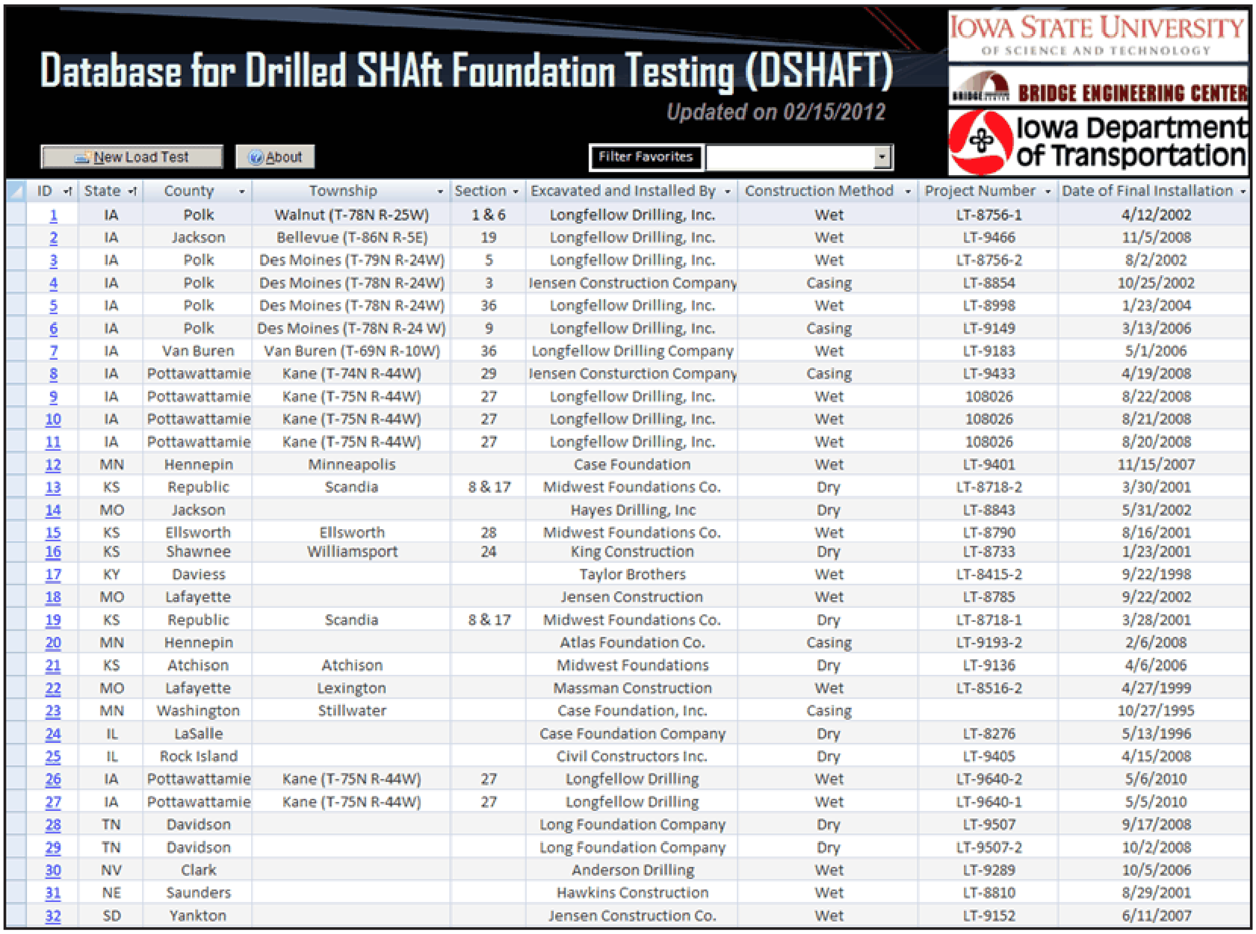
Development of a Database for Drilled SHAft Foundation Testing (DSHAFT)

BRIDGE ENGINEERING CENTER

Final Report
June 2012



Database for Drilled SHAft Foundation Testing (DSHAFT)

Updated on 02/15/2012

ID	State	County	Township	Section	Excavated and Installed By	Construction Method	Project Number	Date of Final Installation
1	IA	Polk	Walnut (T-78N R-25W)	1 & 6	Longfellow Drilling, Inc.	Wet	LT-8756-1	4/12/2002
2	IA	Jackson	Bellevue (T-86N R-5E)	19	Longfellow Drilling, Inc.	Wet	LT-9466	11/5/2008
3	IA	Polk	Des Moines (T-79N R-24W)	5	Longfellow Drilling, Inc.	Wet	LT-8756-2	8/2/2002
4	IA	Polk	Des Moines (T-78N R-24W)	3	Iensen Construction Company	Casing	LT-8854	10/25/2002
5	IA	Polk	Des Moines (T-78N R-24W)	36	Longfellow Drilling, Inc.	Wet	LT-8998	1/23/2004
6	IA	Polk	Des Moines (T-78N R-24 W)	9	Longfellow Drilling, Inc.	Casing	LT-9149	3/13/2006
7	IA	Van Buren	Van Buren (T-69N R-10W)	36	Longfellow Drilling Company	Wet	LT-9183	5/1/2006
8	IA	Pottawattamie	Kane (T-74N R-44W)	29	Iensen Consturction Company	Casing	LT-9433	4/19/2008
9	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling, Inc.	Wet	108026	8/22/2008
10	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling, Inc.	Wet	108026	8/21/2008
11	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling, Inc.	Wet	108026	8/20/2008
12	MN	Hennepin	Minneapolis		Case Foundation	Wet	LT-9401	11/15/2007
13	KS	Republic	Scandia	8 & 17	Midwest Foundations Co.	Dry	LT-8718-2	3/30/2001
14	MO	Jackson			Hayes Drilling, Inc	Dry	LT-8843	5/31/2002
15	KS	Ellsworth	Ellsworth	28	Midwest Foundations Co.	Wet	LT-8790	8/16/2001
16	KS	Shawnee	Williamsport	24	King Construction	Dry	LT-8733	1/23/2001
17	KY	Daviess			Taylor Brothers	Wet	LT-8415-2	9/22/1998
18	MO	Lafayette			Jensen Construction	Wet	LT-8785	9/22/2002
19	KS	Republic	Scandia	8 & 17	Midwest Foundations Co.	Dry	LT-8718-1	3/28/2001
20	MN	Hennepin			Atlas Foundation Co.	Casing	LT-9193-2	2/6/2008
21	KS	Atchison	Atchison		Midwest Foundations	Dry	LT-9136	4/6/2006
22	MO	Lafayette	Lexington		Massman Construction	Wet	LT-8516-2	4/27/1999
23	MN	Washington	Stillwater		Case Foundation, Inc.	Casing		10/27/1995
24	IL	LaSalle			Case Foundation Company	Dry	LT-8276	5/13/1996
25	IL	Rock Island			Civil Constructors Inc.	Dry	LT-9405	4/15/2008
26	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling	Wet	LT-9640-2	5/6/2010
27	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling	Wet	LT-9640-1	5/5/2010
28	TN	Davidson			Long Foundation Company	Dry	LT-9507	9/17/2008
29	TN	Davidson			Long Foundation Company	Dry	LT-9507-2	10/2/2008
30	NV	Clark			Anderson Drilling	Wet	LT-9289	10/5/2006
31	NE	Saunders			Hawkins Construction	Wet	LT-8810	8/29/2001
32	SD	Yankton			Jensen Construction Co.	Wet	LT-9152	6/11/2007

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16. Abstract

Drilled shafts have been used in the US for more than 100 years in bridges and buildings as a deep foundation alternative. For many of these applications, the drilled shafts were designed using the Working Stress Design (WSD) approach. Even though WSD has been used successfully in the past, a move toward Load Resistance Factor Design (LRFD) for foundation applications began when the Federal Highway Administration (FHWA) issued a policy memorandum on June 28, 2000.The policy memorandum requires all new bridges initiated after October 1, 2007, to be designed according to the LRFD approach. This ensures compatibility between the superstructure and substructure designs, and provides a means of consistently incorporating sources of uncertainty into each load and resistance component.

Regionally-calibrated LRFD resistance factors are permitted by the American Association of State Highway and Transportation Officials (AASHTO) to improve the economy and competitiveness of drilled shafts. To achieve this goal, a database for Drilled SHAft Foundation Testing (DSHAFT) has been developed. DSHAFT is aimed at assimilating high quality drilled shaft test data from Iowa and the surrounding regions, and identifying the need for further tests in suitable soil profiles.

This report introduces DSHAFT and demonstrates its features and capabilities, such as an easy-to-use storage and sharing tool for providing access to key information (e.g., soil classification details and cross-hole sonic logging reports). DSHAFT embodies a model for effective, regional LRFD calibration procedures consistent with PIle LOad Test (PILOT) database, which contains driven pile load tests accumulated from the state of Iowa. PILOT is now available for broader use at the project website: http://srg.cce.iastate.edu/lrfd/. DSHAFT, available in electronic form at http://srg.cce.iastate.edu/dshaft/, is currently comprised of 32 separate load tests provided by Illinois, Iowa, Minnesota, Missouri and Nebraska state departments of transportation and/or department of roads. In addition to serving as a manual for DSHAFT and providing a summary of the available data, this report provides a preliminary analysis of the load test data from Iowa, and will open up opportunities for others to share their data through this quality–assured process, thereby providing a platform to improve LRFD approach to drilled shafts, especially in the Midwest region.

17. Key Words
bridge deep foundations—drilled shaft load tests—electronic database—Load and Resistance Factor Design (LRFD)

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Final Report
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The authors would also like to thank the Illinois, Iowa, Minnesota, and Missouri, DOTs and the Nebraska Department of Roads (DOR) for providing valuable drilled shaft load test reports for developing the DSHAFT database, as well as members from the technical advisory committee for their guidance and advice: Ahmad Abu-Hawash, Ken Dunker, Mark Dunn, Kyle Frame, Steve Megivern, Michael Nop, and Bob Stanley. The members of this committee represent Bridges and Structures, Soils Design, Construction, and Research and Technology Bureau of the Iowa DOT. The authors also thank Muhannad Suleiman for his contribution at the initial stage of the project.

EXECUTIVE SUMMARY

Problem Statement

Drilled shafts have been used in the US for more than 100 years in bridges and buildings as a deep foundation alternative. For many of these applications, the drilled shafts were designed using the Working Stress Design (WSD) approach. Even though WSD has been used successfully in the past, a move toward Load Resistance Factor Design (LRFD) for foundation applications began when the Federal Highway Administration (FHWA) issued a policy memorandum in 2000 requiring all new bridges initiated after October 1, 2007 to be designed using the LRFD approach.

The American Association of State Highway and Transportation Officials (AASHTO) recommends resistance factors based on general soil classification, which results in an overly conservative and less cost-effective drilled shaft design. Because bridge foundation systems generally account for as much as 30 percent of the entire bridge cost, a regional calibration of resistance factors is permitted by AASHTO to improve the economy of foundations and to make the drilled shaft option competitive with the driven pile foundation.

The goal of this project was to develop a quality assured, electronic Database for Drilled SHAft Foundation Testing (DSHAFT), which is intended to establish LRFD resistance factors for the design of drilled shafts in the Midwest region. To achieve this goal, available static load test information was collected, reviewed, and integrated into DSHAFT using Microsoft Office Access™. In doing so, an efficient, easy-to-use filtering and capability was provided to DSHAFT, along with easy access to original field records in an electronic format.

Background

Drilled shaft foundations are large diameter, cast-in-place piles that support axial loads though a combination of shaft and end bearing resistances. They are referred to as bored piles, caissons, cast-in-drilled-hole piles (CIDH), continuous-flight-auger piles (CFA), displacement auger-cast piles, and drilled piers. Since the 1900s several cities in the US have used caissons or shafts to support buildings and transportation structures.

Originally, the construction of shafts was done by hand, and it was not until the 1920s that machine-drilled shafts were being developed. Today’s drilling techniques range from small truck-mounted equipment to modern machines capable of drilling large, deep holes suitable for drilled shafts through very hard subsurface materials.

Project Objectives

- Provide a means of electronic storage for all past, present, and future Iowa Department of Transportation (DOT) drilled shaft load test data for subsequent reference and analysis
- Collect, review, and integrate data from available static load tests in Iowa and other states on drilled shafts into a quality assured, electronic database, using Microsoft Office Access™
- Make filtering, sorting, and querying procedures more efficient by using a collective dataset designed in the display form
- Be housed on a website so that the information can be shared with designers and researchers

Research Description

Thirty-two drilled shaft load tests were performed and provided by the Iowa, Illinois, Minnesota, and Missouri DOTs and Nebraska Department of Roads (DOR). In addition, the load test performed in Tennessee was located in a report titled *Load Testing of Drilled Shaft Foundation in Limestone, Nashville, TN* (Brown 2008).

The detailed information provided in most of the reports includes location, construction details, subsurface conditions, drilled shaft geometry, load testing methods and results, and concrete quality. Because the available information was stored in several different locations and formats, the process to calibrate the LRFD resistance factors would have proved inefficient.

After the available information was implemented into the database, a preliminary calibration of LRFD resistance factors was performed to find if a sufficient amount of information is available for a regional calibration. The preliminary analysis was completed using the 13 datasets collected in Iowa.

From this analysis, it was concluded that more load tests must be included into the database for accurate calibration of suitable resistant factors. As a result, load test information was included from surrounding states.

Key Features of DSHAFT

- Because the resistance factors will be calibrated using the information included in the database, it is vital to have a strict acceptance criteria for reports being entered into DSHAFT to make the LRFD regional calibration of superior quality and consistency.
- Not all load test reports found and input into the database contain complete information. This data was included even though some of the information was missing, such as a detailed bore log. The rationale is that each one has the potential to be qualified once the information has been made available. To notify the user when this occurs, the usable data sets are identified by a yes/no category titled usable data.
- Only two axial load test methods, the Osterberg and Statnamic, are included in the database because, they are not only the most prevalent load tests in the region, but they are also preferred by most DOTs.

- The distinctions between Osterberg and Statnamic load tests are critical because the data contained in each of the reports is different. The data from either report can be used to determine the capacity of the drilled shaft by using a different technique.
- A major aspect when analyzing the results of axial load tests on drilled shafts is the soil profile classification, as each category behaves differently and affects the capacity of the drilled shaft accordingly. The soil profile classification system devised for DSHAFT is a series of guidelines to be used on soil information provided in the load test report.
- The performance of a drilled shaft dramatically changes when a portion of the shaft is embedded into rock, known as a rock socket. In DSHAFT, rock sockets are identified by a Rock Socketed? yes/no category to account for the potential increase in end bearing and shaft resistance.
- A quality control measure incorporated into the DSHAFT database is to include the Cross-Hole Sonic Logging (CSL) report, when available.

Implementation Readiness

The construction method and quality control of construction still have a large impact on the drilled shaft and should be taken into consideration when calibrating the regional resistance factors. A set of acceptable guidelines for tolerances during construction should be included with the new resistance factors.

Additional load tests, along with detailed analyses, are needed to provide an accurate statistical calibration of the resistance factors for the final calibration.

Implementation Benefits

- DSHAFT embodies a model for effective, regional LRFD calibration procedures consistent with the PIle LOad Test (PILOT) database available at http://srg.cce.iastate.edu/lrfd/, which currently contains driven pile load tests accumulated from the state of Iowa.
- DSHAFT allows for collecting, reviewing, and integrating data from available static load tests on drilled shafts into an electronic database. In doing so, efficient, easy-to-use filtering and storage capabilities are available to provide a basis for analytical procedures on the datasets.
- DSHAFT is housed on a website so that the information can be easily shared with designers and researchers. The value of DSHAFT comes with the use of this website by Iowa State University and can be found at http://srg.cce.iastate.edu/dshaft.
- The easy-to-query interface for DSHAFT allows researchers and designers to further filter the data to fit their needs.
- To ensure the superior quality of DSHAFT, strict acceptance criteria for the available test information was used. The quality assurance of the data is the driving factor when adding each new dataset to the database.

1. INTRODUCTION

Most bridges in Iowa are supported on deep foundations, with driven steel H-piles being the preferred option. A survey of 298 state highway officials, Transportation Research Board (TRB) representatives and state and Federal Highway Administration (FHWA) geotechnical engineers, was conducted by the FHWA on the use of various foundation alternatives and found that of those who responded, 64 percent prefer driven piles, compared to only 5 percent preferring drilled shafts (Paikowsky 2004). Even though H-piles are almost always used, it does not imply that they are always the most cost-effective substructure solution under all soil and construction conditions.

Drilled shafts have the potential to become an economical alternative when considering a deep foundation due to many advantages associated with this type of foundation. The shafts are relatively easy to construct in firm cohesive soils, and can be constructed in caving or karstic soils through the use of casing or slurry. Some of the biggest advantages of drilled shafts are that they a) can be built directly on rock, b) normally have a higher load-carrying capacity, and c) generally do not have large settlements (NCHRP Report 360 2006). Drilled shafts also do not require pile cap and associated connections. In many cases, a single drilled shaft can replace a pile group (Paikowsky 2006). Several state departments of transportation (DOTs) are increasingly using drilled shafts in substructure design. In Iowa, drilled shafts are not used often even though the soil conditions in many of Iowa’s regions are ideal for using this type of foundation.

The FHWA mandated the use of Load and Resistance Factor Design (LRFD) approach for designing foundation elements on October 1, 2007. The American Association of State Highway and Transportation Officials (AASHTO) recommends resistance factors based on general soil classification, which results in an overly conservative and less cost-effective drilled shaft design. Since bridge foundation systems generally account for as much as 30 percent of the entire bridge cost, a regional calibration of resistance factors is permitted by AASHTO to improve the economy of foundations and to make the drilled shaft option competitive with the driven pile foundation.

New resistance factors for driven piles have been developed for Iowa’s different soil types (AbdelSalam et al. 2011, AbdelSalam et al. 2012), using the PIle LOad Test (PILOT) Database (Roling et al. 2010) and a set of new field tests (Ng et al. 2011). This effort was undertaken to improve the design of driven pile foundations through the use of significantly higher resistance factors than those currently recommended in the AASHTO LRFD Bridge Design Specifications (2007).This effort will make the design of drilled shafts less cost competitive unless a similar effort is undertaken for this foundation option. The current resistance factors recommended by AASHTO LRFD specifications for drilled shaft design were derived from the Working Stress Design (WSD) factors of safety to maintain a consistent level of reliability of previous design. These resistance factors are very conservative because they provide resistance factors for general soil types found in the US.

Allen (2005) compared the resistance factors calibrated for drilled shafts with those obtained from fitting to Allowable Stress Design (ASD) and those determined using the Reliability Theory from various studies. When calibrated from local test data, the regional resistance factors for drilled shafts will produce a more efficient foundation design, with the possibility of significantly reducing the cost of construction. Consequently, regional calibration of resistance factors will make drilled shafts a competitive foundation option when compared to driven piles.

When calibrating resistance factors for drilled shafts, a few challenges need to be taken into consideration to assure the performance of the substructure. Construction practice is a major issue when it comes to the performance of the drilled shaft because the drilling technique influences the disturbance of the bottom of the excavated hole (Osterberg 1999). In addition, high variability between soil types is a major challenge when predicting the capacity of the drilled shaft. It was found that in harder shale bedrock formations, the shaft and end bearing capacities measured from an Osterberg test were well above the predicted capacity of Colorado Standard Penetration Test (SPT) based design method (Abu-Hejleh 2005), as may be the case in other locations. Finally, lower redundancy than traditional steel H-piles leaves little room for error in design and construction. In order to improve the design of drilled shafts, it is vital to calibrate regional resistance factors with a strict set of criteria and guidelines.

The purpose of this report is to introduce the Database for Drilled SHAft Foundation Testing (DSHAFT), which is intended to establish LRFD resistance factors for the design of drilled shafts in the Midwest region. As illustrated in Figure 1.1. Distribution of drilled shaft load tests reported in DSHAFT by location , a total of thirty-two drilled shaft load tests have been performed and provided by the Iowa, Illinois, Minnesota, and Missouri DOTs and Nebraska Department of Roads (DOR). Additionally, the load test performed in Tennessee was located in a report titled "Load Testing of Drilled Shaft Foundation in Limestone, Nashville, TN" (Brown 2008). The detailed information provided in most of the reports included location, construction details, subsurface conditions, drilled shaft geometry, load testing methods and results, and concrete quality. Because the available information was stored in several different locations and formats, the process to calibrate the LRFD resistance factors would have proved inefficient. The goal when creating DSHAFT was to collect, review, and integrate data from available static load tests on drilled shafts into a quality assured, electronic database, using Microsoft Office Access^{TM}. In doing so, an efficient, easy-to-use filtering and storage location was completed to provide a basis for analytical procedures on the available datasets.

After the available information was implemented into the database, a preliminary calibration of LRFD resistance factors was performed to find if sufficient amount of information is available for a regional calibration. The preliminary analysis was completed using the 13 datasets collected in Iowa. Table 1 provides a brief summary of the information used to complete this calibration. From this analysis, it was concluded that more load tests must be included into the database for calibration. As a result, load test information was included from surrounding states.

In the following chapters of this report, a detailed description of the importance of creating DSHAFT, the structure and key parameters used in the development of this database, and the preliminary analysis will be given. A description of the available dataset upon which the database was originally fashioned will also be provided, followed by a comprehensive review of all fields contained within the database.

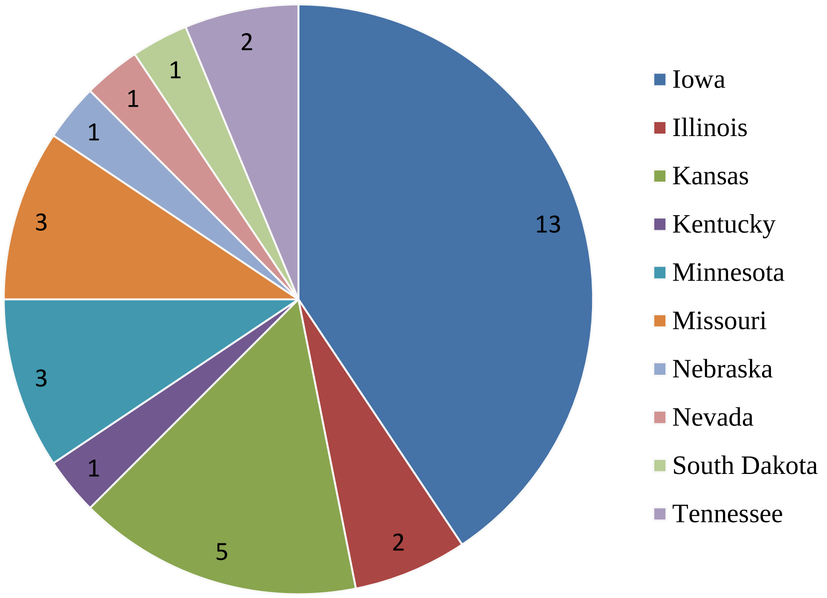


Figure 1.1. Distribution of drilled shaft load tests reported in DSHAFT by location

Table 1.1. Summary of 13 drilled shaft datasets collected in Iowa

ID Number	Diameter (ft)	Embedded Length (ft)	Brief Soil Description		Rock Socketed	Construction Method	Load Test Method
			Shaft	Toe			
1	4	67.9	Silty G.C.	Shale	Yes	Wet	O-cell
2	3	12.7	Weathered Dolomite	Weathered Dolomite	Yes	Wet	O-cell
3	4	65.8	Silty G.C.	Clay Shale	Yes	Wet	O-cell
4	3.5	72.7	Sandy G.C. and Medium Sand	Clay Shale	Yes	Casing	O-cell
5	4	79.3	Sandy Lean Clay and Clay Shale	Clay Shale	Yes	Wet	O-cell
6	2.5	64	Silty Clay	Sandy G.C.	No	Casing	O-cell
7	3	34	Lean Clay and Limestone	Limestone	Yes	Wet	O-cell
8	5.5	105.2	Silty Clay and Sand	Limestone	Yes	Casing	O-cell
9	5	66.25	Silty Clay and Sand	Coarse Sand	No	Wet	Statnamic
10	5	55.42	Silty Clay and Fine Sand	Coarse Sand	No	Wet	Statnamic
11	5	54.78	Silty Clay and Fine Sand	Coarse Sand	No	Wet	Statnamic
26	5	75.17	Lean clay and Fine Sand	Fine Sand	No	Wet	O-cell
27	5	75	Lean clay and Fine Sand	Fine Sand	No	Wet	O-cell

G.C. – glacial clay

2. BACKGROUND

Drilled shaft foundations are large diameter, cast-in-place piles that support axial loads though a combination of shaft and end bearing resistances. They are referred to as bored piles, caissons, cast-in-drilled-hole piles (CIDH), continuous-flight-auger piles (CFA), displacement auger-cast piles, and drilled piers. Since the 1900s, several cities in the US have used caissons or shafts to support buildings and some transportation structures. Originally these shafts were excavated by hand; it was not until the 1920s that machine-drilled shafts were being developed. Today's drilling techniques range from small truck mounted equipment to modern machines capable of drilling large, deep shafts through very hard materials.

Using the different construction techniques, drilled shafts can be installed in a variety of soil and rock profiles. The methods for construction of drilled shafts can be grouped into three broad categories of dry method, casing method, and wet method. For firm clays, intermediate geomaterial (IGM), and rock profiles, the dry method can generally be used for construction. The advantages of using this method are it is the least expensive of the construction methods and it allows the borehole to be visually inspected. The process for constructing a drilled shaft using the dry method is depicted in Figure 2.1. Dry method of construction: (a) drill the hole, (b) clean the base, (c) place reinforcement, and (d) place concrete (FHWA 2010).

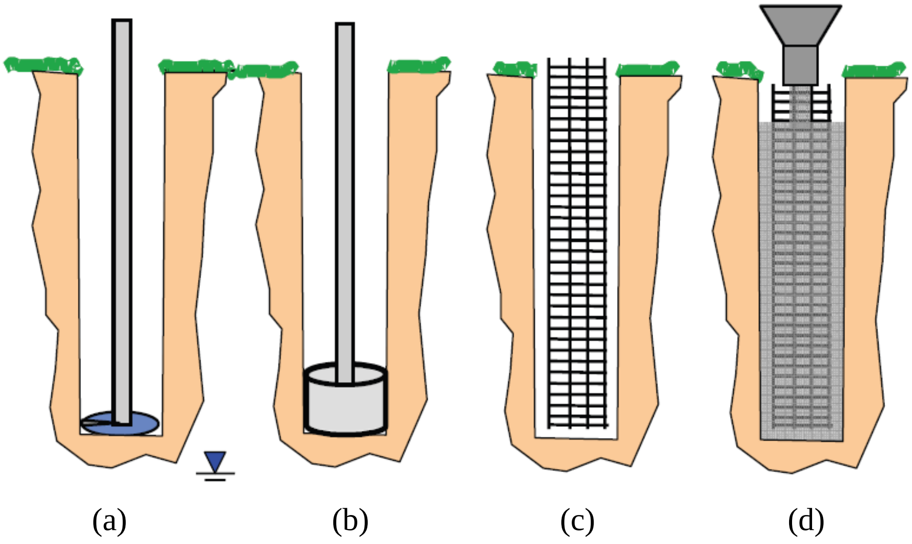


Figure 2.1. Dry method of construction: (a) drill the hole, (b) clean the base, (c) place reinforcement, and (d) place concrete (FHWA 2010)

If the possibility of having caving soils, excessive soil, or rock deformation exists while excavating the drilled shaft is present, the casing method is used. In addition, casing can be used in karstic soils where caves are present below grade and in excavations through water. There are three commonly used methods for installing the casing (FHWA 2010): (1) begin excavation using the dry method and then install the casing into the hole, (2) begin excavation using a starter hole filled with slurry and install the casing to the bearing stratum as shown in Figure 2., and (3) install casing before excavation, depicted in Figure 2..

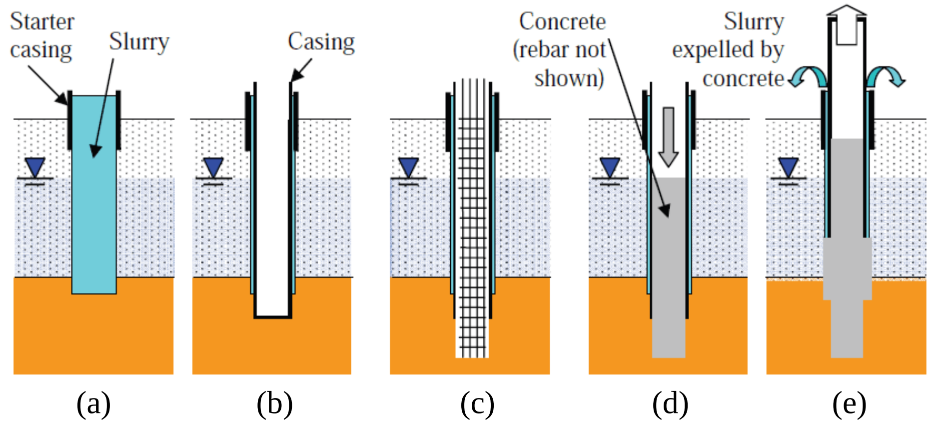


Figure 2.2. Construction using casing through slurry-filled starter hole: (a) drill with slurry; (b) set casing and bail slurry; (c) complete and clean excavation, set reinforcing; (d) place concrete to head greater than external water pressure; (e) pull casing while adding concrete (FHWA 2010)

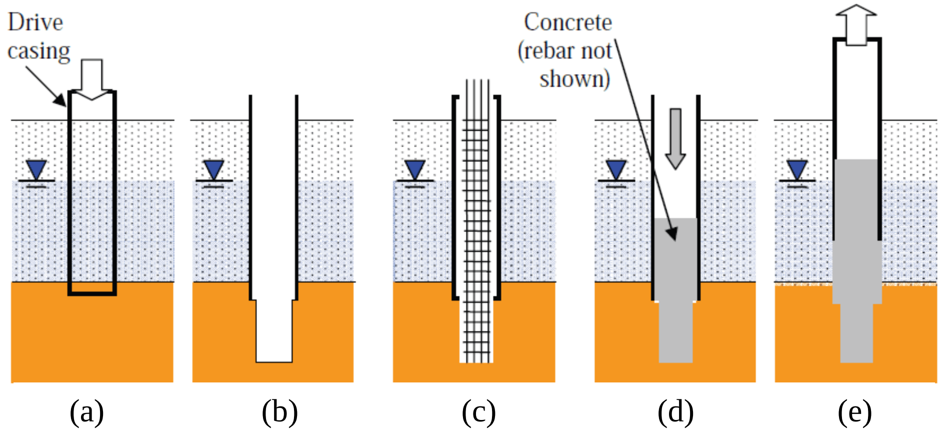


Figure 2.3. Construction using casing advanced ahead of excavation: (a) drive casing into bearing stratum; (b) drill through casing; (c) complete and clean hole, set reinforcing; (d) place concrete to head greater than external water pressure; (e) pull casing while adding concrete (FHWA 2010)

For soil conditions that prohibit the dewatering of the shaft excavation, the wet method for construction is used. The wet method uses a mineral or polymer slurry to provide stability and prevent inflow of groundwater (FHWA 2010). The wet method is normally preferred over permanent casing due to the lower cost. Figure 2. shows the process of constructing a drilled shaft using the wet method.

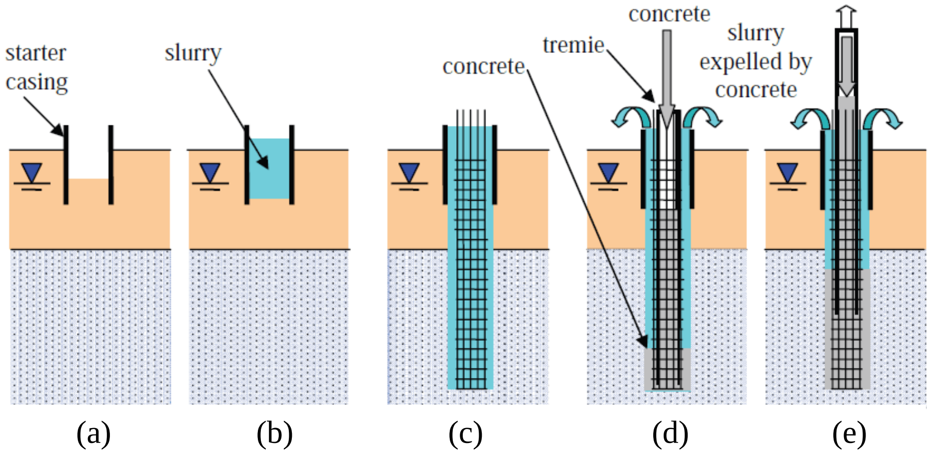


Figure 2.4. Slurry drilling process: (a) set starter casing; (b) fill with slurry; (c) complete and clean excavation, set reinforcing; (d) place concrete through tremie; and (e) pull tremie while adding concrete (FHWA 2010)

The most efficient design for a drilled shaft is when a hard bearing layer is present to allow for large axial resistance by means of end bearing with a small footprint. Many times, one single drilled shaft can take the place of a pile group, eliminating the need for a pile cap and pile-to-cap connections. In addition, when the casing method is employed to construct the drilled shaft in water, the permanent casing eliminates the need for a cofferdam. Drilled shafts reduce noise and vibrations that are caused when piles are driven, which is an important consideration in urban settings.

In many cases, drilled shafts are socketed into rock. The Iowa DOT almost routinely requires a drilled shaft to be socketed into rock a minimum distance of 1½ times the shaft diameter (Iowa DOT 2011). Rock sockets are used because they increase the end bearing capacity, significantly enhancing the efficiency of the drilled shaft due to the large end bearing area when compared to that of a driven pile. For example, a typical steel H-pile would be a HP 10x57 with an area of 16.8 in.^{2}, while a diameter of a drilled shaft typically ranges from 3 to 12 ft. A 3-ft diameter drilled shaft would have an area of 1,018 in.^{2}, which is 60 times more than that of HP 10x57. Drilled shafts that are not socketed into rock are known as floating shafts (FHWA 2010). They still have an end bearing resistance, but it is greatly reduced.

The current design philosophy for drilled shafts used by the Iowa DOT is LRFD, but regional resistance factors for drilled shafts have not been calibrated. The *Iowa LRFD Bridge Design Manual* (Iowa DOT 2011) references *AASHTO LRFD Bridge Design Specifications* (2007) and *Drilled Shafts: Construction Procedures and LRFD Design Methods* (Brown et al. 2010) for general drilled shaft design, unless otherwise specified in the manual. The goal of LRFD foundation design is to ensure compatibility between superstructure and substructure designs and to facilitate uniformity to reduce errors when passing information, such as loads, to the foundation designer. In order to incorporate accurate sources of uncertainty into each load and resistance component, regional calibration of resistance factors must be completed.

3. SIGNIFICANCE OF DSHAFT

AASHTO has developed resistance factors for general soil profiles to provide a means to start moving forward in the process of LRFD design of drilled shafts. These resistance factors were calibrated using the WSD factors of safety to maintain consistent results while still ensuring the same level of safety. AASHTO supports the research for calibrating regional resistance factors in accordance with the desired reliability for design, as a means to improve the reliability, economy, and competitiveness of drilled shafts. In order to accomplish regional calibration, historical drilled shaft load tests must be compiled in order to analyze past experience. Through the use of axial load tests, resistance factors can be developed that will produce a more reliable and economic design.

The PILOT database (Roling et al. 2011), comprising driven pile load tests located in Iowa, provided a template for the design of DSHAFT with the intent for it to embody a model for effective regional LRFD calibration procedures consistent with driven piles. From this database, resistance factors for Iowa were calibrated and are being implemented into the *Iowa LRFD Bridge Design Manual* (Iowa DOT 2010).

Other state DOTs, such as Florida (McVay et al. 2003), Kansas (Yang et al. 2010), Louisiana (Abu-Farsakh et al. 2010), and Ohio (Nusairat et al. 2011), have calibrated regional resistance factors for drilled shafts, but no database information has been made available for the public to use. In addition, NCHRP 507 (Paikowsky 2004) outlines the calibration of resistance factors using a database developed by University of Florida, but has limited information with regards to the actual load tests. Without the data, it is difficult to determine the quality of the information used to calibrate the resistance factors. DSHAFT is housed on a website so that the information can be shared with designers and researchers. The value of DSHAFT comes with the use of this website by Iowa State University and can be found at http://srg.cce.iastate.edu/dshaft.

Because the resistance factors will be calibrated using the information included in the database, it is vital to have a strict acceptance criteria for reports being entered into DSHAFT to make the LRFD regional calibration of superior quality and consistency. The quality of the database due to the acceptance criteria will allow other users to have confidence in the database and know the acceptance criteria for load test reports. The easy-to-query interface for DSHAFT will allow researchers and designers to further filter the data to fit their needs.

4. KEY TERMINOLOGY USED FOR DATA QUALITY ASSURANCE

To ensure the superior quality of DSHAFT, strict acceptance criteria for the available test information was used. The quality assurance of the data is the driving factor when adding each new dataset to the database. The level of quality criteria for each load test, deeming the datasets as usable and complete, were defined by the types of load tests, the soil and rock classification, cross-hole sonic logging (CSL), and the information on where the report was obtained.

It is important to note that not all load test reports found and put into the database meet the expected quality. This data was included even though some the information was missing, such as a detailed bore log. The rationale is that each one has the potential to be qualified once the information has been made available. To notify the user when this occurs, the usable data sets are identified by a yes/no category titled “Usable Data.” This field can easily be sorted to hide the unusable data.

Another notification along with the “Usable Data” notification mentioned above is the “All Record Data Entered?” warning. The notification informs the user when a complete dataset has been added. An additional benefit of the “Usable Data” notification is that it creates a check for those maintaining the database to help eliminate missing information.

Early in the project, it was decided at this time to exclude any lateral load tests from DSHAFT, but allow for the expansion of the database to include lateral load tests in the future. The reason behind this decision is to simplify the database. Only two axial load test methods, the Osterberg and Statnamic, are included in the database because they are not only the most prevalent load tests in the region, but they are also preferred by most DOTs.

Of the two axial load test methods included in DSHAFT, the Osterberg is the most common axial load test method used in the US. It uses a sacrificial load cell that hydraulically applies a static load at or near the bottom of the drilled shaft (Osterberg 1995). The idea behind the test setup is the shaft above the load cell will move upward and measure the shaft resistance from skin friction, while the shaft below will measure toe resistance. The advantage of performing the Osterberg test is that the two components, shaft and toe resistances, are quantified separately. It is essential to note that once the cell is pressurized internally, the upward force is equal but opposite to the downward force, and that the shaft is assumed rigid. The compression of the shaft is considered negligible and therefore ignored.

The Statnamic load test is a dynamic axial load test method that uses fuel burned in a pressure chamber to exert an upward force on a set of reaction masses while an equal but opposite force pushes down on the top of the drilled shaft (NCHRP Report 360 2006). The advantages with using this type of dynamic testing are that it provides a less costly alternative to static load tests, allows for more drilled shafts to be tested because it requires less time than a static load test, and allows for the testing of existing foundations (Mullins 2002). It does not require load reaction piles, reaction beam, hydraulic jack, and sacrificial load cell. The disadvantage of using a Statnamic load test is that the data is regressed to determine the static load derived capacity (Paikowsky 2006).

A major aspect when analyzing the results of axial load tests on drilled shafts is the soil profile classification, as each category behaves differently and affects the capacity of the drilled shaft accordingly. Thus, it is important to use a dependable classification for the soil profile of the drilled shafts. The soil profile classification system devised for DSHAFT is a series of guidelines to be used on soil information provided in the load test report. The three main categories used when classifying the soil profile are clay, sand, and mixed. To maintain consistency with PILOT soil profile classification (Roling et al. 2011) and due to a rational verification of that soil classification (AbdelSalam et al. 2011), the 30 percent rule based was used. The rule is based on the Unified Soil Classification System (USCS) as well as Iowa DOT soil descriptions. Therefore, if less than 30 percent of the competent soil along a shaft is classified as cohesive materials, the soil profile of that shaft is categorized as sand. Similarly, if 30 percent or less of the competent soil profile along the shaft is made of cohesionless materials, the soil of that shaft is classified clay. In all other intermediate cases, the soil profile is categorized as mixed.

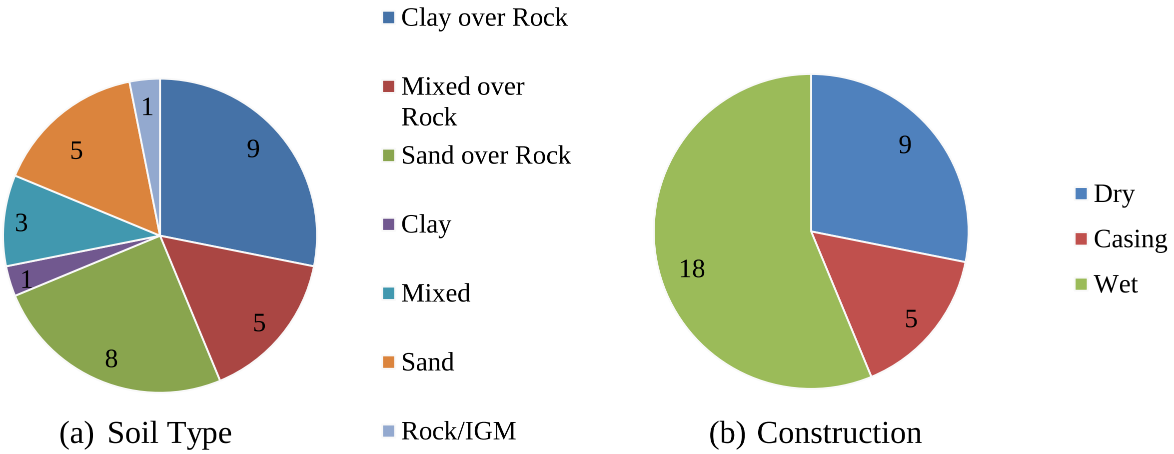
The performance of a drilled shaft dramatically changes when a portion of the shaft is embedded into rock, known as a rock socket. To classify the material as rock, the unconfined compressive strength (q_u) must be greater than 100 ksf. In between rock and soil is a large variation of material known as intermediate geomaterial (IGM). According to Brown et al. (2010), cohesive IGM is defined as material that exhibits q_u in the range of 10 ksf to 100 ksf. Anything below 5 ksf is classified as soil. In DSHAFT, rock sockets are identified by a “Rock Socketed?” yes/no category to account for the potential increase in end bearing and shaft resistance.

A quality control measure incorporated into the DSHAFT database is to include the CSL report when available. The purpose of this test is to use the information to assess the quality of a drilled shaft concrete (Hussein et al. 2005) by showing the location and size of flaws and defects. Due to the large capacities of drilled shafts, there is less redundancy in the bridge foundation when compared to other types of foundations such as H-piles. The reduced redundancy can increase probabilities of flaws within the foundation, but with advancements in technology such as self-consolidating concrete (SCC) these defects are reduced (NCHRP Report 360 2006). To help ensure a safe and effective product, many DOTs require CSL tests in accordance with ASTM D-6760-08 on all drilled shafts.

5. DESCRIPTIVE SUMMARY OF DSHAFT DATA SUBSET

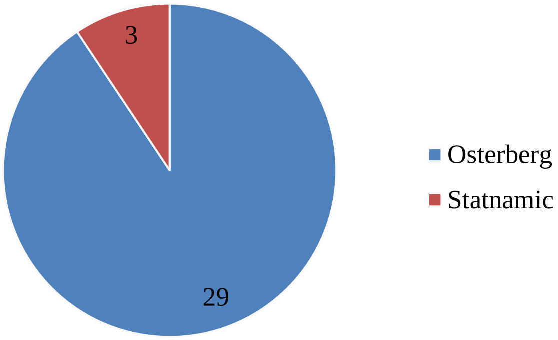
A descriptive summary of the thirty-two drilled shaft load tests completed and submitted by the Iowa, Illinois, Minnesota, and Missouri DOTs and the Nebraska DOR is provided in the following sections. Details of tests including soil types, construction method, and testing method are presented.

Of the dataset information included in DSHAFT, most of the drilled shaft load tests were performed in clay soils overlaying rock, as illustrated by Figure 5.1(a). Seventy-two percent of all datasets included in DSHAFT are rock socketed. When comparing data sets based on construction method, Figure 5.1(b) shows that 28 percent of the drilled shafts in DSHAFT were constructed using the dry method. Between the wet method and casing method, the wet method was used 78 percent of the time out of 23 load test cases. Overall, out of all 32 data sets, the wet and casing method combined were used 72 percent of the time, as compared to the dry method.



(a) Soil Type

(b) Construction Method



(c) Testing Method

Figure 5.1. Distribution of historical drilled shaft data

The distinctions between Osterberg and Statnamic load tests are critical because the data contained in each of the reports is different. The data from either report can be used to determine the capacity of the drilled shaft by using a different technique. For example, the Osterberg test gives the static load versus shaft displacement and toe displacement, while the Statnamic test gives a Statnamic load versus Statnamic displacement that has to be regressed to static loads and corresponding displacements. Figure 5.1(c) indicates that the most utilized load test is the Osterberg load test. All three Statnamic tests available in DSHAFT were performed on the same project site in Council Bluffs, Iowa, by Applied Foundation Testing.

In order to see the grouping of drilled shaft load tests by location, a map is included in Figure 5.2. The significance of the figure is to illustrate natural breaks in the regional grouping of information included in the database for resistance factor calibration. The natural breaks indicate where more load tests may need to be performed. At some of the locations identified by stars in Figure 5.2, multiple load tests were performed, but the purpose of the map is to show where more drilled shaft load tests need to be performed in order to obtain a true regional calibration.

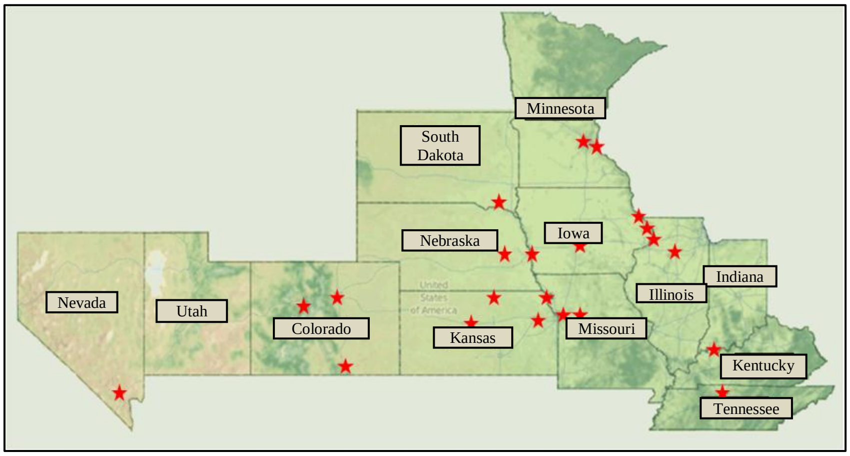


Figure 5.2. Location of drilled shaft test sites

6. DSHAFT USER MANUAL

DSHAFT was developed to provide a means of electronic storage for all past, present, and future Iowa DOT drilled shaft load test data for subsequent reference and analysis. The purpose of the following user manual is to provide a comprehensive explanation of the features incorporated into DSHAFT, the details of how the quality of data was assured, information on how to add new load test data, and the minimum required extent of details for new data.

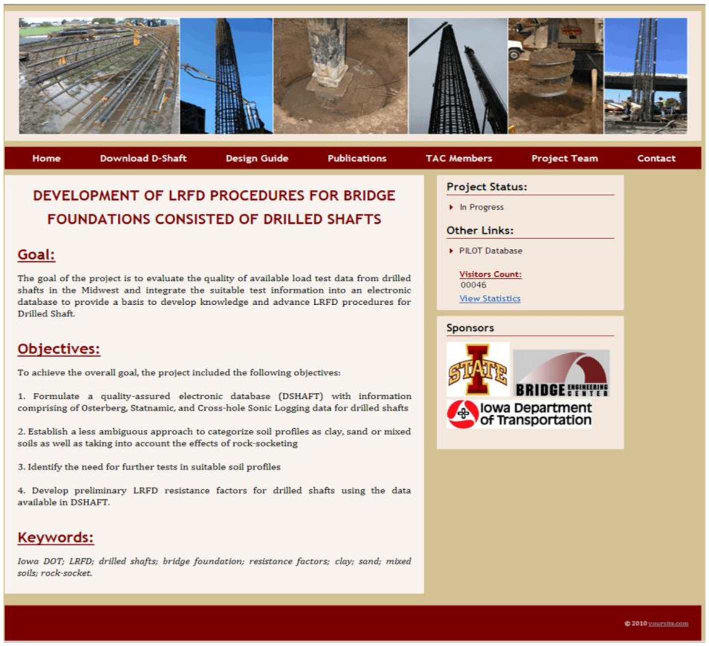
6.1 Accessing DSHAFT

To download and save a copy of the most recent version of DSHAFT, follow the steps listed below:

1. Set Internet Explorer as your default web browser to access PDF files, which contain project information and load test data, via hyperlinks in DSHAFT.

    a) Open Internet Options by clicking the "Start" button, clicking "Control Panel", clicking "Network and Internet", and then clicking Internet "Options."
    b) Click the "Programs" tab, and then "Default Programs."
    c) Click "Set Default Programs", select "Internet Explorer", and then click "Set this program as default."
    d) Click "OK", and then close the window.

2. Open Internet Explorer and go to srg.cce.iastate.edu/dshaft. The home page of the website is shown in Figure 6.1. Click on the "Download D-Shaft" tab.



DEVELOPMENT OF LRFD PROCEDURES FOR BRIDGE FOUNDATIONS CONSISTED OF DRILLED SHAFTS

Goal:

The goal of the project is to evaluate the quality of available load test data from drilled shafts in the Midwest and integrate the suitable test information into an electronic database to provide a basis to develop knowledge and advance LRFD procedures for Drilled Shaft.

Objectives:

To achieve the overall goal, the project included the following objectives:

1. Formulate a quality-assured electronic database (DSHAFT) with information comprising of Osterberg, Statnamic, and Cross-hole Sonic Logging data for drilled shafts

2. Establish a less ambiguous approach to categorize soil profiles as clay, sand or mixed soils as well as taking into account the effects of rock-socketing

3. Identify the need for further tests in suitable soil profiles

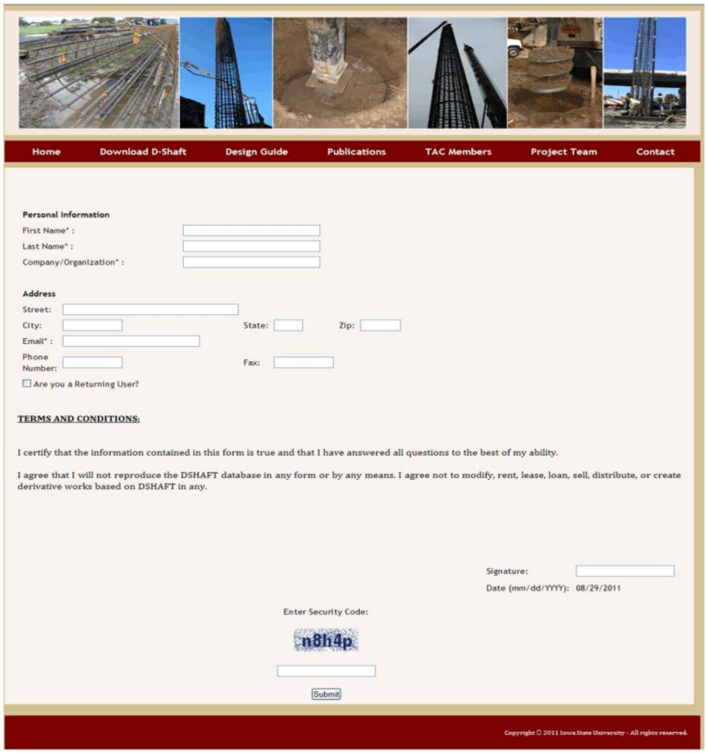
4. Develop preliminary LRFD resistance factors for drilled shafts using the data available in DSHAFT.

Keywords:

Iowa DOT; LRFD; drilled shafts; bridge foundation; resistance factors; clay; sand; mixed soils; rock-socket.

Figure 6.1. DSHAFT website home page (srg.cce.iastate.edu/dshaft)

3. Complete DSHAFT request form as shown in Figure 6.2.



Personal Information

First Name* :

Last Name* :

Company/Organization* :

Address

Street:

City: State: Zip:

Email* :

Phone Number: Fax:

☐ Are you a Returning User?

TERMS AND CONDITIONS:

I certify that the information contained in this form is true and that I have answered all questions to the best of my ability.

I agree that I will not reproduce the DSHAFT database in any form or by any means. I agree not to modify, rent, lease, loan, sell, distribute, or create derivative works based on DSHAFT in any.

Signature:

Date (mm/dd/YYYY): 08/29/2011

Enter Security Code:

n8h4p

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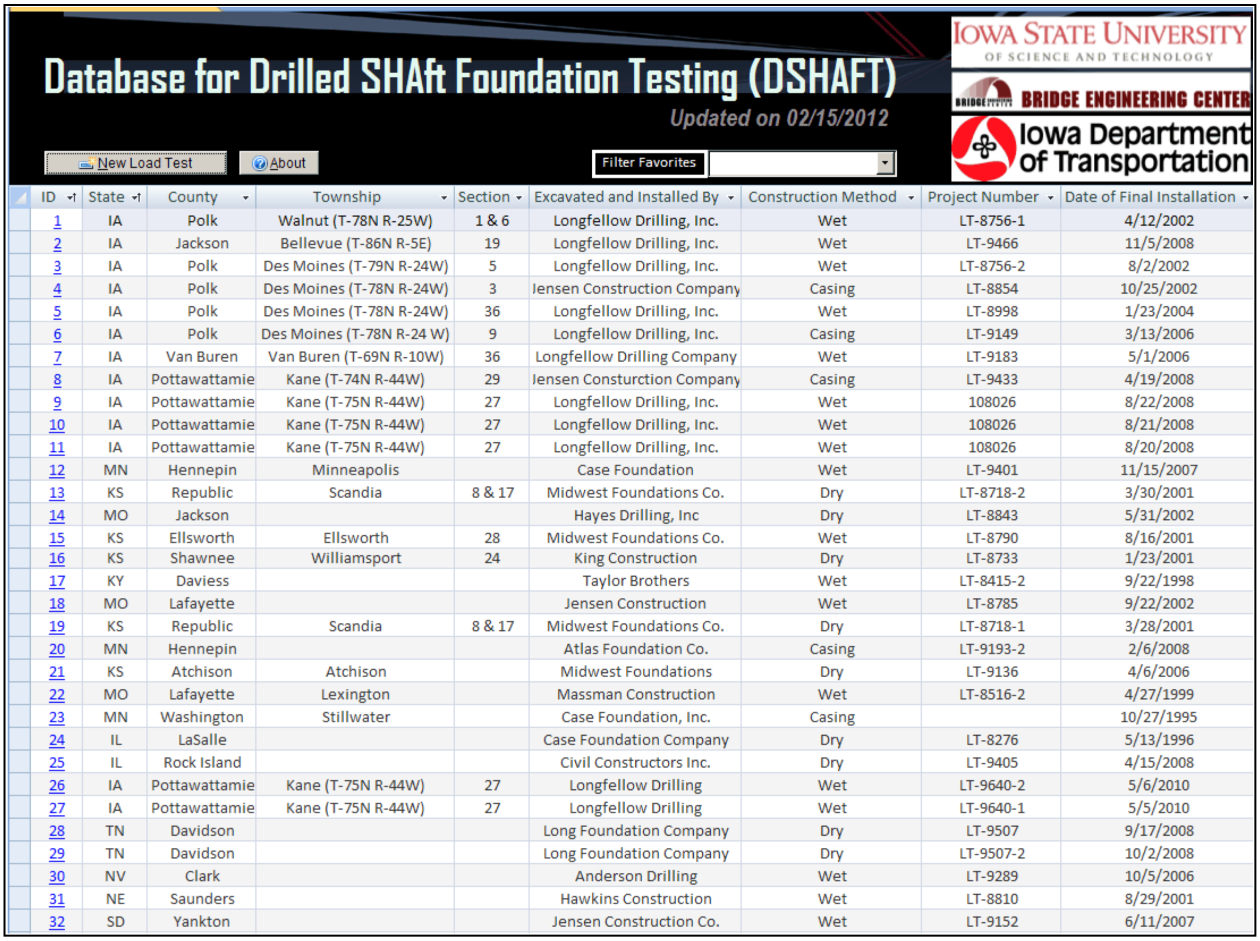
Figure 6.2. DSHAFT request form

4. A link to download DSHAFT will be emailed to you.
5. Click the link to download a copy of DSHAFT. Click Open.

6.2 Description of DSHAFT Database Fields

DSHAFT was developed using Microsoft Office Access^{TM} 2007 with the intent of creating an archive of drilled shaft testing information. The design of the database is to make filtering, sorting, and querying procedures more efficient by using a collective dataset. The database consists of two main forms: DSHAFT Display Form and Drilled Shaft Load Test Record Form.

The first of the two main forms, DSHAFT Display Form, is shown in Figure 6.3. It contains a datasheet view of all available records and two quick access buttons for the insertion of new drilled shaft load test records. The acquisition of additional details concerning DSHAFT, along with a drop-down menu featuring a variety of filtering options are also made available on this form. The DSHAFT Display Form is the home screen guiding the user to the desired information contained in the available dataset.



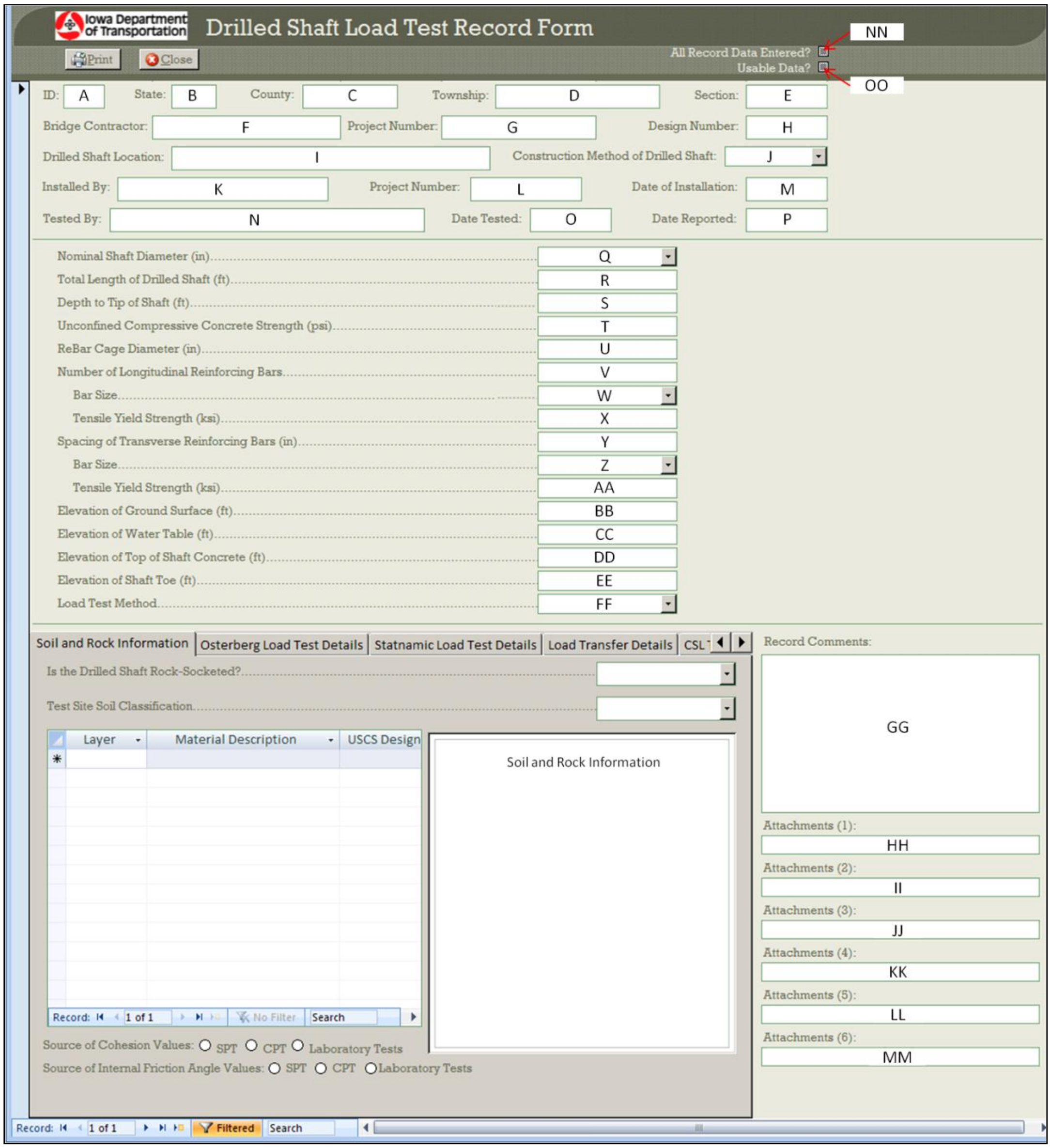
ID	State	County	Township	Section	Excavated and Installed By	Construction Method	Project Number	Date of Final Installation
1	IA	Polk	Walnut (T-78N R-25W)	1 & 6	Longfellow Drilling, Inc.	Wet	LT-8756-1	4/12/2002
2	IA	Jackson	Bellevue (T-86N R-5E)	19	Longfellow Drilling, Inc.	Wet	LT-9466	11/5/2008
3	IA	Polk	Des Moines (T-79N R-24W)	5	Longfellow Drilling, Inc.	Wet	LT-8756-2	8/2/2002
4	IA	Polk	Des Moines (T-78N R-24W)	3	Jensen Construction Company	Casing	LT-8854	10/25/2002
5	IA	Polk	Des Moines (T-78N R-24W)	36	Longfellow Drilling, Inc.	Wet	LT-8998	1/23/2004
6	IA	Polk	Des Moines (T-78N R-24 W)	9	Longfellow Drilling, Inc.	Casing	LT-9149	3/13/2006
7	IA	Van Buren	Van Buren (T-69N R-10W)	36	Longfellow Drilling Company	Wet	LT-9183	5/1/2006
8	IA	Pottawattamie	Kane (T-74N R-44W)	29	Jensen Consturction Company	Casing	LT-9433	4/19/2008
9	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling, Inc.	Wet	108026	8/22/2008
10	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling, Inc.	Wet	108026	8/21/2008
11	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling, Inc.	Wet	108026	8/20/2008
12	MN	Hennepin	Minneapolis		Case Foundation	Wet	LT-9401	11/15/2007
13	KS	Republic	Scandia	8 & 17	Midwest Foundations Co.	Dry	LT-8718-2	3/30/2001
14	MO	Jackson			Hayes Drilling, Inc	Dry	LT-8843	5/31/2002
15	KS	Ellsworth	Ellsworth	28	Midwest Foundations Co.	Wet	LT-8790	8/16/2001
16	KS	Shawnee	Williamsport	24	King Construction	Dry	LT-8733	1/23/2001
17	KY	Daviess			Taylor Brothers	Wet	LT-8415-2	9/22/1998
18	MO	Lafayette			Jensen Construction	Wet	LT-8785	9/22/2002
19	KS	Republic	Scandia	8 & 17	Midwest Foundations Co.	Dry	LT-8718-1	3/28/2001
20	MN	Hennepin			Atlas Foundation Co.	Casing	LT-9193-2	2/6/2008
21	KS	Atchison	Atchison		Midwest Foundations	Dry	LT-9136	4/6/2006
22	MO	Lafayette	Lexington		Massman Construction	Wet	LT-8516-2	4/27/1999
23	MN	Washington	Stillwater		Case Foundation, Inc.	Casing		10/27/1995
24	IL	LaSalle			Case Foundation Company	Dry	LT-8276	5/13/1996
25	IL	Rock Island			Civil Constructors Inc.	Dry	LT-9405	4/15/2008
26	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling	Wet	LT-9640-2	5/6/2010
27	IA	Pottawattamie	Kane (T-75N R-44W)	27	Longfellow Drilling	Wet	LT-9640-1	5/5/2010
28	TN	Davidson			Long Foundation Company	Dry	LT-9507	9/17/2008
29	TN	Davidson			Long Foundation Company	Dry	LT-9507-2	10/2/2008
30	NV	Clark			Anderson Drilling	Wet	LT-9289	10/5/2006
31	NE	Saunders			Hawkins Construction	Wet	LT-8810	8/29/2001
32	SD	Yankton			Jensen Construction Co.	Wet	LT-9152	6/11/2007

Figure 6.3. DSHAFT Display Form (Microsoft Office Access^{TM} 2007)

A unique hyperlinked identification number is created for each available load test to provide a porthole to the second of the two forms, the Drilled Shaft Load Test Record Form (DSLTRF). Here, six descriptive categories are displayed to organize the detailed information contained in the load test report to provide an easy-to-use interface. The DSLTRF consists of general information and five tabbed subforms, as shown in Figure 6.4. The database fields included in this form are explicitly described below.

6.2.1 General Drilled Shaft Load Test Record Form Information

Described in this section are the various fields included in the general DSLTRF, with reference to labels included in Figure 6.4.



Drilled Shaft Load Test Record Form

All Record Data Entered? ☐ NN
Usable Data? ☐ OO

ID: A
State: B
County: C
Township: D
Section: E
Bridge Contractor: F
Project Number: G
Design Number: H
Drilled Shaft Location: I
Construction Method of Drilled Shaft: J
Installed By: K
Project Number: L
Date of Installation: M
Tested By: N
Date Tested: O
Date Reported: P

Nominal Shaft Diameter (in)........ Q
Total Length of Drilled Shaft (ft)........ R
Depth to Tip of Shaft (ft)........ S
Unconfined Compressive Concrete Strength (psi)........ T
ReBar Cage Diameter (in)........ U
Number of Longitudinal Reinforcing Bars........ V
Bar Size........ W
Tensile Yield Strength (ksi)........ X
Spacing of Transverse Reinforcing Bars (in)........ Y
Bar Size........ Z
Tensile Yield Strength (ksi)........ AA
Elevation of Ground Surface (ft)........ BB
Elevation of Water Table (ft)........ CC
Elevation of Top of Shaft Concrete (ft)........ DD
Elevation of Shaft Toe (ft)........ EE
Load Test Method........ FF

Is the Drilled Shaft Rock-Socketed?........
Test Site Soil Classification........

Source of Cohesion Values: ○ SPT ○ CPT ○ Laboratory Tests
Source of Internal Friction Angle Values: ○ SPT ○ CPT ○ Laboratory Tests

Record Comments: GG
Attachments (1): HH
Attachments (2): II
Attachments (3): JJ
Attachments (4): KK
Attachments (5): LL
Attachments (6): MM

Figure 6.4. Drilled Shaft Load Test Record Form (DSLTRF)

A. **ID**: A unique cataloging number automatically assigned by Microsoft Office Access ™ to each record within DSHAFT.

B. **State**: The initials of the state in which the load test was performed is input into this text database field.

C. **County**: The name of the county corresponding to the location of the specified load test is input into this text database field.

D. **Township**: The name of the township corresponding to the location of the specified load test is input into this text database field.

E. **Section**: The section number of the location of the specified load test is input into this numerical database field.

F. **Bridge Contractor**: The name of the contracting company responsible for the construction of the specified bridge project is input into this text database field.

G. **Project Number**: The unique DOT cataloging number assigned to each construction project is input into this text database field.

H. **Design Number**: For every construction project in each state, all bridge projects are assigned a unique design number. The bridge design number corresponding to a specified drilled shaft load test is entered into this text database field.

I. **Drilled Shaft Location**: This text database field allows the user to enter a short description of the drilled shaft location in relation to the features of the bridge under construction. For instance, a typical description will specify if the drilled shaft was located near an abutment or a pier. Either the drilled shaft number or a detailed narrative identifying the exact position of the pile within the abutment or pier is usually provided.

J. **Construction Method of Drilled Shaft**: The method used to construct the drilled shaft is chosen from a drop down menu in this text database field. The options available are: Casing, Dry, or Wet.

K. **Installed By**: The name of the construction company responsible for installing the drilled shaft is input into this text database field.

L. **Project Number**: The unique project number for the load test is entered in this text database field.

M. **Date of Installation**: The date that the drilled shaft was constructed is recorded in this date/time database field. The format to accept dated entries is month/day/year (e.g., 3/8/1984).

N. **Tested By**: The names of the people who were responsible for carrying out the drilled shaft load test on the specified drilled shaft is input into this text database field.

O. **Date Tested**: The date when the drilled shaft load test was performed is recorded in this date/time database field. The format to accept dated entries is month/day/year (e.g., 3/8/1984).

P. **Date Reported**: The date on which the drilled shaft load test results were reported is input into this date/time database field. The format to accept dated entries is month/day/year (e.g., 3/8/1984).

Q. **Nominal Shaft Diameter (in.)**: The nominal shaft diameter. The options available for selection in this database field are as follows: 24”, 30”, 36”, 42”, 46”, 48”, 54”, 60”, 62”, 66”, 72”, 78”, and 96”.

R. **Total Length of Drilled Shaft (ft)**: The total length of the drilled shaft is recorded in this numerical database field. This is measured from the top of the concrete to the toe of the shaft.

S. **Depth to Toe of Shaft (ft)**: The embedded depth of the drilled shaft is input in this numerical database field. This is measured from the ground surface elevation to the toe of the shaft.

T. **Unconfined Compressive Concrete Strength (psi)**: The measured 28-day unconfined compressive concrete strength of the drilled shaft is input into this numerical database field.

U. **ReBar Cage Diameter (in.)**: The diameter of the ReBar cage used to reinforce the drilled shaft is input into this numerical database field.

V. **Number of Longitudinal Reinforcing Bars**: The number of longitudinal reinforcing bars used in the construction of the drilled shaft is input into this numerical database field.

W. **Bar Size**: A bar size chosen from a drop down menu specifying the size of the longitudinal reinforcement used in the construction of the drilled shaft in this numerical database field. The available options for selection are as follows: #3, #4, #5, #6, #7, #8, #9, #10, #11, #14, and #18.

X. **Tensile Yield Strength (ksi)**: The tensile yield strength of the longitudinal reinforcing bars used in the construction of the drilled shaft is specified in this text database field.

Y. **Spacing of Transverse Reinforcing Bars (in.)**: The spacing of the transverse reinforcement along the drill shaft is input in this numerical database field.

Z. **Bar Size**: The bar size is selected from a drop down menu to define the size of the transverse reinforcement used in the construction of the drilled shaft in this numerical database field. The available options for selection are as follows: #3, #4, #5, #6, #7, #8, #9, #10, #11, #14, and #18.

AA. **Tensile Yield Strength (ksi)**: The tensile yield strength of the transverse reinforcing bars used in the construction of the drilled shaft is specified detailed in this text database field.

BB. **Elevation of Ground Surface (ft)**: The measured ground elevation at the site of the tested drilled shaft is input in this numerical database field.

CC. **Elevation of Water Table (ft)**: When applicable, the water table elevation at the location of the tested drilled shaft is inserted in this numerical database field.

DD. **Elevation of Top of Shaft Concrete (ft)**: The measured elevation of the top of shaft concrete is entered into this numerical database field.

EE. **Elevation of Shaft Toe (ft)**: The measured elevation of the shaft toe is input into this numerical database field.

FF. **Load Test Method**: The method used to perform the load test on the drilled shaft is chosen from the drop down menu in this text database field. The options available for selection are as follows: Osterberg Test and Statnamic Test. Based on what the user selects the corresponding tab "Osterberg Load Test Details Tab" or the "Statnamic Load Test Tab" should be completed by the user.

GG. **Record Comments**: Any important information regarding the records is included in this text database field.

HH.-MM. **Attachments (1) - (6)**: These six hyperlink database fields were created so that important information related to each drilled shaft load test could easily be accessed from DSLTRF. The hyperlink text descriptions found within these database fields maintain a direct path to the file of interest.

To add a new hyperlink to the DSLTRF, follow the steps outlined below:

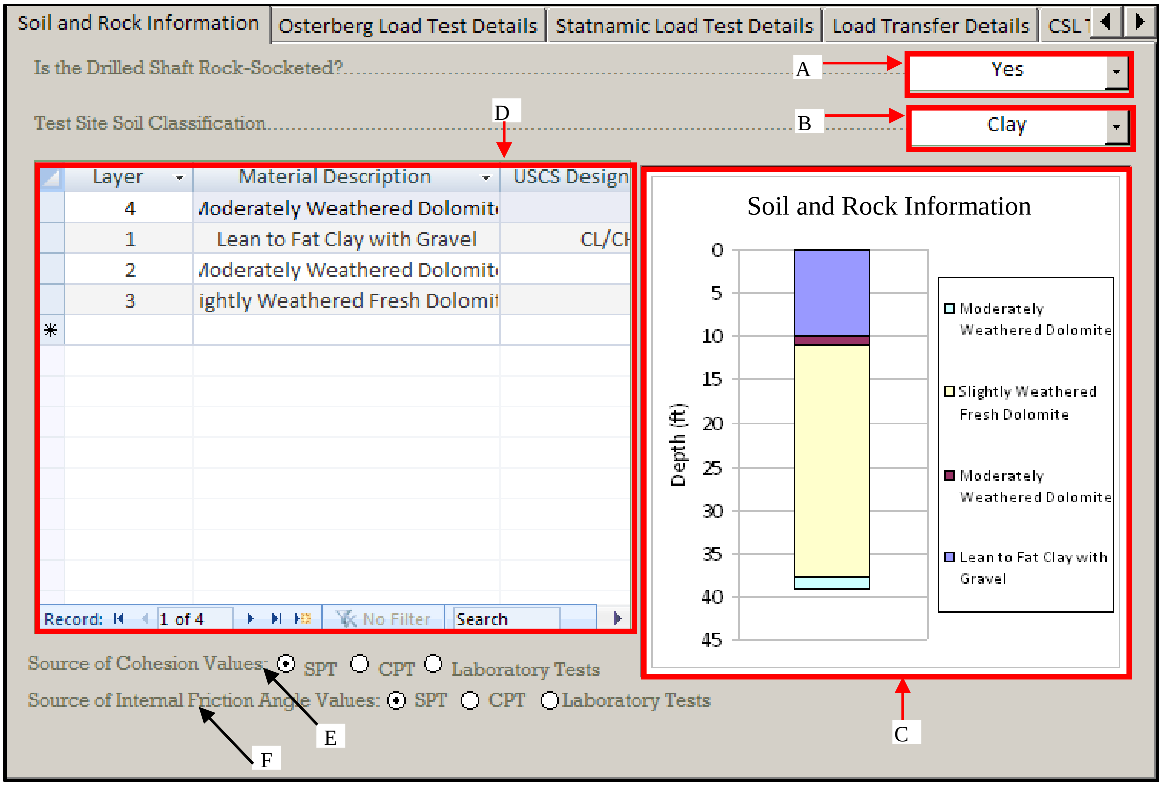
1. Open the desired DSLTRF to which a new hyperlink will be added.
2. Position the cursor over the preferred location, attachments (1) through (6), for the new hyperlink.
3. Right click with the mouse and select Hyperlink. Then click Edit Hyperlink.
4. Locate the file to which the hyperlink will be tied and provide a concise, but meaningful description of the files in the "Text to Display:" option.

NN. **All Record Data Entered?**: This yes/no database field was created for the one(s) responsible for the data entry procedures, so that an easy distinction could be made between those records still requiring data to be entered and those that had been termed complete. When all available information has been entered for a specific record, this field receives a check mark.

OO. **Usable Data?**: This yes/no database field was created for the user, so that an easy identification could be made between usable and unusable datasets. When the available information is deemed complete and acceptable for calibration of resistance factors, this field receives a check mark.

6.2.2 Soil and Rock Information

As illustrated in Figure 6.5, the first tab found on the DSLTRF (i.e., Soil and Rock Information) contains all of the information regarding the soil and rock testing. From this information, a graph of the soil profile is created. The fields listed below are found on this tab.



Is the Drilled Shaft Rock-Socketed? Yes

Test Site Soil Classification Clay

Layer	Material Description	USCS Design
4	oderately Weathered Dolomit	
1	Lean to Fat Clay with Gravel	CL/C
2	oderately Weathered Dolomit	
3	ightly Weathered Fresh Dolomit	

Source of Cohesion Values: ● SPT ○ CPT ○ Laboratory Tests

Source of Internal Friction Angle Values: ● SPT ○ CPT ○ Laboratory Tests

Figure 6.5. Soil and rock information tab of DSLTRF

A. **Is the Drilled Shaft Rock-Socketed?**: The information regarding if the drilled shaft is rock-socketed is specified in the drop down menu for this yes/no database field.

B. **Test Site Soil Classification**: The soil at the test site is classified in the drop down menu for this text database field. The options available are clay, sand, and mixed.

C. **Soil and Rock Information Profile**: This bar graph is generated from the data that has been input into the Soil and Rock Information Table. It uses the Material Description as well as the thickness of the layer to generate the soil profile.

D. **Soil and Rock Information Table**: The table allows the user to input information about the soil and rock. The available categories are:

   - **Layer**: The layer number is input by the user for the main purpose of keeping the soil and rock layers in order. Layer “1” should be the layer closest to the ground surface.

   - **Material Description**: The material description serves the purpose of describing the soil or rock layer. (i.e., Firm Glacial Clay or Moderately Weathered Dolomite). This information can be found in the “Soil Boring Log” in the load test report provided.

   - **USCS Designation**: This designation allows the user to input the soil type using the USCS for each layer specified in the Soil Boring Log Report.

- **Thickness (ft)**: This category is a measure from the top to the bottom of each soil layer. This is useful when classifying the overall soil type.

- **Cohesion (psf)**: The measurement of the shear strength of the soil can be recorded by the user into this category.

- **Internal Friction Angle (degrees)**: In this category, the measurement of the soil to withstand a shear stress can be entered by the user.

- **Unit Weight (pcf)**: The measure of the soil's weight versus volume can be input into this field.

- **Moisture Content (%)**: The measurement representing the amount of water present in the soil can be input into the Moisture Content category as a percentage.

- **Relative Density (%)**: In this category the void ratio of sands and gravels is represented as a percentage.

- **SPT N-Value**: The Standard Penetration Test (SPT) N value is the sum of the blow counts for 12 inches of SPT hammer penetration is included into this category.

- **Unconfined Compressive Strength (psi)**: The strength of the soil or rock tested uniaxially without lateral restraint is input into this category.

- **Elastic Modulus (psi)**: The elastic modulus of the soil can be input into this category.

- **Core Recovery (%)**: The length of the core recovered from a borehole, compared with the depth of the hole cored can be recorded in this category as a percentage.

- **Modified Core Recovery (%)**: The modified core recovery can be represented in this category as a percentage.

- **Rock Quality Designation (%)**: The rock quality designation can be input into this category as a percentage.

   a. **Source of Cohesion Values**: This field allows the user to identify how the cohesion of the soil was tested by marking the appropriate circle. The methods available are SPT, cone penetration test (CPT), and laboratory testing.
   b. **Source of Internal Friction Angle Values**: This field allows the user to identify how the internal friction angle was calculated by marking the appropriate circle. The methods available are SPT, CPT, and laboratory testing.

6.2.3 Osterberg Load Test Details

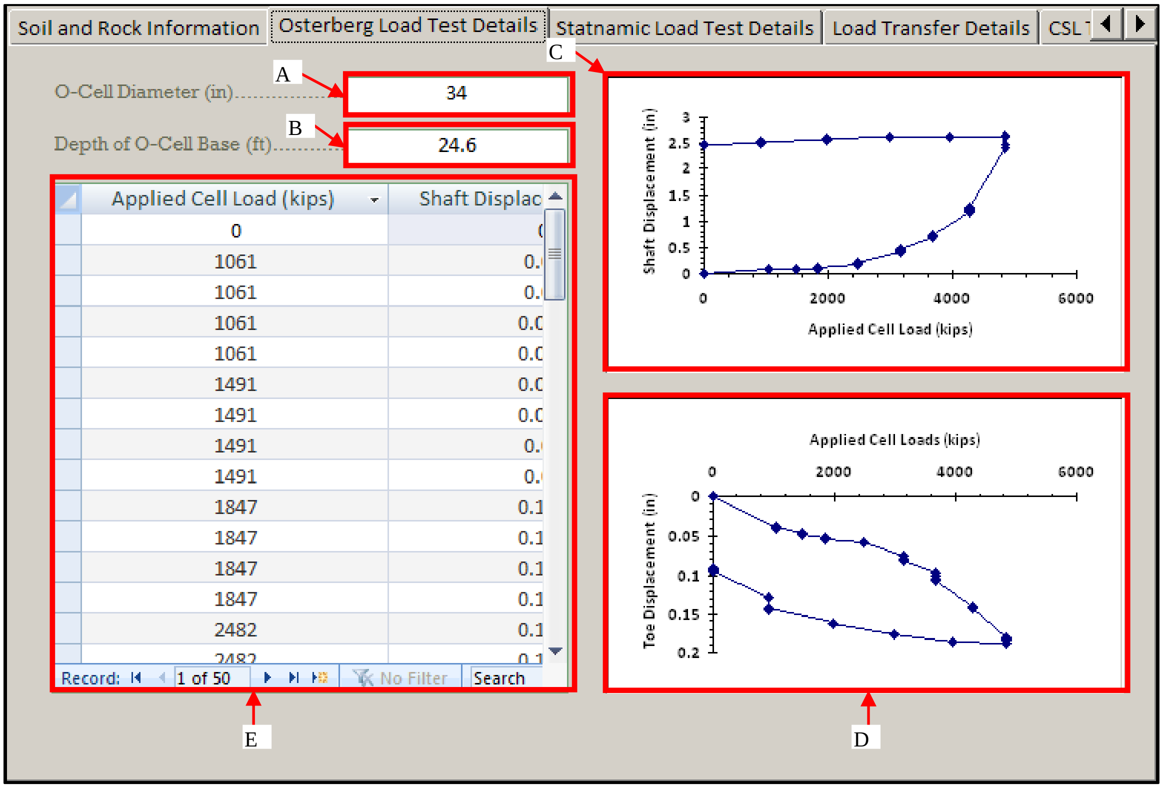
The second tab found on the DSLTRF (i.e., Osterberg Load Test Details) will only be filled out if an Osterberg Test was performed. Otherwise, it will be left blank. Illustrated in Figure 6.6, this tab contains the fields listed below.

A. **O-Cell Diameter (in.)**: The diameter of the O-cell is input into this numerical database field.

B. **Depth of O-Cell Base (ft)**: The location of the O-cell with respect to the ground surface is defined in this numerical database field.

C. **Load vs. Shaft Displacement Graph**: The load vs. shaft displacement graph is automatically created when the user enters the appropriate information into the table described below in subsection E. It depicts the shaft displacement corresponding to the applied O-cell load.

D. **Load vs. Toe Displacement Graph**: The load vs. toe displacement graph is automatically created when the user inputs the information into the table described in subsection E. It illustrates the toe displacement of the drilled shaft corresponding to the applied O-cell load.



O-Cell Diameter (in)........ 34

Depth of O-Cell Base (ft)........ 24.6

Applied Cell Load (kips)	Shaft Displac
0	(
1061	0.
1061	0.
1061	0.0
1061	0.0
1491	0.0
1491	0.0
1491	0.
1491	0.
1847	0.1
1847	0.1
1847	0.1
1847	0.1
2482	0.1
2482	0.1

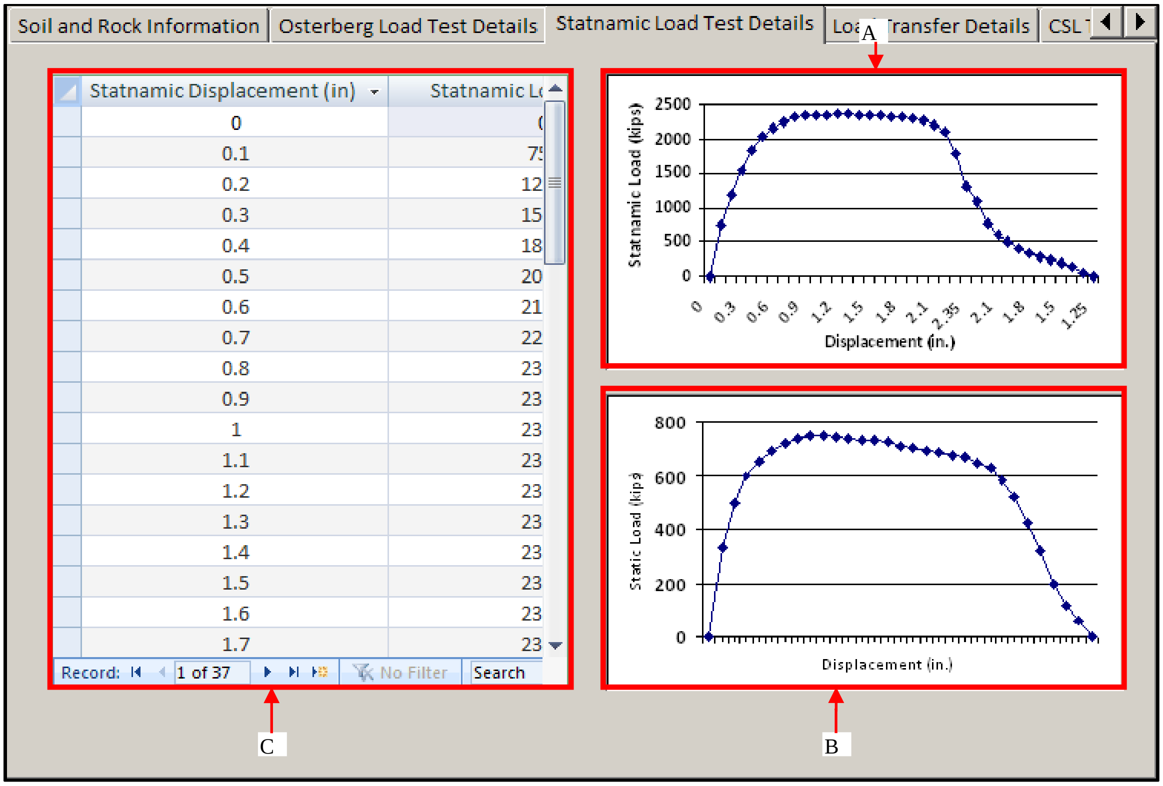
Figure 6.6. Osterberg load test details tab of DSLTRF Load and Displacement table: This table allows the user to input the shaft and toe displacement corresponding to an applied O-cell load. This table includes the following columns:

- **Applied Cell Load (kips)**: This column consists of the measured applied cell load reported in the testing information.
- **Shaft Displacement (in.)**: This column contains the shaft displacement corresponding to the applied cell load that was reported in the testing information.
- **Toe Displacement (in.)**: This column specifies the toe displacement of the drilled shaft

corresponding to the applied cell load that was reported in the testing information.

6.2.4 Statnamic Load Test Details

The third tab found on the DSLTRF (i.e., Statnamic Load Test Details) will only be filled out if a Statnamic test was performed. If not, it will be left blank. Illustrated in Figure 6.7, this tab contains the fields listed below.



Statnamic Displacement (in)	Statnamic Lo
0	(
0.1	7
0.2	12
0.3	15
0.4	18
0.5	20
0.6	21
0.7	22
0.8	23
0.9	23
1	23
1.1	23
1.2	23
1.3	23
1.4	23
1.5	23
1.6	23
1.7	23

Figure 6.7. Illustration of Statnamic load test details tab of DSLTRF

A. **Displacement vs. Statnamic Load Graph**: This displacement vs. Statnamic load graph is automatically created when the user records information into the table specified in C. It depicts the displacement of the drilled shaft corresponding to the applied Statnamic load.

B. **Displacement vs. Static Load Graph**: This displacement vs. static load graph is automatically created when the user enters information into the table specified in C. It portrays the displacement of the drilled shaft corresponding to the applied static load.

C. **Displacement and Load Table**: This table allows the user to input the loads with the corresponding displacement. This table includes the following columns:

- **Statnamic Displacement (in.)**: This column represents the displacement corresponding to the Statnamic load.
- **Statnamic Load (kips)**: This column represents the load applied to the drilled shaft

during Statnamic testing.

- **Static Displacement (in.)**: This column details the displacement corresponding to the static load.
- **Static Load (kips)**: This column denotes the load applied to the drilled shaft during the static testing.

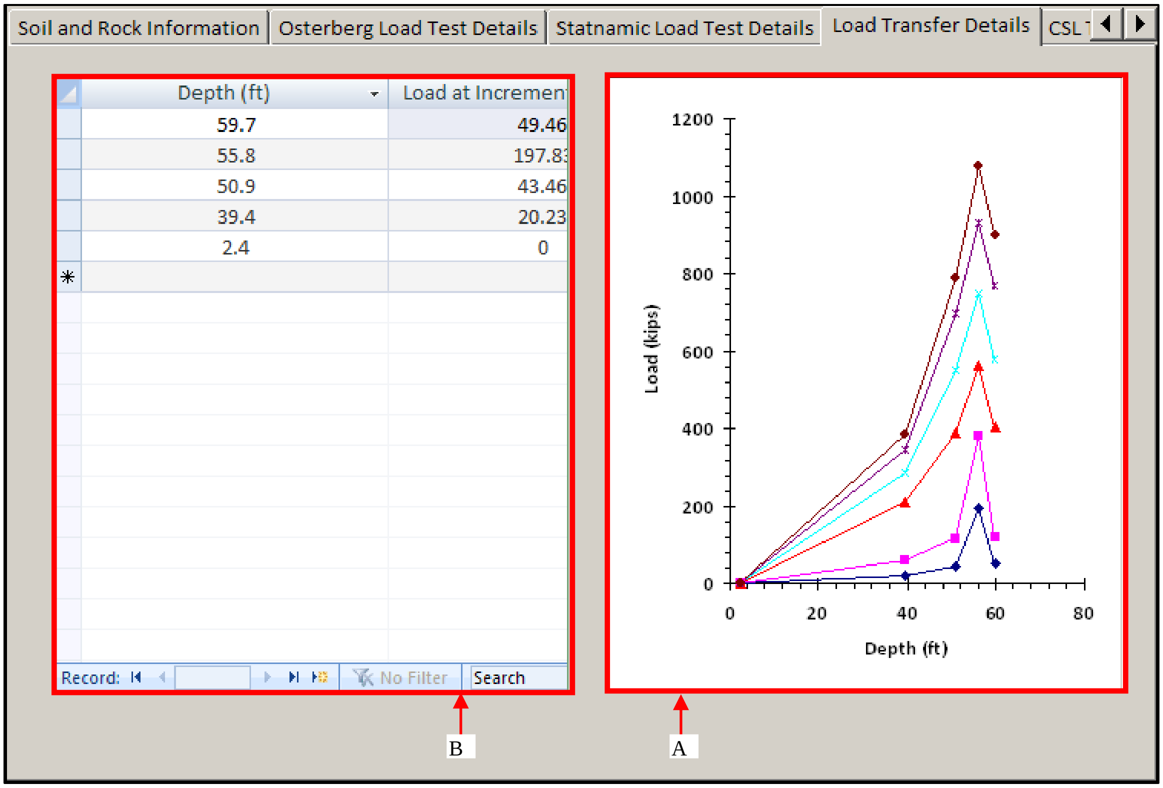
6.2.5 Load Transfer Details

The fourth tab found on the DSLTRF (i.e., Load Transfer Details) is illustrated in Figure 6.8. It contains the fields listed below.

A. **Load vs. Depth Graph**: This load vs. depth graph is automatically created when the user inputs information into the table specified in subsection B. It depicts the load increment versus the depth of the drilled shaft.

B. **Depth and Load Increments Table**: This table allows the user to define the loads for each of the gauges and O-cell, as well as record the corresponding depth of each of the gauges. This table includes Depth(ft) and Load at Increment #1 through Load at Increment #10.

- **Depth (ft)**: This column represents the depth of the strain gages, including the O-cell, with respect to the ground surface.
- **Load Increment #1 – Load Increment #10 (kips)**: These columns signify the average load at each load increment.



Depth (ft)	Load at Incremen
59.7	49.46
55.8	197.8
50.9	43.46
39.4	20.23
2.4	0

Figure 6.8. Load transfer details tab of DSLTRF

6.2.6 Cross-Hole Sonic Log (CSL) Test Details

The fifth tab found on the DSLTRF (i.e., CSL Test Details) is illustrated in Figure 6.9. It contains the fields listed below.

A. **Acceptable Quality of Concrete**: Based on the results from the CSL test, the concrete will be determined to be acceptable or not acceptable by marking the check box for this yes/no database field. Likins (2004) found that the interpretation of CSL results can lead to different conclusions depending on the person interpreting the data. The criteria shown in Table 6.1 will be used to quantify the quality of concrete. Flaws are considered between the 20 percent to 30 percent velocity reduction and should be addressed if they are found in more than 50 percent of the CSL profiles. Anything greater than a 31 percent velocity reduction is considered a defect and should be addressed if found in more than one profile (Likins et al. 2007)

B. **Date of Test**: The date on which the CSL test was performed is recorded in this date/time field. The format to accept dated entries is month/day/year (e.g., 3/8/1984).

C. **Number of Tubes**: The number of tubes used to perform the CSL test is input into this numerical database field.

D. **Comments**: Any important information regarding the CSL test is included in this text database field.

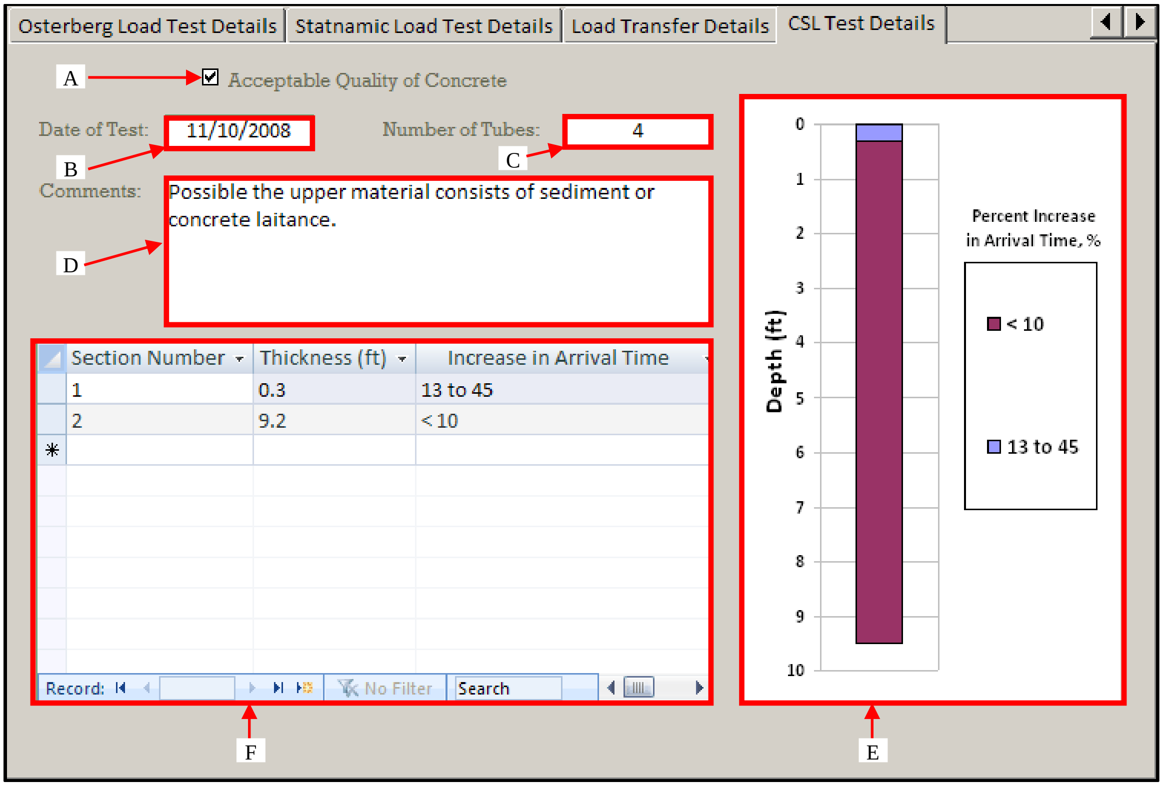
E. **Percent Increase in Arrival Time Graph**: This bar graph is automatically created when the user enters information into the table specified in subsection F. It depicts the percent increase in arrival time along the drilled shaft.

F. **Percent Increase in Arrival Time Table**: This table allows the user to detail the velocity reduction for a given section of the drilled shaft. This table includes:

- **Section Number**: The section number is input by the user for the main purpose of keeping the section numbers in order along the length of the drilled shaft. Section "1" should be the layer at the top of the drilled shaft.
- **Thickness (ft)**: The thickness is the length of the drilled shaft corresponding with the range of increase in arrival time specified in the CSL Test report.
- **Increase in Arrival Time (%)**: The time it takes for the signal produced by the sound source to travel to the receiver is measured as the devices are lowered through access tubes along the drilled shaft. The time at one point is compared with the average time it takes the signal to travel as a percentage.

Table 6.1. Concrete condition rating criteria (MoDOT 2012)

Concrete Condition Rating	Rating Symbol	Velocity Reduction	Indicative Results
Good	G	0 to 10%	Acceptable concrete
Questionable	Q	10 to 25%	Minor concrete contamination or intrusion. Questionable quality concrete.
Poor/Defect	P/D	>25%	Defects exist, possible water or slurry contamination, soil intrusion and/or poor quality concrete.
Water	W	Velocity = 4760 to 5005 ft/sec	Water intrusion, of water filled gravel with few or no fines present.
No Signal	NS	No Signal Received	Soil intrusion or other severe defect absorbed the signal, tube debonding if near shaft top.



☑ Acceptable Quality of Concrete

Date of Test: 11/10/2008

Number of Tubes: 4

Comments: Possible the upper material consists of sediment or concrete laitance.

Section Number	Thickness (ft)	Increase in Arrival Time
1	0.3	13 to 45
2	9.2	< 10

Figure 6.9. An illustration of CSL test details tab of DSLTRF

6.3 Disclaimer Notice

DSHAFT was established as part of a research project funded by the Iowa DOT and has compiled data from different DOTs. The Iowa DOT, other DOTs, or the authors of this report do not make any warranty, expressed or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information contained in DSHAFT. If a problem arises during the usage of DSHAFT or more knowledge is required, contact the Iowa DOT or those currently maintaining the database via http://srg.cce.iastate.edu/dshaft/.

7. PRELIMINARY ANALYSIS

The preliminary analysis began with estimating the nominal axial geotechnical resistance of a drilled shaft in accordance with the AASHTO LRFD Bridge Design Specifications (2010). A nominal total resistance estimated for each drilled shaft is listed in Table 7.1. It was determined by adding nominal shaft resistances (R_s) acting along the embedded length to a nominal toe resistance (R_p) acting at the base of the drilled shaft. The estimation process of R_s, R_p, and nominal total resistance are described in the following subsections.

7.1 Shaft Resistance

The nominal shaft side resistance at each soil layer can be estimated using

$$R_s = A_s q_s \tag{7.1}$$

where

A_s = area of shaft side surface (ft^2); and
q_s = unit side resistance (ksf).

For drilled shafts in cohesive soils, the unit side resistance can be estimated using α-method (O'Neill and Reese 1999) based on an adhesion factor (α) and undrained shear strength (S_u) given as

$$q_s = \alpha\, S_u \tag{7.2}$$

where

α = 0.55 for $\frac{S_u}{P_a} \leq 1.5$;
α = $0.55 - 0.1\left(\frac{S_u}{P_a} - 1.5\right)$ for $1.5 \leq \frac{S_u}{P_a} \leq 2.5$; and
P_a = atmospheric pressure (2.12 ksf).

When the ratio $\left(\frac{S_u}{P_a}\right)$ exceeds 2.5, the material will not be considered as a cohesive soil and equation 7.2 shall not be used to estimate the unit side resistance. This material could be classified as IGM or rock, depending on the magnitude of the unconfined compressive strength and the geology of the material. The undrained shear strength (S_u) for low permeability cohesive soils can be approximated by total stress cohesion (c). In addition, in-situ testing, such as SPT, can be used to estimate S_u based on the correlation established by Bjerrum (1972) given as

$$S_u = \frac{f_1 N_{60} P_a}{100} \tag{7.3}$$

where

f_1 = empirical factor (4.5 for PI = 50; 5.5 for PI = 15);
PI = plasticity index;
N_{60} = corrected SPT N-value; and
P_a = atmospheric pressure (2.12 ksf).

However, the side resistance between cohesive materials and a drilled shaft is not completely effective over the entire embedded length. Due to the effects of seasonal moisture changes, construction disturbance, cyclic lateral loading, and low lateral pressure from freshly placed concrete, the side resistance at the upper 5 ft of a drilled shaft is routinely ignored in accordance with the AASHTO LRFD Bridge Design Specifications (2010). In addition, due to the development of tensile cracks induced by the change in lateral concrete pressure on the soil before and after the hardening of concrete, the side resistance at one diameter length (B) above the shaft base is also ignored.

As identified by O'Neill et al. (1996), cohesive IGM includes the following materials: 1) argillaceous geomaterials such as heavily overconsolidated clays, clay shale, saprolites, and mudstones that are prone to smearing during drilling; and 2) calcareous rocks such as limestone and limerock and argillaceous geomaterials that are not prone to smearing when during drilling. Similar to cohesive materials, the unit side resistance for cohesive IGM can be estimated using a modified α-method given as estimated in equation 7.4.

$$q_s = \alpha\,\phi\,q_u \tag{7.4}$$

where

q_u = compressive strength of intact rock (ksf);
ϕ = a correction factor to account for the degree of jointing (see Table 7.1); and
α = empirical factor determined in Figure 7.1.

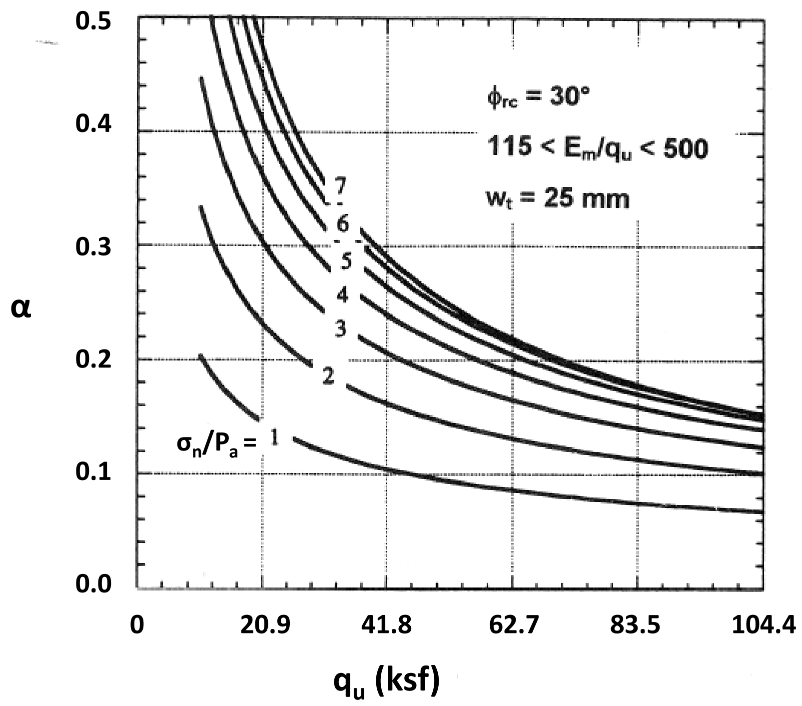


Figure 7.1. Factor α for cohesive IGM (adapted after O'Neill et al. 1996)

Note that the α value determined in Figure 7.1 is based on an assumed value of interface friction angle (ϕ_{rc}) of 30 degrees. If a different ϕ_{rc} value is known, the α value can be adjusted by

$$\alpha = \alpha_{\text{Figure 7.1}} \frac{\tan \phi_{rc}}{\tan 30^{\circ}} \qquad (7.5)$$

Table 7.1. Side resistance reduction factor for cohesive IGM

Rock Quality Designation, RQD (%)	Joint Correction Factor, ϕ	
	Closed Joints	Open or Gouge-Filled Joints
100	1.00	0.85
70	0.85	0.55
50	0.60	0.55
30	0.50	0.50
20	0.45	0.45

In addition, Figure 7.1 is only applicable if the ratio of modulus of rock mass (E_m) to q_u is between 115 and 500. It is assumed that the side resistance can be mobilized if the total vertical displacement (w_t) of a drilled shaft is 1 in. Figure 7.1 shows that the α value is dependent on the ratio of freshly placed concrete pressure at the middle of an IGM layer (σ_n) to atmospheric pressure (P_a). The concrete pressure (σ_n) at the depth below cutoff elevation (z_i^*) can be estimated using equation 7.6 if the concrete has a slump of 7 in. or greater and placed in the borehole at a rate of 40 ft per hour or greater.

$$\sigma_n = 0.65\gamma_c z_i^* \qquad (7.6)$$

where

γ_c = concrete unit weight (kcf); and
z_i^* = depth below cutoff elevation to the middle of a material layer i, which will be limited to 40 ft.

For drilled shafts in cohesionless soils, the unit side resistance can be estimated using β-method (O'Neill and Reese 1999) in terms of a load transfer coefficient (β) given as

$$q_s = \beta\, \sigma_v' \leq 4.0 \tag{7.7}$$

where

β = $1.5 - 0.135\sqrt{z}$ for $N_{60} \geq 15$;
β = $2.0 - 0.06(z)^{0.75}$ for gravelly sands and gravels and $N_{60} \geq 15$;
β = $\frac{N_{60}}{15}\left(1.5 - 0.135\sqrt{z}\right)$ for $N_{60} < 15$;
σ_v' = vertical geostatic effective stress at soil layer mid-depth (ksf);
z = depth below ground at soil layer mid depth (ft); and
N_{60} = average SPT blow count in the design zone under consideration and corrected for hammer efficiency.

For drilled shafts socketed into rock, the unit side resistance can be estimated based on the recommendation suggested by Horvath and Kenney (1979) as such

$$q_s = 0.65\alpha_E P_a \left(\frac{q_u}{P_a}\right)^{0.5} < 7.8 P_a \left(\frac{f_c'}{P_a}\right)^{0.5} \tag{7.8}$$

where

q_u = uniaxial compressive strength of rock (ksf);
P_a = atmospheric pressure (2.12 ksf);
α_E = reduction factor to account for joining in rock as provided in Table 7.2;
f_c' = concrete compressive strength (ksi);
E_m = elastic modulus of the rock mass (ksf) determined from Table 7.3; and
E_i = elastic modulus of intact rock from tests (ksf).

Table 7.2. Estimation of α_E for equation 7.8 (O'Neill and Reese 1999)

E_m/E_i	α_E
1.0	1.0
0.5	0.8
0.3	0.7
0.1	0.55
0.05	0.45

Table 7.3. Estimation of E_m based on RQD (adapted after O'Neill and Reese 1999)

Rock Quality Designation, RQD (%)	E_m/E_i	
	Closed Joints	Open Joints
100	1.00	0.60
70	0.70	0.10
50	0.15	0.10
20	0.05	0.05

7.2 Toe Resistance

The nominal toe resistance (R_p) can be estimated as

$$R_p = A_p q_p \tag{7.9}$$

where

A_p = area of shaft toe surface (ft^2); and
q_p = unit toe resistance (ksf).

For drilled shafts resting on cohesive soils, the unit toe resistance can be estimated in terms of undrained shear strength (S_u) provided in O'Neill and Reese (1999)

$$q_p = N_c S_u \leq 80.0 \tag{7.10}$$

where

N_c = $6\left[1 + 0.2\left(\frac{Z}{D}\right)\right] \leq 9$;
Z = penetration of shaft (ft); and
D = diameter of drilled shaft (ft).

For drilled shafts in cohesionless soils with corrected SPT N-value (N_{60}) smaller than 50, the unit toe resistance can be estimated using the method suggested by O'Neill and Reese (1999):

$$q_p = 1.2\, N_{60} \leq 60.0 \tag{7.11}$$

However, according to AASHTO LRFD Bridge Design Specifications (2010), cohesionless soils with N_{60} greater than 50 are treated as IGM, and the unit toe resistance is estimated as from equation 7.12

$$q_p = 0.59\left[N_{60}\left(\frac{P_a}{\sigma'_v}\right)\right]^{0.8} \sigma'_v \tag{7.12}$$

where

σ'_v = vertical geostatic effective stress at the toe elevation of the shaft (ksf); and
N_{60} = corrected average SPT N-value, limited to 100.

The unit toe resistance for drilled shafts in rock can be estimated using equation 7.13 if the following criteria are met: 1) the rock from below the base of the drilled shaft to a depth of two times the shaft diameter (B) is either intact or tightly jointed, and 2) the depth of the socket is greater than 1.5B (O'Neill and Reese 1999). If the rock at the same region is jointed and has random joint orientation, the unit toe resistance can be estimated using equation 7.14

$$q_p = 2.5\, q_u \tag{7.13}$$

$$q_p = \left[\sqrt{s} + \sqrt{\left(m\sqrt{s} + s\right)}\right] q_u \tag{7.14}$$

where

q_u = uniaxial compressive strength of rock (ksf);
s,m = fractured rock mass parameters (refer to Table 7.4); and
RMR = rock-mass rating determined by summing all the relative ratings obtained in Table 7.5.

Table 7.4. Approximate relationship between rock-mass quality and fractured rock-mass parameters used in defining nonlinear strength (Hoek and Brown 1988)

Rock Quality	**Parameters**	**Rock Type** A = Carbonate rocks with well-developed crystal cleavage: dolomite, limestone and marble B = Lithified argillaceous rocks: mudstone, siltstone, shale and slate (normal to cleavage) C = Arenaceous rocks with strong crystals and poorly developed crystal cleavage: sandstone and quartzite D = Fine grained polyminerallic igneous crystalline rocks: andesite, dolerite, diabase and rhyolite E = Coarse grained polyminerallic igneous & metamorphic crystalline rocks: amphibolite, gabbro gneiss, granite, norite, quartz-diorite				
		A	**B**	**C**	**D**	**E**
INTACT ROCK SAMPLES Laboratory size specimens free from discontinuities. RMR = 100	m s	7.00 1.00	10.00 1.00	15.00 1.00	17.00 1.00	25.00 1.00
VERY GOOD QUALITY ROCK MASS Tightly interlocking undisturbed rock with unweathered joint at 3 to 10 ft. RMR = 85	m s	2.40 0.082	3.43 0.082	5.14 0.082	5.82 0.082	8.567 0.082
GOOD QUALITY ROCK MASS Fresh to slightly weathered rock, slightly disturbed with joints at 3 to 10 ft. RMR = 65	m s	0.575 0.00293	0.821 0.00293	1.231 0.00293	1.395 0.00293	2.052 0.00293
FAIR QUALITY ROCK MASS Several sets of moderately weathered joints spaced at 1 to 3 ft. RMR = 44	m s	0.128 0.00009	0.183 0.00009	0.275 0.00009	0.311 0.00009	0.458 0.00009
POOR QUALITY ROCK MASS Numerous weathered joints at 2 to 12 in.; some gouge. Clean compacted waste rock. RMR = 23	m s	0.029 3×10^{-6}	0.041 3×10^{-6}	0.061 3×10^{-6}	0.069 3×10^{-6}	0.102 3×10^{-6}
VERY POOR QUALITY ROCK MASS Numerous heavily weathered joints spaced < 2 in. with gouge. Waste rock with fines. RMR = 3	m s	0.007 1×10^{-7}	0.010 1×10^{-7}	0.015 1×10^{-7}	0.017 1×10^{-7}	0.025 1×10^{-7}

Table 7.5. Geomechanics classification of rock-masses

<table>
<tr><th colspan="4">Parameter</th><th colspan="12">Ranges of Values</th></tr>
<tr><td rowspan="3">1</td><td rowspan="2">Strength of intact rock material</td><td colspan="2">Point load strength index</td><td>> 175 ksf</td><td colspan="3">85 – 175 ksf</td><td>45 – 85 ksf</td><td colspan="2">20 – 45 ksf</td><td colspan="5">For this low range, uniaxial compressive test is preferred</td></tr>
<tr><td colspan="2">Uniaxial compressive strength, q_u</td><td>> 4320 ksf</td><td colspan="3">2160 – 4320 ksf</td><td>1080 – 2160 ksf</td><td colspan="2">520 – 1080 ksf</td><td colspan="2">215 – 520 ksf</td><td colspan="2">70 – 215 ksf</td><td>20 – 70 ksf</td></tr>
<tr><td colspan="3">Relative Rating</td><td>15</td><td colspan="3">12</td><td>7</td><td colspan="2">4</td><td colspan="2">2</td><td colspan="2">1</td><td>0</td></tr>
<tr><td rowspan="2">2</td><td colspan="3">Drill core quality RQD</td><td colspan="2">90% to 100%</td><td colspan="3">75% to 90%</td><td colspan="3">50% to 75%</td><td colspan="3">25% to 50%</td><td>< 25%</td></tr>
<tr><td colspan="3">Relative Rating</td><td colspan="2">20</td><td colspan="3">17</td><td colspan="3">13</td><td colspan="3">8</td><td>3</td></tr>
<tr><td rowspan="2">3</td><td colspan="3">Spacing of joints</td><td colspan="2">> 10 ft</td><td colspan="3">3 – 10 ft</td><td colspan="3">1 – 3 ft</td><td colspan="3">2 in – 1 ft</td><td>< 2 in</td></tr>
<tr><td colspan="3">Relative Rating</td><td colspan="2">30</td><td colspan="3">25</td><td colspan="3">20</td><td colspan="3">10</td><td>5</td></tr>
<tr><td rowspan="2">4</td><td colspan="3">Condition of joints</td><td colspan="2">• Very rough surface
• Not continuous
• No separation
• Hard joint wall rock</td><td colspan="3">• Slightly rough surfaces
• Separation < 0.05 in
• Hard joint wall rock</td><td colspan="3">• Slightly rough surface
• Separation < 0.05 in
• Soft joint wall rock</td><td colspan="3">• Slicken-sided surface or
• Gouge < 0.2 in thick or
• Joints open 0.05 – 0.2 in
• Continuous joints</td><td>• Soft gouge > 0.2 in thick or
• Joints open > 0.2 in
• Continuous joints</td></tr>
<tr><td colspan="3">Relative Rating</td><td colspan="2">25</td><td colspan="3">20</td><td colspan="3">12</td><td colspan="3">6</td><td>0</td></tr>
<tr><td rowspan="4">5</td><td colspan="2" rowspan="3">Ground water conditions (use one of the three) evaluation criteria as appropriate to the method of exploration</td><td>Inflow per 30 ft tunnel length</td><td colspan="3">None</td><td colspan="3">< 400 gal./hr</td><td colspan="4">400 – 2000 gal./hr</td><td colspan="2">> 2000 gal./hr</td></tr>
<tr><td>Ratio = joint water pressure/ major principal stress</td><td colspan="3">0</td><td colspan="3">0.0 – 0.2</td><td colspan="4">0.2 – 0.5</td><td colspan="2">> 0.5</td></tr>
<tr><td>General conditions</td><td colspan="3">Completely Dry</td><td colspan="3">Moist only (interstitial water)</td><td colspan="4">Water under moderate pressure</td><td colspan="2">Severe water problems</td></tr>
<tr><td colspan="3">Relative Rating</td><td colspan="3">10</td><td colspan="3">7</td><td colspan="4">4</td><td colspan="2">0</td></tr>
</table>

7.3 Results

The estimation of nominal axial geotechnical resistances using the aforementioned methods requires quantification of surrounding soil parameters through in-situ subsurface investigations and/or laboratory material testing. The measured material parameters, such as cohesion (c) for cohesive materials and unconfined compressive strength of rock (q_u), were included in DSHAFT at different soil layers for each drilled shaft data set. Other material parameters that were not available from the DSHAFT database were either estimated or assumed based on the recommendations as described previously. The measured and estimated material parameters for each data set are given in Appendix B.

Using the material parameters presented in Appendix B, the nominal axial geotechnical resistances for the 13 Iowa data sets were estimated, as shown in Table 7.6. The measured nominal total resistances obtained from the load test methods (see Table 1) were also included in this table.

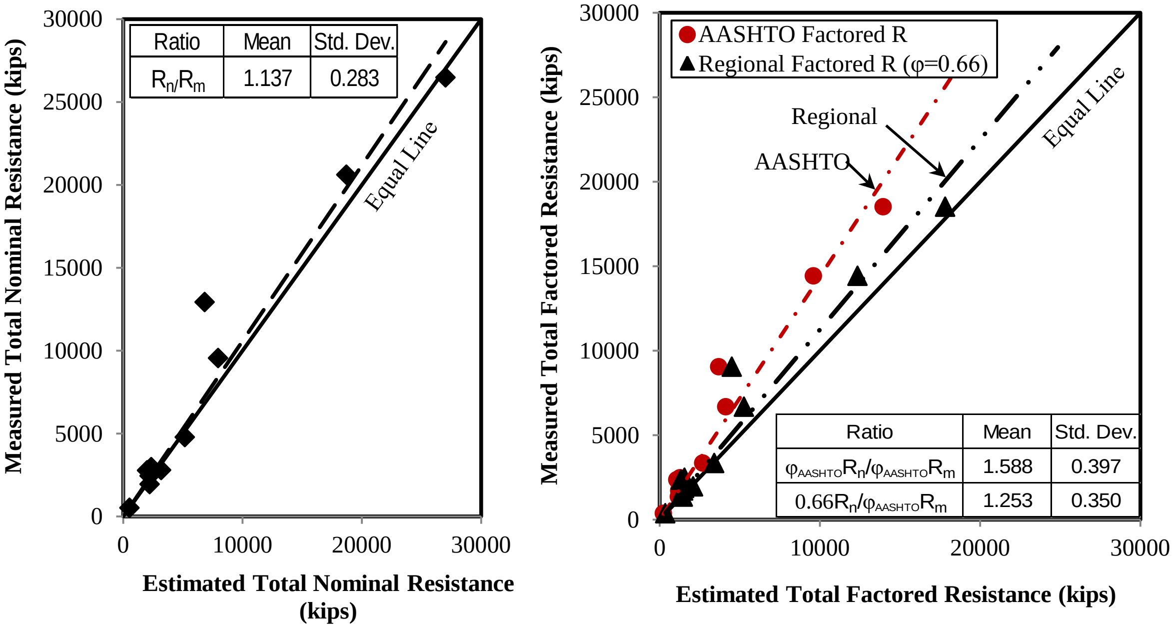
Table 7.6. Summary of total estimated and measured nominal drilled shaft resistances

DSHAFT ID Number	Estimated Nominal Total Resistance, R_n (kips)	Measured Nominal Total Resistance, R_m (kips)	Percent Difference, %
1	No soil Information	2039	-
2	7985	9549	16.4
3	3190	2794	-14.2
4	6846	12921	47.0
5	5181	4786	-8.3
6	546	519	-5.2
7	18730	20604	9.1
8	27040	26468	-2.2
9	2336	2657	12.1
10	2239	2445	8.4
11	2229	1948	-14.4
26	2025	2771	26.9
27	2356	2971	20.7

Using the 13 load test data from Iowa, Figure 7.2(a) compares the measured and estimated total nominal resistances, and illustrates that the ratio between the measured (R_m) and nominal (R_n) resistance has a mean of 1.137 and a standard deviation of 0.283. Furthermore, a preliminary analysis using the First Order Second Moment (FOSM) method for a reliability index (β) of 3.00, representing a non-redundant pile group, yields a resistance factor of 0.66 (see Table 7.7). The resistance factor is based on a total resistance (i.e., shaft resistance and toe resistance), which is higher than those recommended in AASHTO, which range from 0.4 to 0.6 for each individual resistance component.

Table 7.7. Summary of AASHTO and regionally calibrated resistance factors

Soil Type	Shaft/Toe Resistance	Resistance Factor (φ) for β_T =3.00	
		AASHTO	DSHAFT (Iowa)
Clay	Shaft	0.45	0.66 (based on total resistance)
	Toe	0.40	
Sand	Shaft	0.55	
	Toe	0.50	
Rock	Shaft	0.50-0.55	
	Toe	0.50	
Intermediate Geotechnical Materials (IGMs)	Shaft	0.60	
	Toe	0.55	



(a) Nominal Resistance

(b) Factored Resistance

Figure 7.2. Comparison of measured and estimated total resistances

When looking at the data in Figure 7.2(b), it shows that the estimated total factored resistance, using the regionally calibrated preliminary resistance factor of 0.66, has a closer match with the measured total factored resistance, demonstrated with a mean of 1.253 and a standard deviation of 0.350. These values, when compared to those obtained per AASHTO's recommendations (mean = 1.588 and standard deviation= 0.397), reveal that a regional study can lead to a cost-effective LRFD procedure for drilled shafts in Iowa.

8. IMPLEMENTATION BENEFITS AND READINESS

The benefits of using drilled shafts make drilled shafts an attractive option for practice. Most drilled shafts in Iowa are rock-socketed, providing significantly enhanced capacities, and allowing, in many cases, for a single drilled shaft to replace an entire pile group.

With today's technology (e.g., SCC and CSL testing), defects in the drilled shaft concrete are less common and can be detected. The construction method and quality control of construction still have a large impact on the drilled shaft and should be taken into consideration when calibrating the regional resistance factors. A set of acceptable guidelines for tolerances during construction should be included with the new resistance factors.

This report provides the basis for the newly-developed DSHAFT database, which was created to compile quality-assured drilled shaft load test information in an easy-to-use format, with the intent of calibrating dependable regional resistance factors.

To increase the knowledge about drilled shafts, DSHAFT is stored on a website (http://srg.cce.iastate.edu/dshaft) and is open to the public for use. As more drilled shaft load test information becomes available, it will be incorporated into the database.

The calibration for regional resistance factors for drilled shafts is necessary to provide a competitive alternative to driven piles by improving the efficiency of design. From a preliminary analysis of Iowa drilled shaft load tests, it was found that a regional calibration of the LRFD resistance factors could lead to substantial cost savings and, more importantly, a safer and reliable design of drilled shafts.

More load tests, along with detailed analyses, are needed to provide an accurate statistical calibration of the resistance factors for the final calibration. This scope can be achieved successfully in the future for Iowa and the Midwest with the addition of more quality drilled shaft test data to enhance the database.

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APPENDIX A. SUMMARY OF AVAILABLE DSHAFT DATASETS

Table A.1. Columns 1 through 8 of DSHAFT Display Form

ID	State (1)	County (2)	Township (3)	Section (4)	Bridge Project Number (4)	Excavated and Installed By (5)	Construction Method (6)	Project Number (7)
1	IA	Polk	Walnut (T-78N R-25W)	1 & 6	N/A	Longfellow Drilling, Inc.	Slurry	LT-8756-1
2	IA	Jackson	Bellevue (T-86N R-5E)	19	N/A	Longfellow Drilling, Inc.	Slurry	LT-9466
3	IA	Polk	Des Moines (T-79N R-24W)	5	N/A	Longfellow Drilling, Inc.	Slurry	LT-8756-2
4	IA	Polk	Des Moines (T-78N R-24W)	3	N/A	Jensen Construction Company	Casing	LT-8854
5	IA	Polk	Des Moines (T-78N R-24W)	36	N/A	Longfellow Drilling, Inc.	Slurry	LT-8998
6	IA	Polk	Des Moines (T-78N R-24 W)	9	N/A	Longfellow Drilling, Inc.	Casing	LT-9149
7	IA	Van Buren	Van Buren (T-69N R-10W)	36	N/A	Longfellow Drilling Company	Slurry	LT-9183
8	IA	Pottawattamie	Kane (T-74N R-44W)	29	N/A	Jensen Construction Company	Casing	LT-9433
9	IA	Pottawattamie	Kane (T-75N R-44W)	27	NHS-080-1(318)0-11-78	Longfellow Drilling, Inc.	Slurry	108026
10	IA	Pottawattamie	Kane (T-75N R-44W)	27	NHS-080-1(318)0-11-78	Longfellow Drilling, Inc.	Slurry	108026

Table A.1. Columns 1 through 8 of DSHAFT Display Form (continued)

ID	State (1)	County (2)	Township (3)	Section (4)	Bridge Project Number (5)	Excavated and Installed By (6)	Construction Method (7)	Project Number (8)
11	IA	Pottawattamie	Kane (T-75N R-44W)	27	NHS-080-1(318)0-11-78	Longfellow Drilling, Inc.	Slurry	108026
12	MN	Hennepin	Minneapolis	N/A	N/A	Case Foundation	Slurry	LT-9401
13	KS	Republic	Scandia	8 & 17	N/A	Midwest Foundations Co.	Dry	LT-8718-2
14	MO	Jackson	N/A	N/A	N/A	Hayes Drilling, Inc.	Dry	LT-8843
15	KS	Ellsworth	Ellsworth	28	N/A	Midwest Foundations Co.	Slurry	LT-8790
16	KS	Shawnee	Williamsport	24	75-89 K 7317-01	King Construction	Dry	LT-8733
17	KY	Daviess	N/A	N/A	N/A	Taylor Brothers	Slurry	LT-8415-2
18	MO	Lafayette	N/A	N/A	N/A	Jensen Construction	Slurry	LT-8785
19	KS	Republic	Scandia	8 & 17	N/A	Midwest Foundations Co.	Dry	LT-8718-1
20	MN	Hennepin	N/A	N/A	N/A	Atlas Foundation Co.	Casing	LT-9193-2

Table A.1. Columns 1 through 8 of DSHAFT Display Form (continued)

ID	State (1)	County (2)	Township (3)	Section (4)	Bridge Project Number (5)	Excavated and Installed By (6)	Construction Method (7)	Project Number (8)
21	KS	Atchison	Atchison	N/A	N/A	Midwest Foundations	Dry	LT-9136
22	MO	Lafayette	Lexington	N/A	N/A	Massman Construction	Slurry	LT-8516-2
23	MN	Washington	Stillwater	N/A	56327	Case Foundation, Inc.	Casing	N/A
24	IL	LaSalle	N/A	N/A	N/A	Case Foundation Company	Dry	LT-8276
25	IL	Rock Island	N/A	N/A	N/A	Civil Constructors Inc.	Dry	LT-9405
26	IA	Pottawattamie	Kane (T-75N R-44W)	27	N/A	Longfellow Drilling	Slurry	LT-9640-2
27	IA	Pottawattamie	Kane (T-75N R-44W)	27	N/A	Longfellow Drilling	Slurry	LT-9640-1
28	TN	Davidson	N/A	N/A	N/A	Long Foundation Company	Dry	LT-9507
29	TN	Davidson	N/A	N/A	N/A	Long Foundation Company	Dry	LT-9507-2
30	NV	Clark	N/A	N/A	N/A	Anderson Drilling	Slurry	LT-9289

Table A.1. Columns 1 through 8 of DSHAFT Display Form (continued)

ID	State (1)	County (2)	Township (3)	Section (4)	Bridge Project Number (5)	Excavated and Installed By (6)	Construction Method (7)	Project Number (8)
31	NE	Saunders	N/A	N/A	N/A	Hawkins Construction	Slurry	LT-8810
32	SD	Yankton	N/A	N/A	N/A	Jensen Construction Co.	Slurry	LT-9152

Table A.2. Columns 9 through 15 of DSHAFT Display Form

ID	Date of Final Installation (9)	Drilled Shaft Location (10)	Tested By (11)	Date Tested (12)	Date Reported (13)	Diameter (14)	Concrete Compressive Strength (15)
1	12-Apr-02	Test Shaft #1 - 42nd Street/I-235 Overpass	LOADTEST, Inc. (David J. Jakstis)	17-Apr-02	24-Apr-02	48	4470
2	05-Nov-08	TS-1 - US 52 over ICE & Mill Creek	LOADTEST, Inc. (Ahrens and Skiffington)	18-Nov-08	25-Nov-08	36	5860
3	02-Aug-02	Test Shaft #2 - I-235 / 28th St. Overpass	LOADTEST, Inc. (M. D. Ahrens)	07-Aug-02	13-Aug-02	48	3800
4	25-Oct-02	Dedicated Test Shaft - I235 over Des Moines River	LOADTEST, Inc. Tobert C. Simpson	08-Nov-02	18-Nov-02	42	3440
5	23-Jan-04	Test Shaft #1 - I-235 over UP RR	LOADTEST, Inc. (Denton Kort)	03-Feb-04	07-Feb-04	48	3900
6	13-Mar-06	Test Shaft 1 - 9th St. Bridge over I-235	LOADTEST, Inc. (David J. Jakstis)	22-Mar-06	29-Mar-06	30	3480
7	01-May-06	Test Shaft #1 - Hwy 1 over Des Moines River	LOADTEST Inc. (Michael D. Ahrens)	11-May-06	18-May-06	36	4100
8	19-Apr-08	Test Shaft - I-80 over Missouri River, east bank	LOADTEST, Inc. (Jon Sinnreich)	24-Apr-08	30-Apr-08	66	3800
9	22-Aug-08	TS-1: I-80 Bridge Project (Broadway Bridge Viaduct) in Council Bluffs	Applied Foundation Testing	13-Sep-08	09-Oct-08	60	5780
10	21-Aug-08	TS 2: 1-80 Bridge Project (Broadway Bridge Viaduct) in Council Bluffs; south	Applied Foundation Testing	12-Sep-08	09-Oct-08	60	5580

Table A.2. Columns 9 through 15 of DSHAFT Display Form (continued)

ID	Date of Final Installation (9)	Drilled Shaft Location (10)	Tested By (11)	Date Tested (12)	Date Reported (13)	Diameter (14)	Concrete Compressive Strength (15)
11	20-Aug-08	TS-3: I-80 Bridge Project (Broadway Bridge Viaduct) in Council Bluffs	Applied Foundation Testing	13-Sep-08	09-Oct-08	60	5770
12	15-Nov-07	Test Shaft 2 - I-35W over Mississippi River	LOADTEST, Inc. (David Jakstis)	22-Nov-07	26-Nov-07	78	4819
13	30-Mar-01	East Test Shaft - US 36 Over Republican River	LOADTEST, Inc. (M. D. Ahrens)	06-Apr-01	13-Apr-01	72	6011
14	31-May-02	Dedicated Test Shaft - Grandview Triangle	LOADTEST (William G. Ryan)	04-Jun-02	11-Jun-02	72	6000
15	16-Aug-01	KS-K-156 over Union Pacific Railroad and Side Road	LOADTEST, Inc.	23-Aug-01	30-Aug-01	42	4550
16	23-Jan-01	Pier 1 West, US 75 at 77th St.	LOADTEST, Inc. (Robert Simpson)	01-Feb-01	15-Feb-01	72	5620
17	22-Sep-98	U.S. 231 over Ohio River	LOADTEST, Inc. (Michael D. Ahrens)	28-Sep-98	30-Sep-98	96	N/A
18	22-Sep-02	Rt. 65 Missouri River Bridge - TS at Pier 11	LOADTEST, Inc. (Robert Simpson & William Ryan)	30-Sep-02	02-Oct-02	78	7520
19	28-Mar-01	West Test Shaft - US 36 over Republican River	LOADTEST, Inc. (M. D. Arhans)	05-Apr-01	13-Apr-01	72	5419
20	06-Feb-08	TP-2 - Crosstown Commons Project	LOADTEST, Inc. (William G. Ryan)	18-Mar-08	26-Mar-08	72	5900

Table A.2. Columns 9 through 15 of DSHAFT Display Form (continued)

ID	Date of Final Installation (9)	Drilled Shaft Location (10)	Tested By (11)	Date Tested (12)	Date Reported (13)	Diameter (14)	Concrete Compressive Strength (15)
21	06-Apr-06	Test Pile - Amelia Earhart Bridge over Missouri River	LOADTEST, Inc. (David J. Jakstis)	18-Apr-06	26-Apr-06	60	6470
22	27-Apr-99	TS @ Sta 0+146 25m Lt. - Missouri River Bridge, Lexington	LOADTEST, Inc. (M. D. Ahrens)	03-May-99	13-May-99	46	4070
23	27-Oct-95	T-36 Bridge over the St. Croix River; 200m west of Minnesota bank along the alignment of the bridge	LOADTEST, Inc.	08-Nov-95	05-Jul-95	48	N/A
24	13-May-96	F.A.U. Route 6265 CH-15 Over the Illinois River, Marseilles (West drilled shaft of Pier 2)	LOADTEST, Inc. (Jeff Coodwin)	20-May-96	01-Sep-96	62	5280
25	15-Apr-08	Test Shaft #1 - IL 5/ IL 84 Interchange	LOADTEST, Inc. (Jon Sinnreich)	21-Apr-08	24-Apr-08	42	4100
26	06-May-10	Broadway Viaduct - Council Bluffs, IA - TS 3	LOADTEST, Inc. (Bill Ryan)	20-May-10	26-May-10	66	6010
27	05-May-10	Broadway Viaduct - Council Bluffs, IA - TS 4	LOADTEST, Inc. (Bill Ryan)	21-May-10	28-May-10	66	5630
28	17-Sep-08	Long Foundation Drilling equipment Yard	Loadtest, Inc.	26-Sep-08	N/A	48	5771
29	02-Oct-08	Long Foundation Drilling Equipment Yard	Loadtest, Inc.	14-Oct-08	15-Oct-08	48	5900

Table A.2. Columns 9 through 15 of DSHAFT Display Form (continued)

ID	Date of Final Installation (9)	Drilled Shaft Location (10)	Tested By (11)	Date Tested (12)	Date Reported (13)	Diameter (14)	Concrete Compressive Strength (15)
30	05-Oct-06	I-215 Airport Connector - Las Vegas, NV - TS-1	Loadtest, Inc. (Mr. Simpson and Mr. Graman)	17-Oct-06	20-Oct-06	48	N/A
31	29-Aug-01	Wahoo South Connector - Wahoo, Nebraska - TS 1	Loadtest, Inc. (Mr. Simpson and Mr. Jakstis)	05-Sep-01	11-Sep-01	66	4670
32	11-Jun-07	TS #1 - Highway 81 over Missouri River Yankton, SD	Loadtest, Inc. (Mr. Ahrens and Mr. Usab)	20-Jun-07	02-Jul-07	96	3256

Table A.3. Columns 16 through 23 of DSHAFT Display Form

ID	ReBar Cage Diameter (16)	Number of Longitudinal ReBars (17)	Longitudinal ReBar Size (18)	Longitudinal ReBar Tensile Yield Strength (19)	Transverse ReBar Spacing (20)	Transverse ReBar Size (21)	Transverse ReBar Tensile Yield Strength (22)	Ground Surface Elevation (23)
1	42	18	#10	60	12	#5	60	974.40
2	30	8	#10	60	12	#5	60	599.3
3	42	18	#11	60	12	#4	60	891.5
4	36	16	#10	60	12	#4	60	805.3
5	N/A	14	#10	60	N/A	#5	60	813.6
6	22	10	#8	60	12	#5	60	918.6
7	30	20	#9	60	10	#5	60	572.0
8	60	18	#14	60	10	#5	60	975.3
9	N/A	23	#10	60	12	#5	60	988.5

Table A.3. Columns 16 through 23 of DSHAFT Display Form (continued)

ID	ReBar Cage Diameter (16)	Number of Longitudinal ReBars (17)	Longitudinal ReBar Size (18)	Longitudinal ReBar Tensile Yield Strength (19)	Transverse ReBar Spacing (20)	Transverse ReBar Size (21)	Transverse ReBar Tensile Yield Strength (22)	Ground Surface Elevation (23)
10	N/A	23	#10	60	12	#5	60	988.84
11	N/A	23	#10	60	12	#5	60	990.47
12	70	13	#11	60	5	#6	60	743
13	66	N/A	N/A	N/A	60	#5	N/A	1434.4
14	66	N/A	N/A	N/A	60	#5	N/A	942.4
15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1529
16	N/A	33	#10	N/A	N/A	#5	N/A	1013.9
17	N/A	N/A	N/A	N/A	N/A	N/A	N/A	341
18	N/A	22	#14	N/A	30	#5	N/A	637.5

Table A.3. Columns 16 through 23 of DSHAFT Display Form (continued)

ID	ReBar Cage Diameter (16)	Number of Longitudinal ReBars (17)	Longitudinal ReBar Size (18)	Longitudinal ReBar Tensile Yield Strength (19)	Transverse ReBar Spacing (20)	Transverse ReBar Size (21)	Transverse ReBar Tensile Yield Strength (22)	Ground Surface Elevation (23)
19	66	N/A	N/A	N/A	60	#5	N/A	1433.4
20	60	32	#10	N/A	12	#4	N/A	835
21	N/A	N/A	N/A	N/A	N/A	N/A	N/A	789
22	N/A	N/A	N/A	N/A	N/A	N/A	N/A	671.0
23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	700
24	54	18	#14	N/A	3	#7	N/A	501
25	38	32	#10	N/A	N/A	#5	N/A	622.8
26	N/A	19	#11	60	10	#4	60	987.65
27	N/A	19	#11	60	10	#4	60	987.65

Table A.3. Columns 16 through 23 of DSHAFT Display Form (continued)

ID	ReBar Cage Diameter (16)	Number of Longitudinal ReBars (17)	Longitudinal ReBar Size (18)	Longitudinal ReBar Tensile Yield Strength (19)	Transverse ReBar Spacing (20)	Transverse ReBar Size (21)	Transverse ReBar Tensile Yield Strength (22)	Ground Surface Elevation (23)
28	36	6	#10	60	13	#5	60	N/A
29	30	5	#9	60	24	#3	60	N/A
30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0
31	N/A	32	#11	60	N/A	#4	60	1190.09
32	90	48	#11	60	12	#5	60	1156.9

Table A.4. Columns 24 through 32 of DSHAFT Display Form

ID	Water Table Elevation (24)	Elevation of Top of Shaft Concrete (25)	Elevation of Shaft Toe (26)	Test Method (27)	Rock-Socketed (28)	Test Site Soil Classification (29)	Acceptable Quality of Concrete (30)	Record Complete (31)	Usable Data (32)
1	Not Encountered	972.00	905.60	Osterberg Test	Yes	Clay	**Yes**	**Yes**	**Yes**
2	590.0	585.7	573.0	Osterberg Test	Yes	Clay	**Yes**	**Yes**	**Yes**
3	Not Encountered	890.0	824.2	Osterberg Test	Yes	Clay	N/A	N/A	**Yes**
4	787.8	803.5	730.8	Osterberg Test	Yes	Mixed	**Yes**	**Yes**	**Yes**
5	Unknown	813.6	734.3	Osterberg Test	Yes	Clay	N/A	N/A	**Yes**
6	N/A	916.5	852.5	Osterberg Test	No	Clay	**Yes**	**Yes**	**Yes**
7	559.0	572.0	538.0	Osterberg Test	Yes	Clay	**Yes**	**Yes**	**Yes**
8	955.5	973.5	868.3	Osterberg Test	Yes	Sand	**Yes**	**Yes**	**Yes**
9	983	990.04	923.74	Statnamic Test	No	Mixed	**Yes**	**Yes**	**Yes**

Table A.4. Columns 24 through 32 of DSHAFT Display Form (continued)

ID	Water Table Elevation (24)	Elevation of Top of Shaft Concrete (25)	Elevation of Shaft Toe (26)	Test Method (27)	Rock-Socketed (28)	Test Site Soil Classification (29)	Acceptable Quality of Concrete (30)	Record Complete (31)	Usable Data (32)
10	972.84	988.72	933.30	Statnamic Test	No	Sand	**Yes**	**Yes**	**Yes**
11	973.47	991.52	935.69	Statnamic Test	No	Sand	**Yes**	**Yes**	**Yes**
12	725	739	645.1	Osterberg Test	Yes	Sand	N/A	**Yes**	**?**
13	1426.1	1412.4	1385.4	Osterberg Test	Yes	Sand	N/A	**Yes**	**?**
14	917.4	934	893.4	Osterberg Test	Yes	Rock	N/A	**Yes**	**?**
15	1515.7	1473.8	1454.8	Osterberg Test	Yes	Mixed	N/A	**Yes**	**?**
16	953.9	1008.9	974.9	Osterberg Test	Yes	Clay	N/A	**Yes**	**?**
17	360	337.1	231.9	Osterberg Test	Yes	Clay	N/A	**Yes**	**?**
18	657.5	627.5	558.0	Osterberg Test	Yes	Sand	N/A	**Yes**	**?**

Table A.4. Columns 24 through 32 of DSHAFT Display Form (continued)

ID	Water Table Elevation (24)	Elevation of Top of Shaft Concrete (25)	Elevation of Shaft Toe (26)	Test Method (27)	Rock-Socketed (28)	Test Site Soil Classification (29)	Acceptable Quality of Concrete (30)	Record Complete (31)	Usable Data (32)
19	1426.1	1410.9	1384.7	Osterberg Test	Yes	Sand	N/A	-	**?**
20	825.5	829.3	774	Osterberg Test	No	Sand	N/A	**Yes**	**?**
21	762	723.02	629.03	Osterberg Test	Yes	Sand	N/A	-	**?**
22	Variable	605.0	573.0	Osterberg Test	Yes	Mixed	N/A	**-**	**?**
23	698	549	521	Osterberg Test	Yes	Sand	N/A	**-**	**?**
24	Unknown	496	421	Osterberg Test	Yes	Mixed	N/A	**-**	**?**
25	Unknown	622.8	585.4	Osterberg Test	Yes	Mixed	N/A	**-**	**?**
26	971.65	987.65	912.48	Osterberg Test	No	Sand	N/A	**-**	**Yes**
27	971.65	687.65	912.65	Osterberg Test	No	Sand	N/A	**-**	**Yes**

Table A.4. Columns 24 through 32 of DSHAFT Display Form (continued)

ID	Water Table Elevation (24)	Elevation of Top of Shaft Concrete (25)	Elevation of Shaft Toe (26)	Test Method (27)	Rock-Socketed (28)	Test Site Soil Classification (29)	Acceptable Quality of Concrete (30)	Record Complete (31)	Usable Data (32)
28	Not Encountered	N/A	N/A	Osterberg Test	Yes	Clay	N/A	**Yes**	**?**
29	Not Encountered	N/A	N/A	Osterberg Test	Yes	Clay	N/A	**-**	**?**
30	-85	-19	-122	Osterberg Test	No	Mixed	N/A	**-**	**?**
31	1172.08	1190.35	1121.26	Osterberg Test	No	Mixed	N/A	**-**	**?**
32	1151	1149.1	1041.8	Osterberg Test	Yes	Sand	N/A	**-**	**?**

Table A.5. Columns 33 through 38 of DSHAFT Display Form

ID	Attachments (1) (33)	Attachments (2) (34)	Attachments (3) (35)	Attachments (4) (36)	Attachments (5) (37)	Attachments (6) (38)
1	Report on Drilled Shaft Load Test	Map	CSL Report	-	-	-
2	Drilled Shaft Load Test Report	Map	CSL Report	-	-	-
3	Report on Drilled Shaft Load Test	Map	-	-	-	-
4	Report on Drilled Shaft Load Testing	CSL Report	Map	-	-	-
5	Report on Drilled Shaft Load Testing	Map	-	-	-	-
6	Report on Drilled Shaft Load Testing	CSL Report	Map	-	-	-
7	Report on Drilled Shaft Load Testing	CSL Report	Map	-	-	-
8	Report on Drilled Shaft Load Testing	CSL Report	Map	-	-	-
9	Report on Drilled Shaft Load Testing	Report on Drilled Shaft Post Grouting	CSL Report	Map	-	-
10	Report on Drilled Shaft Load Testing	Report on Drilled Shaft Post Grouting	CSL Report	Map	-	-

Table A.5. Columns 33 through 38 of DSHAFT Display Form (continued)

ID	Attachments (1) (33)	Attachments (2) (34)	Attachments (3) (35)	Attachments (4) (36)	Attachments (5) (37)	Attachments (6) (38)
11	Report on Drilled Shaft Load Testing	CSL Report	Map	-	-	-
12	Report on Drilled Shaft Load Test	-	-	-	-	-
13	Report on Drilled Shaft Load Testing	-	-	-	-	-
14	Report on Drilled Shaft Load testing	-	-	-	-	-
15	Report on Drilled Shaft Load Testing	-	-	-	-	-
16	Report on Drilled Shaft Load Testing	-	-	-	-	-
17	Report on Drilled Shaft Load Testing	Additional Information	-	-	-	-
18	Report on Drilled Shaft Load Testing	-	-	-	-	-
19	Report on Drilled Shaft Load Testing	CSL Report	-	-	-	-
20	Report on Drilled Shaft Load Testing	-	-	-	-	-

Table A.5. Columns 33 through 38 of DSHAFT Display Form (continued)

ID	Attachments (1) (33)	Attachments (2) (34)	Attachments (3) (35)	Attachments (4) (36)	Attachments (5) (37)	Attachments (6) (38)
21	Report on Drilled Shaft Load Testing	-	-	-	-	-
22	Report on Drilled Shaft Load Testing	-	-	-	-	-
23	Report on Drilled Shaft Load Testing	Digitized Load Transfer Data	Osterberg Load Test Data	-	-	-
24	Report on Drilled Shaft Load Testing	-	-	-	-	-
25	Load Test Report	-	-	-	-	-
26	Drilled Shaft Load Test Report	CSL Report	-	-	-	-
27	Drilled Shaft Load Test Report	Post Grouting Details	CSL Report	-	-	-
28	Load Test Report	-	-	-	-	-
29	Load Test Report	-	-	-	-	-
30	Drilled Shaft Load Test Report	-	-	-	-	-

Table A.5. Columns 33 through 38 of DSHAFT Display Form (continued)

ID	Attachments (1) (33)	Attachments (2) (34)	Attachments (3) (35)	Attachments (4) (36)	Attachments (5) (37)	Attachments (6) (38)
31	Drilled Shaft Load Test Report - Part 1	Drilled Shaft Load Test Report - Part 2	Drilled Shaft Load Test Report - Part 3	-	-	-
32	Drilled Shaft Load Test Report - Part 1	Drilled Shaft Load Test Report - Part 2	Drilled Shaft Load Test Report - Part 3	-	-	-

APPENDIX B. SUMMARY OF SUBSURFACE PROFILE AND MATERIAL PARAMETERS FOR DATASETS USED IN PRELIMINARY ANALYSIS

Table B.1. Subsurface profile and material parameters for data point ID No. 1

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Firm glacial clay	8.2	Cohesive	-	-
2	Firm silty glacial clay	7.9	Cohesive	-	-
3	Stiff silty clay	20	Cohesive	-	-
4	Firm glacial clay	12.1	Cohesive	-	-
5	Soft shale	16.4	Cohesive IGM or rock	-	-
6	Firm shale	3.3	Cohesive IGM or rock	-	-

Table B.2. Subsurface profile and material parameters for data point ID No. 2

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Slightly weathered dolomite	12.7	Rock	q_u (shaft/toe) = 637.2 ksf; RQD = 90%	$E_m/E_i = 0.90$(a);); $\alpha_E = 0.96$(d); RMR = 84(b); m = 2.4(c); s = 0.082(c)

(a) –estimated from Table 7.3; (b) –determined from Table 7.5; (c) –determined from Table 7.5; (d) –estimated from Table 7.2.

Table B.3. Subsurface profile and material parameters for data point ID No. 3

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Stiff to firm silty glacial clay	39	Cohesive	$N_{60} = 12$; c = 1.572 ksf	$S_u = 1.572$ ksf(d)
2	Firm silty clay	4.92	Cohesive	$N_{60} = 22$; c = 2.934 ksf	$S_u = 2.934$ ksf(d)
3	Clay shale bedrock	21.88	Rock	q_u (shaft) = 196.56 ksf; q_u (toe) = 24.37 ksf; RQD = 33%	$E_m/E_i = 0.093$(a); $\alpha_E = 0.536$(e); RMR = 49(b); m = 0.183(c); s = 0.00009(c)

(a) –estimated from Table 7.3; (b) –determined from Table 7.5; (c) –determined from Table 7.5; (d) –assumed similar to cohesion; (e) –estimated from Table 7.2.

Table B.4. Subsurface profile and material parameters for data point ID No. 4

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Stiff sandy glacial clay	10.496	Cohesive	N_{60} = 23; c = 3.067 ksf	S_u = 3.067 ksf(d); γ = 0.128 kcf(a)
2	Fine to medium sand	32.5	Cohesionless	N_{60} = 14; c = 1.857 ksf	γ = 0.114 kcf(a)
3	Clay shale	29.7	Cohesive IGM	q_u (shaft) = 91.584 ksf; q_u (toe) = 93.67 ksf; RQD = 93%	σ_n = 3.9(b); RMR = 83(c); m = 3.43 (e); s = 0.082(e)

(a) –estimated using N_{60} based on recommendation provided by Bowles (1996); (b) –estimated using equation 7.6; (c) –determined from Table 7.5; (d) –assumed similar to cohesion; (e) –determined from Table 7.5.

Table B.5. Subsurface profile and material parameters for data point ID No. 5

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Silty sandy lean clay	7.9	Cohesive	N_{60} = 5; c = 0.625 ksf	S_u = 0.625 ksf(g); γ = 0.115 kcf(a)
2	Silty lean clay	4.9	Cohesive	N_{60} = 11; c = 1.429 ksf	S_u = 1.429 ksf(g); γ = 0.127 kcf(a)
3	Silty sandy lean clay	27.6	Cohesive	N_{60} = 15; c = 2 ksf	S_u = 2 ksf(g); γ = 0.138 kcf(a)
4	Gravel with sand	1.6	Cohesionless	N_{60} = 100; c = 4 ksf;	γ = 0.15 kcf(a)
5	Clay shale	23.3	Cohesive IGM	γ = 0.126 kcf; q_u = 14.4 ksf; RQD = 58%	σ_n = 3.9
6	Coal	3	Cohesive IGM	-	q_u = 5.76 ksf(b); σ_n = 3.9
7	Clay shale	7.5	Cohesive IGM	γ = 0.12 kcf; q_u = 5.76 ksf	σ_n = 3.9
8	Carboniferous clay shale	3.5	Rock	γ = 0.131 kcf; q_u (shaft) = 138.63 ksf; q_u (toe) = 191.81 ksf	RQD = 37%(c); E_m/E_i = 0.106(d); RMR = 38(e); m = 0.183(f); s = 0.00009(f)

(a) –estimated using N_{60} based on recommendation provided by Bowles (1996); (b) –assumed similar value of clay shale; (c) –estimated based on q_u value; (d) –estimated from Table 7.3; (e) –determined from Table 7.5; (f) –determined from Table 7.5; (g) –assumed similar to cohesion.

Table B.6. Subsurface profile and material parameters for data point ID No. 6

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Firm clay fill	5.9	Cohesive	N_{60} = 10; c = 1.286 ksf	S_u = 1.286 ksf[(a)]
2	Stiff silty clay	21	Cohesive	N_{60} = 5; c = 0.625 ksf	S_u = 0.625 ksf[(a)]
3	Firm glacial clay	18.7	Cohesive	N_{60} = 13; c = 1.715 ksf	S_u = 1.715 ksf[(a)]
4	Very Firm sandy glacial clay	18.4	Cohesive	N_{60} = 23; c = 3.067 ksf	S_u = 3.067 ksf[(a)]

[(a)] –assumed similar to cohesion.

Table B.7. Subsurface profile and material parameters for data point ID No. 7

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Lean clay	4	Cohesive	N_{60} = 20; c = 1.286 ksf	S_u = 1.286 ksf[(a)]; γ = 0.125 kcf[(b)]
2	Lean clay with sand	9	Cohesive	N_{60} = 10; c = 2.667 ksf	S_u = 2.667 ksf[(a)]; γ = 0.125 kcf[(b)]
3	Mod weathered limestone	1.1	Rock	q_u = 555.84 ksf;	RQD = 70%[(c)]; E_m/E_i = 0.7[(d)]; α_E = 0.88[(e)]
4	Fresh limestone	2.3	Rock	q_u = 1388.16 ksf; RQD = 79%	E_m/E_i = 0.79[(d)]; E_m/E_i = 0.79[(d)]; α_E = 0.916[(e)]
5	Calcareous sandstone	4.3	Rock	q_u = 862.56 ksf; RQD = 83%	E_m/E_i = 0.83[(d)]; α_E = 0.932[(e)]
6	Fractured Limestone with weathered shale	1.3	Rock	q_u = 1175.04 ksf	RQD = 50%[(c)]; E_m/E_i = 0.15[(d)]; α_E = 0.55[(e)]
7	Fresh limestone	12	Rock	q_u (shaft) = 817.2 ksf; q_u (toe) = 760.32 ksf; RQD = 96%	E_m/E_i = 0.96[(d)]; α_E = 0.984[(e)]

[(a)] –assumed similar to cohesion; [(b)] –estimated using N_{60} based on recommendation provided by Bowles (1996); [(c)] –estimated based on q_u value; [(d)] –estimated from Table 7.3; [(e)] –estimated from Table 7.2.

Table B.8. Subsurface profile and material parameters for data point ID No. 8

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Silty clay	10	Cohesive	N_{60} = 12; c = 1.572 ksf	S_u = 1.572 ksf(a); γ = 0.13 kcf(b)
2	Silt with minor sand	17	Cohesive	N_{60} = 2; c = 0.25 ksf	S_u = 0.25 ksf(a); γ = 0.121 kcf(b)
3	Fine to medium sand with fine gravel	42	Cohesionless	N_{60} = 30; c = 4 ksf	γ = 0.13 kcf(b)
4	Medium to coarse sand with gravel	21.5	Cohesionless	N_{60} = 21; c = 2.8 ksf	γ = 0.121 kcf(b)
5	Fresh limestone	14.7	Rock	q_u (shaft) = 510.34 ksf; q_u (toe) = 553.40 ksf; RQD = 77%	E_m/E_i = 0.96(c); α_E = 0.984(d); RMR = 60(e); m = 0.58(f); s = 0.0029(f)

(a) –assumed similar to cohesion; (b) –estimated using N_{60} based on recommendation provided by Bowles (1996); (c) –estimated from Table 7.3; (d) –estimated from Table 7.2; (e) –determined from Table 7.5; (f) –determined from Table 7.5.

Table B.9. Subsurface profile and material parameters for data point ID No. 9

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Stiff silty clay	10	Cohesive	N_{60} = 7; c = 0.875 ksf	S_u = 0.875 ksf(a); γ = 0.125 kcf(b)
2	Soft to stiff silty clay	10	Cohesive	N_{60} = 4; c = 0.5 ksf	S_u = 0.5 ksf(a); γ = 0.110 kcf(b)
3	Silty fine sand	10	Cohesionless	N_{60} = 13; c = 1.715 ksf	γ = 0.113 kcf(b)
4	Fine sand	25	Cohesionless	N_{60} = 20; c = 2.667 ksf	γ = 0.120 kcf(b)
5	Soft silty sand	5	Cohesionless	N_{60} = 2; c = 0.25 ksf	γ = 0.085 kcf(b)
6	Coarse sand	6.25	Cohesionless	N_{60} = 16; c = 2.134 ksf	γ = 0.116 kcf(b)

(a) –assumed similar to cohesion; (b) –estimated using N_{60} based on recommendation provided by Bowles (1996).

Table B.10. Subsurface profile and material parameters for data point ID No. 10

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Stiff silty clay	5	Cohesive	N_{60} = 12; c = 1.572 ksf	S_u = 1.572 ksf(a); γ = 0.130 kcf(b)
2	Soft to stiff silty clay	10	Cohesive	N_{60} = 7; c = 0.875 ksf	S_u = 0.875 ksf(a); γ = 0.127 kcf(b)
3	Soft silty clay	5	Cohesive	N_{60} = 5; c = 0.625 ksf	S_u = 0.625 ksf(a); γ = 0.122 kcf(b)
4	Fine sand	35	Cohesionless	N_{60} = 15; c = 2 ksf	γ = 0.115 kcf(b)
5	Coarse sand with trace gravel	0.42	Cohesionless	N_{60} = 18; c = 2.4 ksf	γ = 0.118 kcf(b)

(a) –assumed similar to cohesion; (b) –estimated using N_{60} based on recommendation provided by Bowles (1996).

Table B.11. Subsurface profile and material parameters for data point ID No. 11

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Stiff silty clay	5	Cohesive	N_{60} = 14; c = 0.625 ksf	S_u = 0.625 ksf[(a)]; γ = 0.135 kcf[(b)]
2	Soft to stiff silty clay	15	Cohesive	N_{60} = 5; c = 1.857 ksf	S_u = 1.857 ksf[(a)]; γ = 0.115 kcf[(b)]
3	Fine sand	34.78	Cohesionless	N_{60} = 17; c = 2.267 ksf	γ = 0.117 kcf[(b)]

(a) –assumed similar to cohesion; (b) –estimated using N_{60} based on recommendation provided by Bowles (1996).

Table B.12. Subsurface profile and material parameters for data point ID No. 26

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Lean clay	10	Cohesive	N_{60} = 4	S_u = 0.424 ksf[(a)]; γ = 0.120 kcf[(b)]
2	Fine sand	8.5	Cohesionless	N_{60} = 4	γ = 0.090 kcf[(b)]
3	Silty clay	5	Cohesive	N_{60} = 3	S_u = 0.350 ksf[(a)]; γ = 0.110 kcf[(b)]
4	Fine sand	51.67	Cohesionless	N_{60} = 11	γ = 0.110 kcf[(b)]

(a) –estimated using equation 7.3; (b) –estimated using N_{60} based on recommendation provided by Bowles (1996).

Table B.13. Subsurface profile and material parameters for data point ID No. 27

Soil Layer	Material Description	Thickness (ft)	Material Type	Measured Material Parameters	Estimated Material Parameters
1	Lean clay	10	Cohesive	N_{60} = 7	S_u = 0.742 ksf[(a)]; γ = 0.125 kcf[(b)]
2	Fine sand	8.5	Cohesionless	N_{60} = 5	γ = 0.094 kcf[(b)]
3	Silty clay	5	Cohesive	N_{60} = 5	S_u = 0.53 ksf[(a)]; γ = 0.115 kcf[(b)]
4	Fine sand	51.5	Cohesionless	N_{60} = 13	γ = 0.113 kcf[(b)]

(a) –estimated using equation 7.3; (b) –estimated using N_{60} based on recommendation provided by Bowles (1996).