzer (PDA) to determine the drivability and/or bearing capacity of vibratory-driven piles?
    i. List the main questions/difficulties of using PDA?
17. Does your jurisdiction use Case Pile Wave Analysis Program (CAPWAP) to determine the drivability and/or bearing capacity of vibratory-driven piles?
    ii. List the main questions/difficulties of using CAPWAP?
18. List any other technology/software used by your jurisdiction to determine the drivability and/or bearing capacity of vibratory-driven piles.
19. How does your jurisdiction confirm the bearing capacity of an installed vibratory-driven pile?