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EVALUATION/MODIFICATION OF IDOT FOUNDATION PILING DESIGN AND CONSTRUCTION POLICY

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16. Abstract

The Illinois Department of Transportation (IDOT) estimates pile lengths based on a static analysis method; however, the final length of the pile is determined with a dynamic formula based on the pile driving resistance exhibited in the field. Because different methods are used for estimating and for acceptance, there is usually a lack of agreement between the estimated length and the driven length of pile. The objective of this study is to assess the ability of the methods currently used by IDOT, to assess other methods for estimating pile capacity, to improve the methods if possible, and to determine resistance factors appropriate for the methods.

This study reports pile load test data along with pile driving information and subsurface information, and uses this information to investigate and quantify the accuracy and precision with which five different static methods and five different dynamic formulae predict capacity. These static methods are the IDOT Static method, the Kinematic IDOT (K-IDOT) method, the Imperial College Pile (ICP) method, Olson's method and Driven. The dynamic formulae are the EN-IDOT formula, the FHWA-Gates Formula, the Washington State Department of Transportation (WSDOT) formula, the FHWA-UI formula, and WEAP. Three databases were assembled and used to quantify the ability of these methods to predict capacity.

Results suggest that the three dynamic formulae: WS-DOT, the FHWA-Gates, and the UI-Gates provide similar accuracy. However, the WS-DOT formula is simple to implement and predicts capacity most consistently for the databases reviewed in this study. A value of 0.55 is recommended for the resistance factor for redundant piling.

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The contents of this report reflect the view of the author(s), who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Center for Transportation, the Illinois Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

EXECUTIVE SUMMARY

Pile sizes and lengths are estimated in the office based on an understanding of the thickness of soil layers and the soil properties for each layer. However, piles are driven in the field using different criteria than are used for estimating. The field criteria used by the Illinois Department of Transportation (IDOT) is typically based on a pile dynamic formula and driving resistance measured at the end-of-driving (EOD). Using one formula for estimating the required length and a different formula for controlling the driven length inevitably results in final pile lengths different than estimated lengths. One of the main purposes of the research effort reported herein is to improve and quantify the agreement between the two methods. It is also desirable to improve the precision of each predictive method as a means to improve the agreement between the methods. Finally, it is important to quantify the level of precision for these methods to enable a selection for a resistance factor for their use in LRFD design based on relevant pile data. Accordingly, the goals of this research effort are as follows:

1. Improve the agreement between estimated pile lengths and driven pile lengths.
2. Improve and quantify several methods for determining pile capacity based on pile driving behavior.
3. Improve and quantify several methods for determining pile capacity based on soil properties behavior.
4. Select the combination of static and dynamic pile driving formula that provide the best agreement (item #1) and determine resistance factors for each method.

A significant amount of pile data was reviewed, recorded, analyzed, and interpreted to address these four goals. Ideally, one collection of data would provide all the information necessary for all four tasks, but no such database currently exists. Alternatively, three databases were developed to quantify specific goals. The three databases are described below:

Database 1: The International Database - this database consisted on 132 pile load tests in which static load tests were conducted and enough information on pile driving to allow the prediction of pile capacity using a simple dynamic formula and EOD conditions. This database provided the advantage that static load tests were conducted to provide a measure of capacity, and the number of tests (132) was large enough to provide a statistically significant number of tests. This database provided the information necessary to develop resistance factors for dynamic formula. The number of load tests also allowed for the development of a new method optimized to improve the agreement between predicted capacity and capacity measured from a static load test.

Database 2: The Comprehensive Database - this database consisted of a much smaller number of piles. Twenty-six static load test cases were entered into this database in which there was enough soil information and driving information to allow predictions with both static and dynamic formulae based on EOD conditions. This was the only database that allowed determination for resistance factors for static methods, but the load tests are too few, and the resistance factors developed with this dataset can only be considered as tentative. Additionally, this database provided an independent source of information to confirm, or reject trends observed in databases 1 and 3.

Database 3: The Illinois Database - This was a collection of 92 driven pile cases in which there was enough to predict capacity using both static and dynamic formulae, but there were no static load tests performed on the piles. This database contained a nearly even distribution of H-piles in sand, H-piles in clay, pipe piles in sand, and pipe piles in clay. This database was used to quantify agreement between predictions of capacity using static and dynamic formulae, and it was also used to develop methods to improve the agreement between static and dynamic predictions.

Several static and dynamic methods were investigated in this study. A list is given below of the methods:

Static Methods	Dynamic Methods
IDOT -Static	EN
Olson's Method	FHWA-Gates
Driven (FHWA)	WSDOT
ICP	WEAP
K-IDOT	UI-FHWA

The last two methods K-IDOT and UI-FHWA were methods that were developed to improve the ability to predict capacity.

Best Dynamic Formula - Based on database 1, the three most precise dynamic formulae, listed in order of decreasing precision are UI-FHWA, WSDOT, and FHWA-Gates. The method with the greatest precision (UI-FHWA) was expected since we used database 1 to optimize parameters for predicting capacity. However, results with database 2 showed the WSDOT method to be the most precise, followed by FHWA-Gates, followed by UI-Gates. Finally, database 3, used to quantify inter-agreement between static and dynamic methods, demonstrated that agreement between static and dynamic methods was best when the WSDOT formula was used. Accordingly, the WSDOT formula appears to be the dynamic formula that exhibited the best overall tendency to predict capacity with precision and agree with static formula.

Best Static Formula - Based on database 2, the corrected K-IDOT method resulted in the best agreement with static load tests and the best agreement with prediction of capacity from dynamic formula. The corrected K-IDOT method is based on the current IDOT method for determining pile capacity based on soil properties. The K-DOT method for closed ended pipe piles (shell piles) is the same method as the current IDOT method. However, for H-piles the K-IDOT method differs. Two capacities are determined: one assumes a failure along a box outlining the H-pile, and end bearing is developed across the enclosed area. A second capacity is determined by assuming the failure surface occurs along the soil-pile interface and end bearing is developed only for the cross-sectional area of the steel. The two capacities are compared and the smaller capacity is used. The "corrected" term refers to the optimization procedure used to calibrate the K-IDOT method. Database 3 was used to develop the optimized parameters, and database 2 confirmed that the optimization resulted in a more precise method. Accordingly, Database 2 and 3 identify the corrected K-IDOT method to be the most precise. Accordingly, the findings of this effort identify the WSDOT method to be the most reliable formula of the dynamic methods investigated. Pile capacity using the WSDOT formula is as follows:

$$R_n = 6.6 F_{eff} WH \ln(10N)$$

where R_n = ultimate capacity in kips, F_{eff} = a hammer efficiency factor based on hammer and pile type, W = weight of hammer in kips, H = drop of hammer in feet, and N = average penetration resistance in blows/inch. F_{eff} = 0.55 for air/steam hammers for all pile types, 0.37 for open-ended diesel hammers for concrete or timber piles, 0.47 for open-ended diesel hammers for steel piles, and 0.35 for closed-ended diesel hammers for all pile types. A resistance factor of 0.55 is recommended for redundant piling (for piles in a group of 5 or more).

The most precise static method is the corrected K-IDOT method. The method requires keeping track of the quantity of pile load carried by sand and by clay and then determining the total pile capacity as

$$Q_{total} = Q_{sand}*\text{Factor(based on pile type)} + Q_{clay}*\text{Factor(based on pile type)}$$

where the factors are as follows factor for H-pile in clay = 1.5, factor for H-pile in sand = 0.30, factor for pipe pile in sand = 0.758, factor for pipe pile in clay = 1.174.

Use of the WSDOT as the dynamic formula and the corrected K-IDOT formula for estimating pile lengths will, on the average, result in good agreement between estimated and driven length. A cumulative distribution for the agreement between WSDOT and K-IDOT can be used to control the likelihood that piles may be driven to depths greater than estimated (Fig. 6.6).

IDOT may prefer to slightly overestimate lengths to minimize the occurrence of delivering piles that are too short. If the static capacity used for estimating purposes is equal to the dynamic capacity, then the chance is 50 percent that the estimated pile length will be too short. However, the chance that piles will be driven to depths greater than estimated is only 20 percent if the pile's static capacity is designed to 1.42 times the dynamic capacity. Fig. 6.6 can be used to select a ratio for a desired degree of certainty.

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CHAPTER 1 INTRODUCTION

The Illinois Department of Transportation (IDOT) estimates pile lengths based on a static analysis method; however, the final length of the pile is determined with a dynamic formula based on the pile driving resistance exhibited in the field at the end-of-driving (EOD). Because different methods are used for estimating and for acceptance, there is usually a lack of agreement between the estimated length and the driven length of pile. Currently (2008), IDOT uses a static method that has been internally developed and adjusted over several decades termed herein as the IDOT static method, and IDOT uses the FHWA-Gates method as a dynamic formula for determining pile capacity based on driving resistance at the end of driving. The objective of this study is to assess the ability of the methods currently used by IDOT, to assess other methods for estimating pile capacity, to improve the methods if possible, and to determine resistance factors appropriate for the methods. Three different pile databases are used to address these objectives.

This study reports pile load test data along with pile driving information and subsurface information and uses this information to investigate and quantify the accuracy and precision with which five different static methods and five different dynamic formulae predict capacity. These static methods are the IDOT Static method, the Kinematic IDOT (K-IDOT) method, the Imperial College Pile (ICP) method, Olson's method and Driven. The dynamic formulae are the EN-IDOT formula, the FHWA-Gates Formula, the Washington State Department of Transportation (WSDOT) formula, the FHWA-UI formula, and WEAP.

Pile information gathered for this study was grouped into three databases. The Comprehensive Database was assembled for this study and consists of piles with information adequate to predict pile capacity with all ten methods mentioned previously. Static load test data are available for these piles as well. The Illinois Database consists of pile information provided by IDOT. Information for each pile is available to allow predictions of axial capacity for each method above; however, no static load tests were conducted on these piles. The third database, the International Database, consists of piles with sufficient driving information to allow predictions of axial capacity with dynamic formulae; however, information is insufficient for predicting pile capacity with static methods. Static load test data are available for each pile in this database.

Chapter 2 discusses the methods used to determine pile capacity. The history and theory behind the methods is presented. The equations necessary to predict pile capacity for each method are also introduced. The limitations of each method, as well as advantages and disadvantages are presented.

Chapter 3 provides information regarding the International Database. This database of 132 piles from around the world contains information adequate to predict pile capacity with dynamic formulae. These predicted capacities are compared to the piles' static load test capacities. The accuracy and precision of each method, compared to static load test results, are quantified and presented.

Chapter 4 provides information on the Comprehensive Database. This database of 26 piles contains information adequate to predict pile capacity with every method investigated, and static load test results are available for each pile. The predicted capacity of each pile using each capacity prediction method is calculated. The accuracy and precision of each method is then quantified and reported. The accuracy and precision of each method compared to static load test results is presented, as well as the agreement between dynamic and static predictions.

The Illinois Database is presented and discussed in Chapter 5. This database of 92 piles driven throughout the State of Illinois contains information adequate to predict capacity using each method investigated, but no static load test data are available. The capacity of each pile is calculated using both static and dynamic methods, and the agreement between static and dynamic predictions is quantified and presented.

Chapter 6 proposes correction factors to be applied to static methods for improving agreement between static and dynamic methods. The agreement between dynamic and corrected static methods is quantified and compared. Recommendations are made for which static and dynamic methods would offer the most accuracy and precision and which correction factors should be adopted.

Chapter 7 develops the resistance factors using two methods (FOSM and FORM) and relates the statistics developed in the previous chapters to values of reliability as a function of a target reliability index.

Chapter 8 provides a summary and conclusion of the findings.

Chapter 9 lists the references cited in the report.

Several appendices follow to provide more details of the study. Comparisons of static and dynamic methods, with and without static load tests are sub-divided into groups based on pile type and soil type. The discussion and illustration of all these comparisons require more pages than allowed in the main report. Therefore, these detailed, but relevant results are included in Appendices A through E.

CHAPTER 2 DEFINITION AND DESCRIPTION OF DYNAMIC AND STATIC METHODS

2.1 INTRODUCTION

Eleven methods were used to estimate the capacity of the piles in the databases analyzed. This chapter describes and defines each method used. Broadly, these methods can be broken down into dynamic methods, which use data from the end of pile driving to estimate capacity, and static methods, which use data from a subsurface investigation (such as N_{SPT} and s_u).

2.2 DYNAMIC METHODS

Four dynamic methods exist for predicting pile capacity. These methods use data recorded during the driving of a pile to determine its capacity. The most important parameters for these methods are the energy delivered to the pile due to the weight and drop of the pile hammer and the number of blows to drive the pile a given distance at the end-of-driving. Several dynamic methods are considered in this study. They are the IDOT-Modified Engineering News Formula (EN-IDOT), the FHWA-Gates Formula, the Washington State DOT Formula (WSDOT), the University of Illinois-modified FHWA-Gates Formula (FHWA-UI), and WEAP.

2.2.1 FHWA-Gates Method

The dynamic formula (Gates, 1957) originally proposed by Gates is:

$$Q_u = (6/7)\sqrt{eE}\,\log\left(10/s\right) \tag{2.1}$$

Where Q_u = ultimate pile capacity (tons), E = energy of pile driving hammer (ft-lb), e = efficiency of hammer (0.75 for drop hammers, and 0.85 for all other hammers, or efficiency given by manufacturer), s = pile set per blow (inches). A factor of safety equal to 3 is recommended by Gates (Gates, 1957) to determine the allowable bearing capacity.

The Federal Highway Administration has modified Gates' original equation and recommends the following:

$$Q_u = 1.75\sqrt{WH}\,\log(10N) - 100 \tag{2.2}$$

Where Q_u = ultimate pile capacity in kips, W = weight of hammer in pounds, H = drop of hammer in feet, and N = driving resistance in blows/in. This equation is currently used by IDOT (2008).

2.2.2 WSDOT Formula

The State of Washington uses the following formula (Allen, 2005) to determine pile capacity:

$$R_n = 6.6F_{eff}WH\ln(10N) \tag{2.3}$$

Where R_n = ultimate pile capacity in kips, F_{eff} = a hammer efficiency factor based on hammer and pile type, W = weight of hammer in kips, H = drop of hammer in feet, and N = average penetration resistance in blows/inch. The parameter, F_{eff} = 0.55 for air/steam hammers with all pile types, 0.37 for open-ended diesel hammers with concrete or timber piles, 0.47 for open-ended diesel hammers with steel piles, and 0.35 for closed-ended diesel hammers with all pile types.

2.2.3 FHWA-UI Formula

Based on a study performed for the Wisconsin Department of Transportation, Long et al. (2009) developed corrections to the FHWA-Gates formula based on an overall correction, a hammer correction, a soil type correction, and a pile type correction. The formula is only applicable to piles with capacities less than 750 kips. The FHWA-UI formula is:

$$Q_u = Q_{FHWA\text{-}Gates} * F_o * F_H * F_S * F_P \qquad (2.4)$$

Where the correction factors are as follows:

F_o - Overall adjustment factor
- F_o = 0.94

F_S - Adjustment factor for Soil type
- F_S = 1.00 Mixed soil profile
- F_S = 0.87 Sand soil profile
- F_S = 1.20 Clay soil profile

F_P - Adjustment factor for Pile type
- F_P = 1.00 Closed-end pipe (CEP)
- F_P = 1.02 Open-end pipe (OEP)
- F_P = 0.80 H-pile (HP)

F_H - Adjustment factor for Hammer type
- F_H = 1.00 Open-ended diesel (OED)
- F_H = 0.84 Closed- end diesel (CED)
- F_H = 1.16 Air/Steam - single acting
- F_H = 1.01 Air/Steam - double acting
- F_H = 1.00 Hydraulic (truly unknown)

2.2.4 Other Dynamic Formula Investigated

The EN-IDOT formula and WEAP were also used to analyze the piles in this report. However, the performance of these methods was not as promising as other formulae; therefore, discussion of the theory and use of EN-IDOT and WEAP are described in Appendix A.

2.3 STATIC METHODS

Five static methods can be used to estimate the capacity of a pile before pile driving has occurred. These methods are based on the soil stratigraphy of the site and properties of the soil. Typical soil properties required include unit weight, undrained shear strength, and SPT N-values. Information on pile geometry is also required. The static methods investigated in this report are Driven, the IDOT Static Method, the Kinematic IDOT Method, the ICP Method, and Olson's Method.

2.3.1 IDOT Static

IDOT currently uses the IDOT Static Method to estimate the capacity of a pile. The user inputs information based on the soil profile and pile type to determine pile capacity. Specifically, for each layer of the soil profile, the user must input the layer thickness, soil type (either hard till, very fine silty sand, fine sand, medium sand, clean medium to coarse sand, or sandy gravel), the SPT N-value, and, if applicable, the undrained shear strength. The total pile capacity is determined as the sum of the base capacity and side capacity.

For granular (cohesionless) soils, the unit base capacity is determined as

$$q_p = (0.8N_{1(60)}*D_b)/D \leq q_l \qquad (2.5)$$

Where $N_{1(60)}$ is the SPT N-value corrected for hammer efficiency and overburden pressure, D_b is the depth from the ground surface to the pile tip, D is the pile diameter, and q_l is a limiting unit base capacity where

$$q_l = 8N_{1(60)} \text{ for sands, and } q_l = 6N_{1(60)} \text{ for non-plastic silts}$$

q_p is multiplied by the area of the base of the pile to determine the pile's base capacity. For H-Piles, the base area is taken as the cross-sectional area of steel, for both granular and cohesive soils.

For cohesive soils, the unit base capacity is determined based on the undrained shear strength as

$$q_p = 9s_u \qquad (2.6)$$

Where s_u is the undrained shear strength of the soil. q_p is multiplied by the area of the base of the pile to determine the pile's base capacity.

The side capacity of a pile is determined on a layer-by-layer basis. For a granular soil, the unit side capacity is determined based on the soil type and the N-value input. The formulas used are empirical. There are 17 different formulae used to determine the unit side capacity of a granular soil, depending on the soil type and N-value of the soil. For cohesive soils, the unit side resistance is based on s_u. Depending on the value of s_u, one of four empirical formulae is used. Also, for very stiff soils (s_u > 3 tsf and N > 30), the soil is treated as a granular soil with the Hard Till soil type. For H-piles in cohesive soils, the pile perimeter is taken as the boxed pile perimeter. When the H-pile is in a granular soil, the pile perimeter is taken as one-half of the boxed pile perimeter. In the IDOT Method spreadsheet, a granular non-displacement factor of 0.5 is used to accomplish this.

2.3.2 Kinematic IDOT Method

As mentioned in the previous section, when H-piles are being analyzed using the IDOT Method no attempt is made to determine if the pile should be considered plugged or unplugged. Instead, conservatively, the boxed perimeter is used for determining side capacity and the cross-sectional area of steel is used to determine base capacity.

In the Kinematic IDOT Method, an attempt is made to determine if the pile is plugged or unplugged. The criteria used are those suggested by Olson and Dennis (1982). Dennis used the following criteria: "[H-piles] were considered to be unplugged if the tip capacity, calculated using the end of an enclosing prism, was greater than the side capacity, calculated using the steel-soil contact area. If an H-pile was found to be unplugged the steel-soil contact area was used for calculating both side and tip capacity. A plugged H-pile was considered as a solid rectangular prism." This modification to the IDOT Method treats the entire pile as plugged or unplugged, and accordingly, should improve the precision of the method.

The granular non-displacement factor, which is used in the IDOT Static method, is not applied in the Kinematic IDOT Method. Otherwise, the unit capacities are determined exactly as in the IDOT Static Method. When determining total capacity, the surface area is determined based on the entire pile being either plugged or unplugged, rather than the combination of plugged/unplugged used in the IDOT Static Method.

2.3.3 Other Static Methods Investigated

Olson's Method, the ICP method, and DRIVEN were also used to analyze the piles in this study. Olson's Method and DRIVEN calculate pile capacity based on SPT N-values and undrained shear strength values. The ICP Method is based on effective stress values and pile-soil interface friction angles. Results of this study provided evidence that these methods provided no clear advantage for predicting capacity. Accordingly, the detailed description of the theory and application of these methods is presented in Appendix B.

CHAPTER 3 INTERNATIONAL DATABASE

3.1 INTRODUCTION

Three pile databases were analyzed to quantify agreement between different methods for predicting axial pile capacity. The relationships examined were 1) the agreement between dynamic formulae and static load tests, 2) the agreement between static methods and static load tests, and 3) the agreement between dynamic formulae and static methods. The three databases are: 1) a composite of several different studies (International Database), 2) a database of piles driven by IDOT (IDOT Database), and 3) a database of piles on which static load tests were performed (Comprehensive Database).

The International Database is a composite database made up of piles from several different studies. Criteria for a pile's inclusion in this database are: the pile must be either a steel pipe pile or H-pile, and adequate information must be available from the end-of-driving so that the pile capacity can be estimated using the EN-IDOT, WSDOT, FHWA-Gates, and FHWA-UI dynamic formulae. Results from a static load test must be available for each pile in the database. Capacity estimates based on static methods are not available for these piles due to insufficient information on the soil profile and subsurface conditions.

The International Database is composed of piles from five different studies presented and discussed in the following sections. A more detailed description of the piles included in the International Database is given in Appendix B.

3.2 FLAATE, 1964

Flaate's work includes 116 load tests on timber, steel, and precast concrete piles driven into sandy soils. All driving resistance values were obtained at the end-of-driving (EOD). The capacity of the piles was estimated using the Hiley, Janbu, and Engineering News formulae. Flaate reported that the Janbu, Hiley, and Engineering News formulae give very good, good, and poor predictions of static capacity, respectively. Flaate suggested that a Factor of Safety equal to 12 may be required for the EN formula.

3.3 OLSON AND FLAATE, 1967

The load tests used by Olson and Flaate are similar to those presented in Flaate's (1964) work, but only 93 of the 116 load tests were used. Twenty-five of these piles are included in the International Database. Information on the piles included in this study is presented in Appendix B. Olson and Flaate eliminated load tests exceeding 100 tons for timber piles and 250 tons for concrete and steel piles because it is common practice for load tests to be conducted when pile capacities greater than 250 tons are required. However, the exclusion of these load tests has minimal effect on the conclusions.

Olson and Flaate compared seven different dynamic pile-driving formulae: Engineering News, Gow, Hiley, Pacific Coast Uniform Building Code, Janbu, Danish and Gates (1957). The Janbu formula was found to be the most accurate of the seven formulae for timber and steel piles, but it was concluded that no formula was clearly superior. The Danish, Janbu, and Gates formulae exhibited the highest average correlation factors. Olson and Flaate modified the original Gates (1957) formula to improve the agreement between predicted and measured capacity. The FHWA-Gates method uses a predictive formula similar to that recommended by Olson and Flaate.

3.4 FRAGASZY ET AL. 1988, 1989

The purpose of the study by Fragaszy et al. was to clarify whether the Engineering News formula should be used in western Washington and northwest Oregon. Fragaszy et al.

collected 103 static load tested piles which were driven into a variety of soil types. Thirty-eight of these piles had incomplete data, while two of them were damaged during driving. The remaining 63 piles were used by Fragaszy et al., 16 of which are included in the International Database. Information on those piles in the International Database is presented in Appendix B. The data are believed to be representative of driving resistances at the end-of-driving. As a result of the study, the following conclusions were drawn: (1) the EN formula with a factor of safety 6 may not provide a desirable level of safety, (2) other formulae provide more reliable estimates of capacity than the Engineering News formula, (3) no dynamic formula is clearly superior, although the Gates (1957) method performed well, and (4) the pile type and soil conditions can influence the accuracy of a formula.

3.5 FHWA DATABASE

The Federal Highway Administration (FHWA) made available their database on driven piling as developed and described by Rausche et al. (1996). Although the database includes details for 200 piles, only 27 piles met the requirements for inclusion in the International Database. Information on the piles included is presented in Appendix B.

The FHWA database includes several pile types, lengths, soil conditions, and pile driving hammers. Of the databases included in the International Database, this is the only one for which capacity estimates based on WEAP were available.

3.6 ALLEN (2005) AND NCHRP 507

This dataset was expanded by Paikowsky from the FHWA database described previously. However, the stroke height for variable stroke hammers, such as diesel hammers, was not reported. Allen (2005) used this database and inferred hammer stroke information to develop a dynamic formula for the Washington State Department of Transportation (WSDOT). Allen's database consists of 141 piles, 64 of which are included in the International Database. Detailed information on the piles is presented in Appendix B.

3.7 DATA ANALYSIS

For the piles included in the International Database, capacity estimates were made using the dynamic formulae discussed in Chapter 2. These estimates were compared to static load test results by determining the ratio of the dynamic to static load test capacity ($Q_{dynamic}/Q_{SLT}$). The average, standard deviation, and COV of these ratios were determined to quantify the agreement between the capacities.

3.7.1 FHWA-Gates vs. SLT

The average FHWA-Gates/SLT capacity ratio is 1.22 with a COV = 0.49. The statistics for the FHWA-Gates/SLT data are presented in Table 3.1 and the data are plotted in Figure 3.1. A more detailed description of the statistics for each analysis is given in Appendix B. The average capacity ratio of 1.22 indicates that the FHWA-Gates formula tends to overpredict capacity. This is the largest average overprediction of capacity observed for any of the methods, although the magnitude of the overprediction is less than the magnitude of the underpredictions by the EN-IDOT formula and WEAP. There is an appreciable amount of scatter, but the COV is much less than that for the EN-IDOT formula.

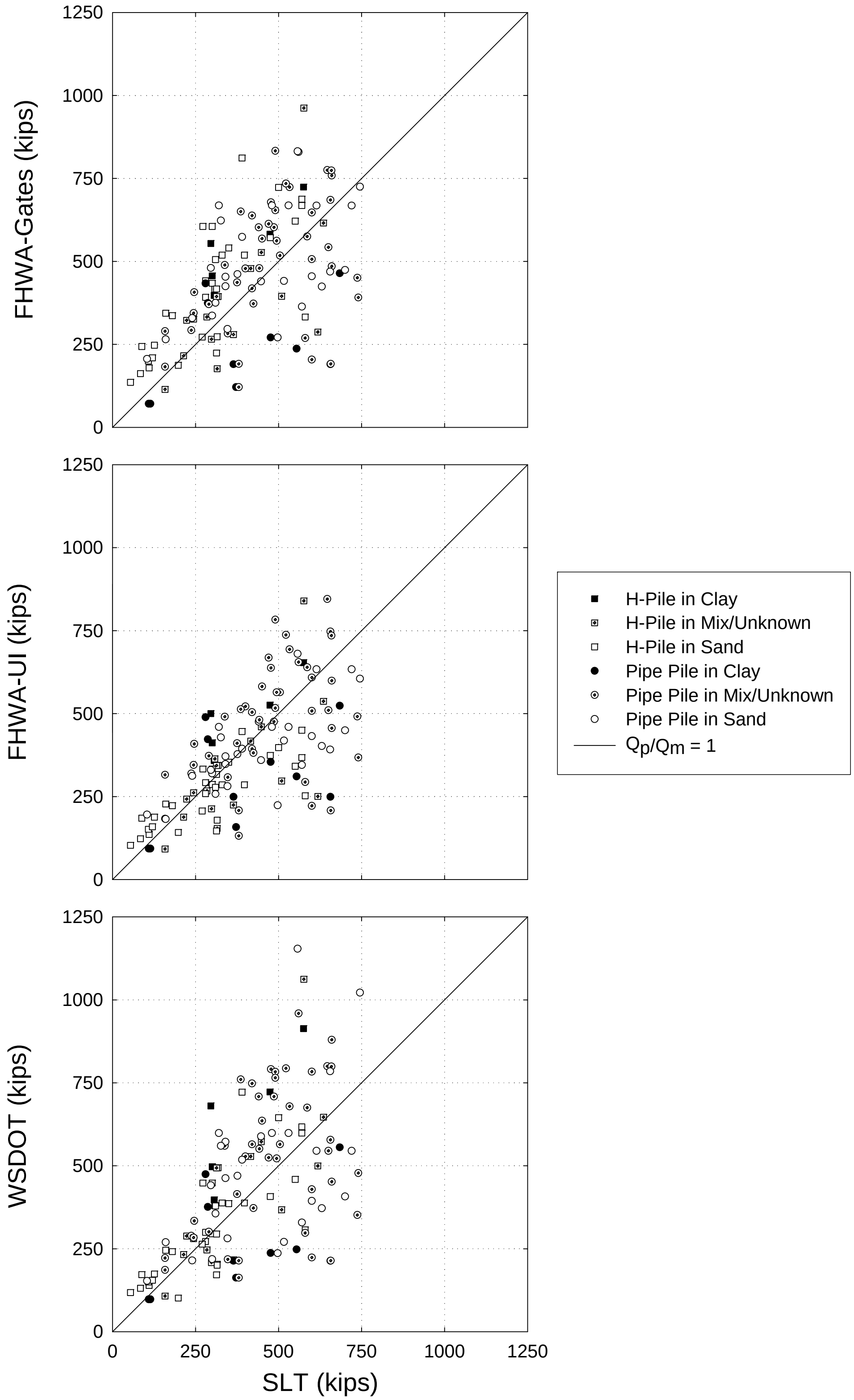

Figure 3.1. Selected Dynamic/SLT capacity ratio data.

Table 3.1. Selected Dynamic/SLT Statistics for All Piles

		WSDOT	FHWA-Gates	FHWA-UI
vs. SLT	Mean:	1.14	1.22	1.02
	Std. Dev:	0.51	0.59	0.41
	COV:	0.45	0.49	0.41
	r^2:	0.35	0.31	0.42
	n:	132	132	132

3.7.2 FHWA-UI vs. SLT

The average FHWA-UI/SLT capacity ratio is 1.02 with a COV = 0.41. Statistics for the FHWA-UI/SLT data are presented in Table 3.1. The FHWA-UI/SLT data are plotted in Figure 3.1. The average capacity ratio of 1.02 indicates a very good agreement with capacities predicted by static load tests. The COV of 0.41 is the smallest of the dynamic methods analyzed using this database. It is noteworthy that the FHWA-UI formula was developed based on data in the International Database and that only piles with capacities less than 750 kips were used to develop the statistics. As a result it is expected that the average capacity ratio will be close to unity and that the COV will n be relatively small. The method is only applicable for piles with capacities less than 750 kips.

3.7.3 WSDOT vs. SLT

The average WSDOT/SLT capacity ratio is 1.14 with a COV = 0.45. Statistics for the WSDOT/SLT data are presented in Table 3.1. The data are presented graphically in Figure 3.1. The WSDOT formula shows some bias towards overpredicting pile capacity in the International Database. The degree of scatter is smaller than that of the FHWA-Gates formula and larger than that of the FHWA-UI formula.

3.7.4 Other Dynamic Formulae Studied

The EN-IDOT formula and WEAP were also used to analyze pile capacity. Based on the summary statistics of the data, these methods are not considered promising. The results were considered when drawing conclusions about the data, and the results of the analysis are presented in Appendix B.

3.8 SUMMARY

Based on the piles in the International Database, the FHWA-UI formula predicts capacity with the most accuracy and precision. This formula is followed by the WSDOT, then FHWA-Gates formulae in degree of accuracy and precision. Based on the analysis of the data, it would be fair to group the FHWA-Gates, FHWA-UI, and WSDOT formulae into one group that performs fairly well and to group WEAP and the EN-IDOT formula into a group that does not perform as well.

CHAPTER 4 COMPREHENSIVE DATABASE

4.1 INTRODUCTION

The Comprehensive Database consists of a collection of 26 load tests on driven piles. For a pile to be included in the database, the following criteria had to be satisfied: a static load test must have been conducted to failure on the pile, pile driving information such as hammer type and penetration resistance at the end-of-driving must be available, subsurface information such as SPT results and shear strength data must be available, and it must be possible to estimate the capacity of the pile with all of the static and dynamic methods investigated. Detailed information on piles included in the Comprehensive Database is included in Appendix C.

The capacity of the piles was estimated using the static and dynamic methods discussed in Chapter 2. The agreement between the methods and static load test results was quantified. Additionally, based on the results of analyzing the methods relative to static load tests, the agreement between the three most promising dynamic formulae and static methods was quantified.

A thorough statistical analysis of each of the following capacity ratios was conducted. This includes an analysis of the effect of pile type and soil type. Graphs illustrating these trends were also produced and studied to draw the conclusions presented in the following. One result of these studies was to identify methods that do not appear to improve dynamic/static agreement. Only tables of the statistical results of the most promising methods are presented in this chapter. Additional statistics and graphs illustrating the agreement between different methods, as well as an extended discussion of the results of the analyses, are presented in Appendix C. The Comprehensive Database consists of only 26 piles. Accordingly, it is possible that trends observed for this data would not be observed in a larger database.

4.2 ANALYSIS OF THE DYNAMIC FORMULAE

4.2.1 FHWA-Gates/SLT

The average FHWA-Gates/SLT capacity ratio is 1.02 with a COV = 0.31. Statistics for the data are presented in Table 4.1. Figure 4.1 presents a plot of the data. The average capacity ratio of 1.02 indicates very good agreement between the FHWA-Gates formula and static load test results. The COV of 0.31 indicates that the degree of scatter is fairly small.

Table 4.1. Dynamic and Static Methods vs. SLT Statistics

	WSDOT/SLT	**FHWA-Gates/SLT**	**FHWA-UI/SLT**	**IDOT-S/SLT**	**K-IDOT/SLT**	**ICP/SLT**
Mean:	1.02	1.02	0.97	1.30	2.00	1.85
Std. Dev:	0.29	0.31	0.42	0.88	1.37	0.94
COV:	0.29	0.31	0.43	0.67	0.68	0.51
r^2:	0.52	0.73	0.52	0.36	0.41	0.55
n:	26	23	23	26	26	26

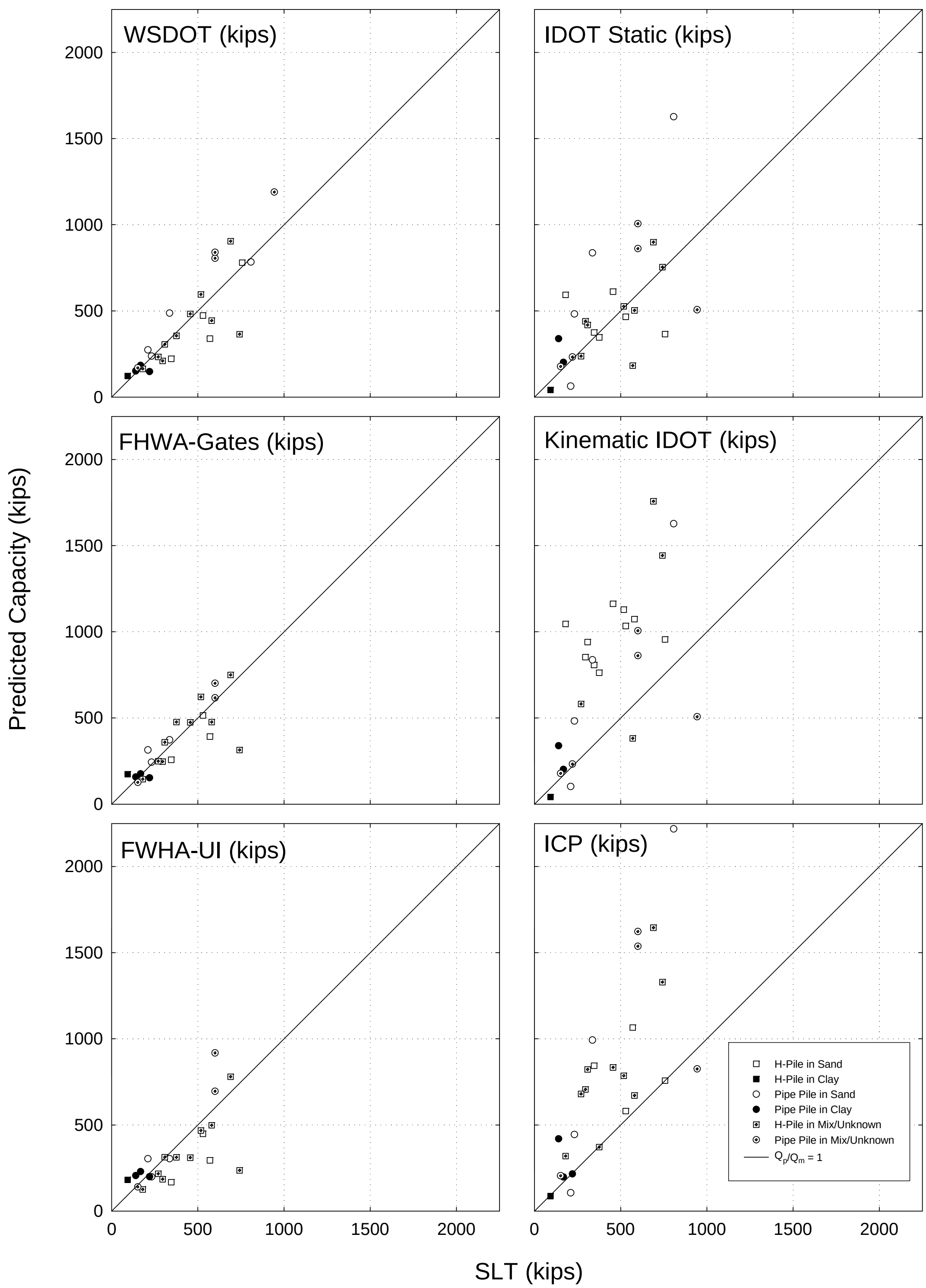

Figure 4.1. Dynamic and static methods vs. SLT.

4.2.2 FHWA-UI/SLT

The average FHWA-UI/SLT capacity ratio is 0.97 with a COV = 0.43. Statistics for the data are presented in Table 4.1 and plotted in Figure 4.1. The average capacity ratio of 0.97 indicates that, on the average, the formula predicts a capacity very similar to the result of a static load test. The COV = 0.43 indicates that the formula has a moderate amount of scatter associated with it.

4.2.3 WSDOT/SLT

The average WSDOT/SLT capacity ratio is 1.02 with a COV = 0.29. Statistics for the WSDOT/SLT data are presented in Table 4.1. The data are plotted in Figure 4.1. The average capacity ratio of 1.02 indicates very good agreement between the WSDOT formula and static load test results for the Comprehensive Database. The COV of 0.29 indicates that there is a fairly small amount of scatter in the capacity predictions. The COV of the WSDOT/SLT data is the smallest of any of the dynamic methods analyzed using the Comprehensive Database.

4.2.4 Dynamic Formulae Summary

There does not appear to be any overall trend throughout the Dynamic/SLT data. For instance, there is no tendency for all or most of the formulae to overpredict capacity for pipe piles, or for all formulae to predict capacity exceptionally well for H-piles in clay.

It is fairly simple to apply an empirical correction to a group of capacity predictions so that the average capacity ratio becomes unity. It is much more difficult to reduce the COV of a group of capacity predictions. Using the COV of the average capacity ratios as a metric, the formulae can be grouped into three sets.

The first group consists of the FHWA-Gates and WSDOT formulae. Their COV's are very similar and the lowest of the dynamic formulae (FHWA-Gates/SLT COV = 0.31, WSDOT/SLT COV = 0.29). The second group is the FHWA-UI formula and WEAP, with COV's of 0.43 and 0.40, respectively. The final group is the EN-IDOT formula with a COV = 0.56. Capacity can be estimated quickly and simply for each method except WEAP.

4.3 ANALYSIS OF THE STATIC METHODS

4.3.1 ICP/SLT

The average ICP/SLT capacity ratio is 1.85 with a COV = 0.51. The statistics are presented in Table 4.1, and the data are plotted in Figure 4.1. The average capacity ratio of 1.85 indicates that the ICP method strongly overpredicts capacity. However, the ICP method predicts capacity while exhibiting scatter smaller than any of the other static methods analyzed with the Comprehensive Database.

4.3.2 IDOT Static/SLT

The average IDOT Static/SLT capacity ratio is 1.30 with a COV = 0.67. The statistics for the data are presented in Table 4.1, and the data are plotted in Figure 4.1. The average capacity ratio of 1.30 indicates that the IDOT Static method tends to somewhat overpredict capacity. The amount of scatter is the second-smallest displayed by the static methods analyzed in the Comprehensive Database.

4.3.3 K-IDOT/SLT

The average K-IDOT/SLT capacity ratio is 2.00 with a COV = 0.68. The statistics for this data are presented in Table 4.1, and the data are plotted in Figure 4.1. The average capacity ratio indicates that the K-IDOT method predicts, on the average, a capacity twice that measured by a static load test. The amount of scatter is fairly large, but is comparable to that displayed by other static methods analyzed using the Comprehensive Database. Based on the assumptions used when estimating the capacity of a pile, the average K-IDOT/SLT capacity ratio will always be greater than or equal to the average IDOT-S/SLT capacity ratio.

4.3.4 Static Methods Summary

One trend appears for all of the static methods. The average capacity ratio in sand tends to be larger than the average capacity ratio in clay. Sometimes the difference is small. The K-IDOT method displays a large difference between the average capacity ratio in sand and clay. This is to be expected, based on the K-IDOT assumptions. The K-IDOT method was developed with the goal of improving agreement between methods, while acknowledging that empirical corrections would be required to bring predicted and measured capacity into agreement.

The static methods analyzed using the Comprehensive Database fall into three groups based on their COV's. The first is the ICP method. Its COV is appreciably smaller than the COV for any other static method. The second group consists of the IDOT Static method, the Kinematic IDOT method, and Olson's method. These methods show a moderate amount of scatter. The final group consists of Driven. The COV for Driven is much larger than for any of the other static methods.

The ICP method, the IDOT Static method, and the K-IDOT method showed the greatest potential for predicting capacity accurately based on the agreement between static methods and static load test results. These static methods also had the smallest values of COV for the average Dynamic/Static capacity ratios.

4.4 AGREEMENT BETWEEN STATIC METHODS AND DYNAMIC FORMULAE

Based upon the results discussed in the preceding sections, the following dynamic formulae and static methods were selected for quantifying the Dynamic/Static data: the WSDOT, FHWA-Gates, FHWA-UI, IDOT Static, K-IDOT, and ICP methods.

It was decided that some methods were too inaccurate, based on static load test results, to justify analyzing their agreement with other methods. The above methods showed the most accuracy compared to static load tests, and the results of a Dynamic/Static analysis were determined to be most useful based on these methods.

4.4.1 WSDOT/IDOT Static

The average WSDOT/IDOT Static capacity ratio is 1.16 with a COV = 0.74. The statistics for the data are presented in Table 4.2. This average capacity ratio indicates that the WSDOT and IDOT Static methods agree, on the average, fairly well. The WSDOT formula predicts a higher capacity, on the average, than the IDOT Static method. In other words, the length of pile predicted to be necessary by the IDOT Static method is longer than needed according to the WSDOT formula, on the average. There is a fairly large amount of scatter in the data. One implication of this is that there will be occasions where the driven length of pile required according to the WSDOT formula will be greater than that predicted by the IDOT Static method.

Table 4.2. Dynamic vs. Static Method Statistics

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	1.16	1.11	1.12
	Std. Dev:	0.86	0.88	0.97
	COV:	0.74	0.80	0.87
	r^2:	0.37	0.29	0.29
	n:	26	23	23
vs. Kinematic IDOT	Mean:	0.79	0.74	0.77
	Std. Dev:	0.66	0.64	0.81
	COV:	0.84	0.87	1.05
	r^2:	0.27	0.30	0.18
	n:	26	23	23
vs. ICP	Mean:	0.72	0.69	0.72
	Std. Dev:	0.46	0.47	0.58
	COV:	0.63	0.67	0.81
	r^2:	0.47	0.41	0.38
	n:	26	23	23

4.4.2 WSDOT/K-IDOT

The average WSDOT/K-IDOT capacity ratio is 0.79 with a COV = 0.84. The statistics for this data are presented in Table 4.2. This average capacity ratio indicates that the K-IDOT method tends to predict a higher capacity than the WSDOT formula. Or, the length of pile necessary based on the K-IDOT prediction will tend to be shorter than is necessary based on the WSDOT formula. There is significant scatter within the data which indicates that the agreement between the two methods is poor.

4.4.3 WSDOT/ICP

The average WSDOT/ICP capacity ratio is 0.72 with a COV = 0.63. The statistics for the data are presented in Table 4.2. The average capacity ratio indicates that the ICP method tends to predict a higher capacity than the WSDOT formula. The COV is somewhat large, but is the smallest of any of the average Dynamic/Static capacity ratios.

4.4.4 FHWA-Gates/IDOT Static

The average FHWA-Gates/IDOT Static capacity ratio is 1.11 with a COV = 0.80. The statistics for the data are presented in Table 4.2, and the data are graphed in Figure 4.2. Graphs of the FHWA-Gates data vs. Static methods are presented as the most similar to current IDOT practice and are thus particularly relevant. The average capacity ratio of 1.11 indicates that the two methods agree fairly well, on the average. The FHWA-Gates formula tends to predict a higher capacity than the IDOT Static method. The COV of 0.80 indicates that there is a considerable amount of scatter within the data.

4.4.5 FHWA-Gates/K-IDOT

The average FHWA-Gates/Kinematic IDOT capacity ratio is 0.74 with a COV = 0.87. The statistics are presented in Table 4.2, and the data are graphed in Figure 4.2. The average capacity ratio less than unity indicates that the Kinematic IDOT method tends to predict a higher capacity than the FHWA-Gates formula. There is a significant amount of scatter in the

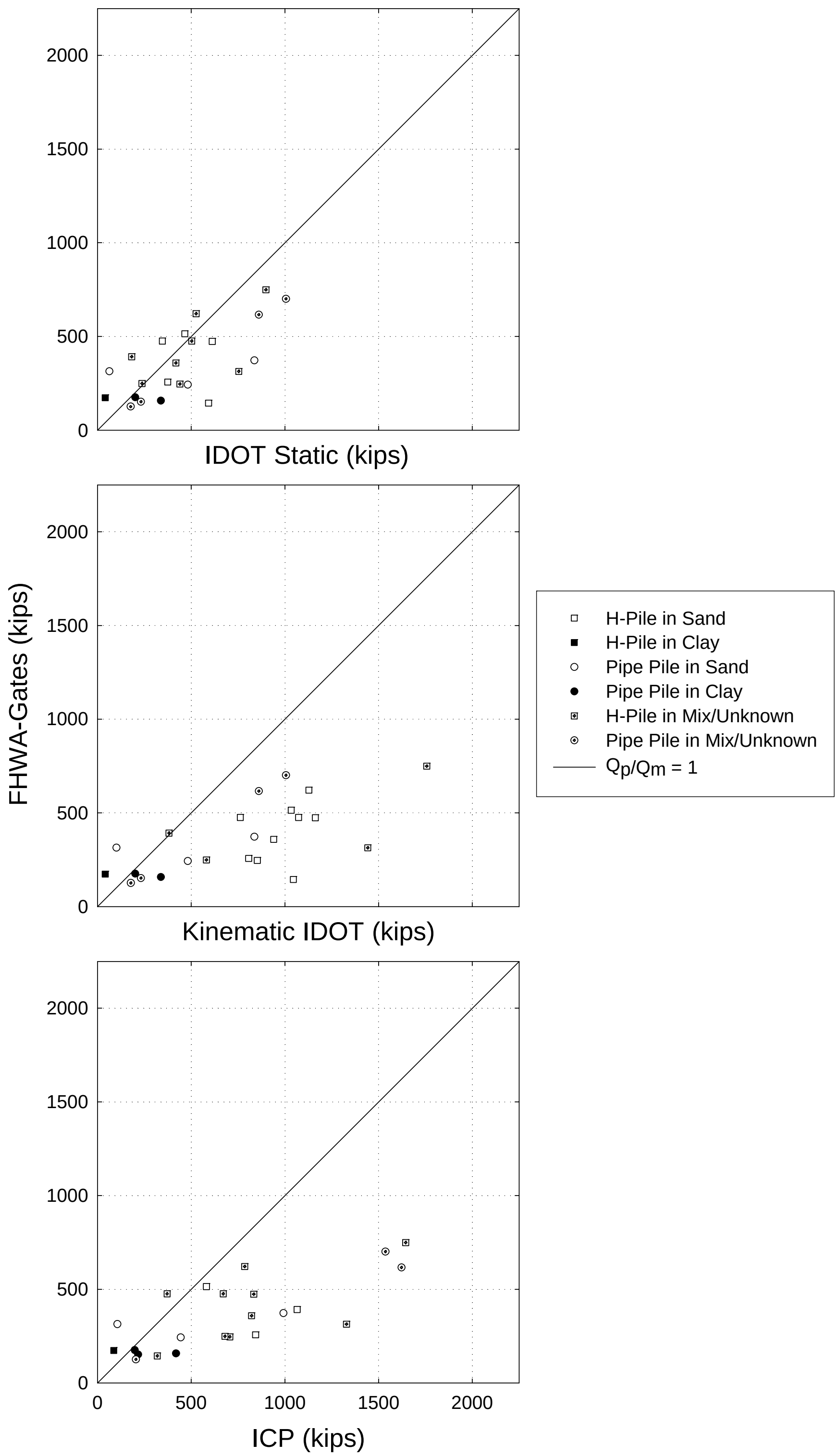

Figure 4.2. FHWA-Gates vs. static methods.

data, which indicates that it would not be unexpected for the FHWA-Gates formula to predict a higher capacity than the Kinematic IDOT method.

4.4.6 FHWA-Gates/ICP

The average FHWA-Gates/ICP capacity ratio is 0.69 with a COV = 0.67. The data are presented in Table 4.2, and the data are plotted in Figure 4.2. This capacity ratio indicates that the ICP method tends to predict a larger capacity than the FHWA-UI formula. The scatter of the data is appreciable, but it is the second-lowest overall COV of the average Dynamic/Static capacity ratios.

4.4.7 FHWA-UI/IDOT Static

The average FHWA-UI/IDOT Static capacity ratio is 1.12 with a COV = 0.87. The data are presented in Table 4.2. Based on the average capacity ratio, it would be expected that the IDOT Static method will predict a longer required pile length than the FHWA-UI formula will indicate is necessary. The COV of 0.87 for the data indicates there is a large degree of scatter in the data. This means that it is likely that for any given pile, the FHWA-UI/IDOT Static ratio will be appreciably different than 1.12.

4.4.8 FHWA-UI/K-IDOT

The average FHWA-UI/Kinematic IDOT capacity ratio is 0.77 with a COV of 1.05. The data are presented in Table 4.2. The average capacity ratio of 0.77 indicates that the Kinematic IDOT formula predicts a larger capacity than the FHWA-UI formula. Based only on the average capacity ratio, the Kinematic IDOT method will predict a required pile length that is shorter than would be required based on the FHWA-UI formula. However, the COV of 1.05 indicates that there is very significant scatter within the data, and any given pile could deviate appreciably from the average.

4.4.9 FHWA-UI/ICP

The average FHWA-UI/ICP capacity ratio is 0.72 with a COV = 0.81. The data are presented in Table 4.2. The average capacity ratio of 0.72 indicates that the ICP method tends to predict a capacity greater than that predicted by the FHWA-UI formula. There is appreciable scatter within the data, but the COV = 0.81 is the smallest of the FHWA-UI/Static method analyses.

4.4.10 Dynamic/Static Summary

There do appear to be some general trends in the Dynamic/Static data. In clay, the general trend is for the dynamic formula to predict a higher capacity than the static method. The single exception to this is the WSDOT/ICP data. In sand, the K-IDOT and ICP methods predict higher capacities than the dynamic formulae. The IDOT Static method does the opposite, predicting a smaller capacity in sand than dynamic formulae. In pipe piles, the dynamic formula will generally predict a higher capacity than the IDOT-S and K-IDOT methods. The opposite occurs with the ICP method, it predicts a higher capacity than the dynamic formulae. In H-piles, the K-IDOT and ICP methods tend to predict higher capacities than the dynamic formulae. The dynamic formulae tend to predict higher capacities in H-piles than the IDOT-S method.

These dynamic/static analyses provide information only on the agreement between a dynamic and static method; they do not indicate how accurately either method predicts actual pile capacity. Appreciable scatter was present in all of the Dynamic/Static analyses. This indicates it would not be uncommon for any single pile to produce capacity ratios appreciably different than the average capacity ratios.

The COV for any Dynamic/Static analysis best indicates how well the two methods agree. It is important to note that good agreement between any two methods does not indicate that either of the methods accurately predicts the capacity of a pile; it only indicates that the methods agree well with each other. Based on the COV, the following observations can be made.

The ICP method appears to offer the best agreement with dynamic formulae. The WSDOT, FHWA-Gates, and FHWA-UI/Static average capacity ratios all display the lowest COV with the ICP method, followed by the IDOT Static method, then the K-IDOT method. The WSDOT formula appears to offer the best agreement with the static methods. The average Dynamic/IDOT Static, K-IDOT, and ICP capacity ratios all display the lowest COV with the WSDOT formula, followed by the FHWA-Gates formula, then the FHWA-UI formula. The average WSDOT/ICP capacity ratio displays the least scatter of the average Dynamic/Static capacity ratios. The second-best and third-best average capacity ratio COV's are for the FHWA-Gates/ICP and WSDOT/IDOT Static data, respectively. The largest COV is for the FHWA-UI/K-IDOT data.

4.5 SUMMARY

For the Comprehensive Database, the following comparisons are made: Dynamic Formula/Static Load Test, Static Method/Static Load Test, and Dynamic Formula/Static Method. The first two comparisons quantify the accuracy and precision of a given method. The third comparison quantifies the agreement between different predictive methods. This category does not provide any information about the accuracy of the dynamic formula or static method.

Based on the Dynamic/SLT data, the WSDOT and FHWA-Gates formulae appear to predict capacity fairly accurately and with limited degrees of scatter. Based on the Static/SLT data, the ICP method predicts capacity with the most precision (COV = 0.58). Because any given method can be empirically corrected so that its average capacity ratio is unity, the precision of the method was considered the primary indicator of performance. Based on the Dynamic/Static data, the WSDOT formula used with the ICP method yields the best agreement. The FHWA-Gates formula with the ICP method yields the second-best agreement.

Based on the Comprehensive Database, the WSDOT and FHWA-Gates formulae are the most precise dynamic formulae, while the EN-IDOT formula is the least precise. WEAP and the FHWA-UI formulae have precisions intermediate between these two. The ICP method is the most precise static method, while Driven is the least precise static method. The IDOT Static method, the K-IDOT method, and Olson's method are intermediate in precision. For the Dynamic/Static data, the ICP method and the WSDOT formula offer the best agreement. Generally, the ICP method best agrees with any given dynamic formula, while the K-IDOT method displays the least agreement with any given dynamic formula. Generally, the WSDOT formula most strongly agrees with any given static method, while the FHWA-UI formula offers the least agreement with any given static method. However, there are limited data points in this database from which to draw conclusions. Before any definite recommendations are made, it is also worthwhile to quantify the effects of introducing empirical correction factors to each method with the goal of increasing the methods' accuracy with respect to static load tests and to other methods.

CHAPTER 5 ILLINOIS DATABASE

5.1 INTRODUCTION

One hundred test cases were collected from the State of Illinois to examine the relationship between capacity based on static and dynamics formulae. The database of piles was separated into four categories, with a target of 25 cases each. The four categories were: H-piles driven into primarily coarse-grained soils (Sand), H-piles driven into primarily fine-grained soils (Clay), pipe piles driven into primarily coarse-grained soils (Sand), and pipe piles driven into primarily fine-grained soils (Clay). All cases required sufficient information to estimate pile capacity using each static and dynamic method discussed in Chapter 2.

Over 300 cases were reviewed when selecting piles for the database. In addition to requiring adequate pile driving and soil profile information, end-bearing piles (piles that developed more than 80 percent of their capacity through end-bearing) were excluded. When possible, the number of piles from a given site was limited to two. However, due to the limited availability of acceptable piles driven into primarily coarse-grained soils, this number is as high as four. H-piles identified on the driving data as having shoes were discarded. Pile length was limited to 150 feet.

Cases of piles driven into primarily coarse-grained soils were difficult to find. Twenty-one acceptable cases were found for H-piles and pipe piles driven into primarily coarse-grained soils, each. For H-piles and pipe piles driven into primarily fine-grained soils, there were 25 cases each, thus a total of 92 piles were collected and interpreted for the Illinois Database. A detailed description of the piles included in the database is presented in Appendix D.

Each pile in the database was analyzed using static and dynamic prediction methods outlined in Chapter 2. When possible, static methods were analyzed using the ground surface given on the pile driving record. If this was not available, it was assumed that the elevation of the ground surface on the boring log was the same elevation of the ground surface as for the pile. If the elevation of the ground surface at the pile was higher than the elevation of the soil boring, it was assumed that fill was placed before the pile was driven. For analysis, this was assumed to be a medium sand with γ = 115 pcf and ϕ = 30°.

The location of the groundwater table was taken as the elevation 24 hours after completion of the soil boring, if available. In some cases, only the first encountered groundwater elevation was available, or a designation of "free water" on the boring log. If no data were available concerning the elevation of the groundwater table, it was assumed to be 3 ft below the ground surface. If the groundwater table elevation was higher than the ground surface elevation, a capacity estimate was made assuming there were no seepage forces in the soil. No artesian conditions were used in the analyses.

Piles displayed a significant increase in blow count over the last few feet of driving in some cases. Accordingly, the portion of the pile displaying this increase was not considered in the analyses. The elevation of the pile tip was taken as the last measurement above this cutoff, and the blow count used in the dynamic formulae was the blow count at this elevation.

Figures of predicted capacity based on a dynamic formula versus predicted capacity based on a static method are presented in Figures 5.1 and 5.2. Figures for additional capacity combinations besides those presented in Figures 5.1 and 5.2 and included in Appendix D. The information included in Appendix D is considered important for a complete understanding of the performance of different pile capacity prediction methods. However, only information on

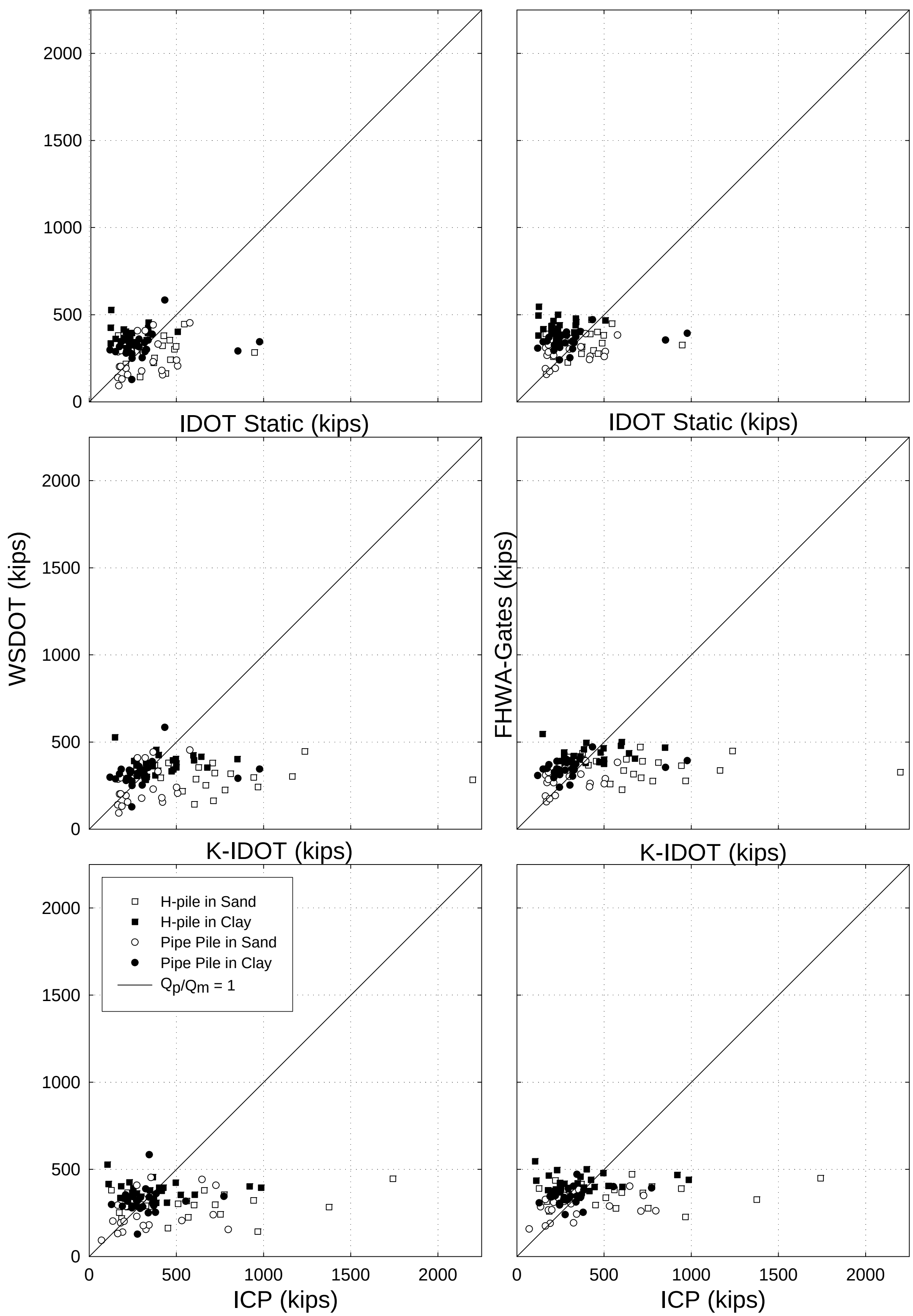

Figure 5.1. Dynamic vs. static capacities for the Illinois Database.

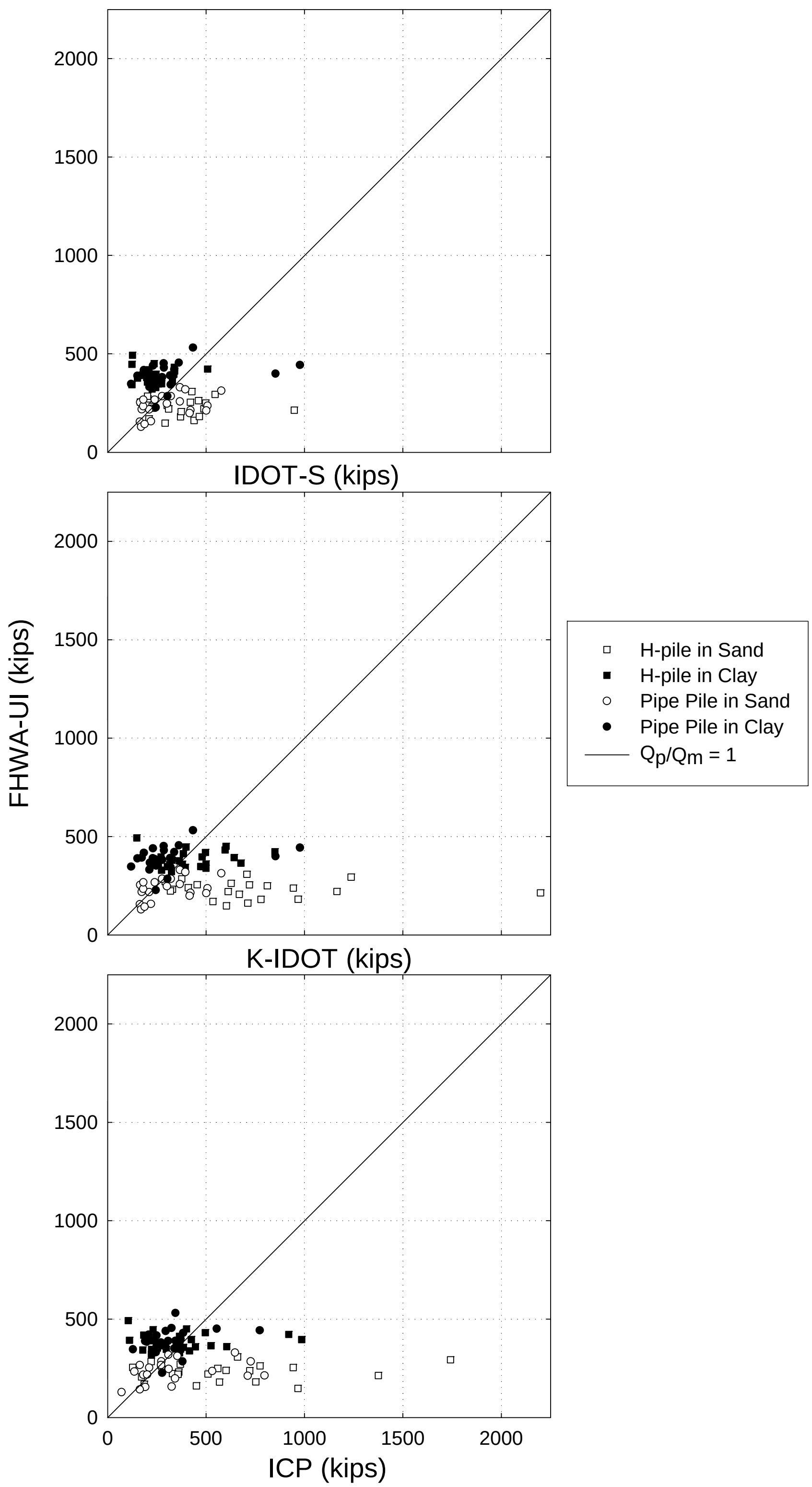

Figure 5.2. Dynamic vs. static capacities for the Illinois Database.

those prediction methods which were determined to be the most accurate for the given data were included in this chapter.

5.2 STATISTICAL ANALYSIS

Statistical analyses were performed on each of the nine database subcategories. Ratios of the capacity of each method were calculated by Q_{p1}/Q_{p2} where Q_{p1} and Q_{p2} are the predicted capacities for a given pile using two different methods. The mean, standard deviation, coefficient of variation, and correlation coefficient were calculated for each set of ratios. The mean and correlation coefficient indicate perfect agreement when they are equal to one. The standard deviation and coefficient of variation indicate perfect agreement when they are equal to zero. The statistics for the analyses of selected categories are presented in Tables 5.1 to 5.9. Statistics for additional analyses not presented here are included in Appendix D.

An initial analysis of the data was done using the following methods: the EN-IDOT formula, the FHWA-Gates formula, the WSDOT formula, WEAP, the IDOT Static method, Driven, and Olson's method. Based on these results, and results from the analyses of the other databases, it was determined that some methods (EN-IDOT, WEAP, Driven, and Olson's method) were not promising given the particulars of this study. The K-IDOT, ICP, and FHWA-UI methods were introduced in place of some of these rejected methods.

Table 5.1. Capacity Ratio Statistics for All Piles in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	1.20	1.40	1.28
	Std. Dev:	0.60	0.70	0.74
	COV:	0.50	0.50	0.58
	r^2:	0.00	0.00	0.00
	n:	92	92	92
vs. Kinematic IDOT	Mean:	0.94	1.08	1.02
	Std. Dev:	0.59	0.63	0.75
	COV:	0.63	0.57	0.74
	r^2:	0.01	0.03	0.03
	n:	92	92	92
vs. ICP	Mean:	1.07	1.21	1.13
	Std. Dev:	0.75	0.76	0.85
	COV:	0.70	0.63	0.75
	r^2:	0.01	0.02	0.01
	n:	92	92	92

Table 5.2. Capacity Ratio Statistics for H-Piles in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	1.4	1.6	1.33
	Std. Dev:	0.8	0.8	0.86
	COV:	0.5	0.5	0.65
	r^2:	0.05	0.06	0.15
	n:	46	46	46
vs. Kinematic IDOT	Mean:	0.80	0.91	0.76
	Std. Dev:	0.55	0.58	0.57
	COV:	0.68	0.63	0.75
	r^2:	0.05	0.07	0.16
	n:	46	46	46
vs. ICP	Mean:	1.09	1.24	1.04
	Std. Dev:	0.91	0.97	0.93
	COV:	0.84	0.78	0.90
	r^2:	0.01	0.01	0.07
	n:	46	46	46

Table 5.3. Capacity Ratio Statistics for Pipe Piles in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	1.1	1.2	1.25
	Std. Dev:	0.5	0.5	0.67
	COV:	0.4	0.4	0.53
	r^2:	0.06	0.10	0.05
	n:	46	46	46
vs. Kinematic IDOT	Mean:	1.09	1.23	1.25
	Std. Dev:	0.57	0.54	0.67
	COV:	0.52	0.44	0.53
	r^2:	0.06	0.10	0.05
	n:	46	46	46
vs. ICP	Mean:	1.05	1.19	1.20
	Std. Dev:	0.56	0.56	0.65
	COV:	0.53	0.47	0.55
	r^2:	0.05	0.06	0.01
	n:	46	46	46

Table 5.4. Capacity Ratio Statistics for Piles in Sand in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	0.9	1.1	1.62
	Std. Dev:	0.4	0.5	0.73
	COV:	0.5	0.4	0.45
	r^2:	0.06	0.07	0.06
	n:	50	50	50
vs. Kinematic IDOT	Mean:	0.72	0.86	0.71
	Std. Dev:	0.49	0.53	0.52
	COV:	0.67	0.62	0.74
	r^2:	0.05	0.08	0.00
	n:	50	50	50
vs. ICP	Mean:	0.85	1.01	0.82
	Std. Dev:	0.64	0.72	0.64
	COV:	0.75	0.71	0.78
	r^2:	0.02	0.11	0.0
	n:	50	50	50

Table 5.5. Capacity Ratio Statistics for Piles in Clay in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	1.5	1.7	1.62
	Std. Dev:	0.7	0.7	0.73
	COV:	0.5	0.4	0.45
	r^2:	0.00	0.00	0.06
	n:	50	50	50
vs. Kinematic IDOT	Mean:	1.11	1.24	1.26
	Std. Dev:	0.51	0.55	0.66
	COV:	0.46	0.44	0.52
	r^2:	0.07	0.14	0.05
	n:	50	50	50
vs. ICP	Mean:	1.24	1.36	1.35
	Std. Dev:	0.66	0.68	0.70
	COV:	0.53	0.50	0.52
	r^2:	0.01	0.05	0.02
	n:	50	50	50

Table 5.6. Capacity Ratio Statistics for H-Piles in Sand in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	0.9	1.1	0.82
	Std. Dev:	0.5	0.5	0.45
	COV:	0.5	0.5	0.55
	r^2:	0.00	0.00	0.00
	n:	21	21	21
vs. Kinematic IDOT	Mean:	0.51	0.62	0.45
	Std. Dev:	0.32	0.37	0.30
	COV:	0.62	0.59	0.66
	r^2:	0.00	0.01	0.01
	n:	21	21	21
vs. ICP	Mean:	0.75	0.90	0.64
	Std. Dev:	0.63	0.72	0.54
	COV:	0.84	0.80	0.84
	r^2:	0.05	0.02	0.02
	n:	21	21	21

Table 5.7. Capacity Ratio Statistics for H-Piles in Clay in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	1.7	2.0	1.72
	Std. Dev:	0.8	0.8	0.64
	COV:	0.4	0.4	0.37
	r^2:	0.00	0.00	0.00
	n:	25	25	25
vs. Kinematic IDOT	Mean:	1.00	1.13	0.99
	Std. Dev:	0.43	0.46	0.43
	COV:	0.43	0.41	0.43
	r^2:	0.00	0.02	0.02
	n:	25	25	25
vs. ICP	Mean:	1.36	1.53	1.33
	Std. Dev:	0.87	0.95	0.84
	COV:	0.65	0.62	0.63
	r^2:	0.00	0.00	0.00
	n:	25	25	25

Table 5.8. Capacity Ratio Statistics for Pipe Piles in Sand in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	0.9	1.1	0.94
	Std. Dev:	0.4	0.4	0.39
	COV:	0.5	0.4	0.42
	r^2:	0.14	0.18	0.18
	n:	21	21	21
vs. Kinematic IDOT	Mean:	0.91	1.09	0.94
	Std. Dev:	0.45	0.43	0.39
	COV:	0.50	0.39	0.42
	r^2:	0.14	0.18	0.18
	n:	21	21	21
vs. ICP	Mean:	0.93	1.13	0.99
	Std. Dev:	0.58	0.67	0.60
	COV:	0.62	0.59	0.61
	r^2:	0.11	0.10	0.10
	n:	21	21	21

Table 5.9. Capacity Ratio Statistics for Pipe Piles in Clay in the Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. IDOT Static	Mean:	1.2	1.3	1.52
	Std. Dev:	0.5	0.5	0.79
	COV:	0.4	0.4	0.52
	r^2:	0.04	0.10	0.10
	n:	25	25	25
vs. Kinematic IDOT	Mean:	1.23	1.35	1.52
	Std. Dev:	0.61	0.61	0.79
	COV:	0.50	0.45	0.52
	r^2:	0.04	0.10	0.10
	n:	25	25	25
vs. ICP	Mean:	1.13	1.23	1.37
	Std. Dev:	0.48	0.43	0.56
	COV:	0.43	0.35	0.41
	r^2:	0.02	0.11	0.10
	n:	25	25	25

5.3 AGREEMENT BETWEEN METHODS

It is necessary to look at more than the mean and coefficient of variation for each subcategory to draw conclusions about which methods have the closest correlations. One must also consider the COV of all data for a given average capacity ratio. A simple correction factor can be used to bring the average capacity ratio to unity, but it is significantly more difficult to lower the COV. For all of the following cases, reported values of mean and COV are with respect to $Q_{DYNAMIC}/Q_{STATIC}$.

5.3.1 H-Piles in Sand

The least scatter between static and dynamic methods for H-piles in sand was exhibited by:

- IDOT Static and FHWA Gates (COV 0.48)
- IDOT Static and WEAP (COV 0.51)
- IDOT Static and WSDOT (COV 0.52)
- IDOT Static and FHWA-UI (COV 0.52)

For H-piles in sand, the IDOT Static method stands out as offering the best agreement with any given dynamic formula. Excluding the results for Dynamic/Driven and for the EN-IDOT formula, the dynamic formulae appear to all predict similar capacities.

5.3.2 H-Piles in Clay

The least scatter between static and dynamic methods for H-piles in clay was exhibited by:

- IDOT Static and FHWA-UI (COV 0.37)
- IDOT Static and FHWA-Gates (COV 0.41)
- K-IDOT and FHWA-Gates (0.41)

As with H-piles in sand, the IDOT Static method tended to give the best agreement with dynamic formulae. The K-IDOT method also tends to agree very well with dynamic formulae. Results for the FHWA-Gates, WSDOT, and FHWA-UI/IDOT Static and K-IDOT capacity ratios show the range for COV is fairly small. This suggests that any combination of these five methods would yield similar results.

5.3.3 Pipe Piles in Sand

The least scatter between static and dynamic methods for pipe piles in sand was exhibited by:

- IDOT Static and FHWA Gates (COV 0.37)
- Driven and WSDOT (COV 0.37)
- IDOT Static and WEAP (COV 0.38)

As with the previous subcategories, the IDOT Static method performs well when analyzed with respect to any given dynamic formula. The Driven/WSDOT capacity ratio exhibited a small amount of scatter. This stands out, as for previous subcategories the Dynamic/Driven capacity ratios exhibited some of the worst agreement.

5.3.4 Pipe Piles in Clay

The least scatter between static and dynamic methods for pipe piles in clay was exhibited by:

- Driven and FHWA Gates (COV 0.25)
- Driven and EN-IDOT (COV 0.27)
- Driven and WSDOT (COV 0.27)

Driven offers very good agreement with any of the dynamic formulae analyzed in this subcategory. Furthermore, the lowest COV's in this subcategory are about 0.1 smaller than displayed in the previous subcategories. They are the smallest COV's displayed in the Illinois Database analyses. The FHWA-Gates formula has performed very well to this point, and the WSDOT formula also appears to perform well across the range of subcategories analyzed.

5.3.5 H-Piles

The least scatter between static and dynamic methods for all H-piles was exhibited by:

- IDOT Static and FHWA-Gates (COV 0.51)
- IDOT Static and WEAP (COV 0.53)
- IDOT Static and WSDOT (COV 0.55)

The IDOT Static method appears to perform well when analyzed with any given dynamic method, as observed in previous categories. The WSDOT and FHWA-Gates formulae also appear to offer good agreement with static methods.

5.3.6 Pipe Piles

The least scatter between static and dynamic methods for all pipe piles was exhibited by:

- Driven and WSDOT (COV 0.32)
- IDOT Static and WEAP (COV 0.37)
- Driven and EN-IDOT (COV 0.38)
- Driven and FHWA-Gates (0.38)

As with pipe piles in clay, Driven appears to offer good agreement with the various dynamic formulae. It is noteworthy that Driven appears to offer good agreement with dynamic formulae for pipe piles and pipe piles in clay, but for any other subcategory, it is often near the bottom of the rankings.

5.3.7 Piles in Sand

The least scatter between static and dynamic methods for piles in sand was exhibited by:

- IDOT Static and FHWA Gates (COV 0.42)
- IDOT Static and WEAP (COV 0.46)
- IDOT Static and WSDOT (COV 0.48)

The IDOT Static method appears to offer the best agreement with dynamic methods for piles in sand. The Dynamic/IDOT Static COV's were fairly small for both H-piles and pipe piles in sand, suggesting that the method does not display much bias with regard to pile type. As observed in several other categories, the FHWA-Gates and WSDOT formulae tend to offer good agreement with static methods.

5.3.8 Piles in Clay

The least scatter between static and dynamic methods for piles in clay was exhibited by:

- K-IDOT and FHWA-Gates (0.44)
- IDOT Static and FHWA-UI (0.45)
- IDOT Static and FHWA-Gates (0.45)

The FHWA-Gates/K-IDOT capacity ratio exhibited the least scatter for piles in clay. The IDOT Static method also performed well. While Driven performed very well for pipe piles in clay, this trend does not hold when all piles in clay are examined. The Dynamic/Driven COV's were among the largest for all piles in clay.

5.3.9 All Piles

The least scatter between static and dynamic methods for all piles was exhibited by:

- IDOT Static and FHWA-Gates (COV 0.49)
- IDOT Static and WSDOT (COV 0.53)
- IDOT Static and WEAP (COV 0.56)

When analyzing all piles, the IDOT Static method tends to offer good agreement with dynamic formulae. As observed in other subcategories, the FHWA-Gates and WSDOT formulae tend to display the best results among dynamic formulae.

5.4 SUMMARY

The following discussion is based solely on the data available in the Illinois Database. This database offers useful information as it consists of data gathered only from the State of Illinois. One limitation of the database is that static load tests were not performed on any of the piles. Because of this, no firm conclusions can be drawn about the accuracy of any given method. Instead, conclusions can be drawn about how well a given dynamic formula agrees with a given static method. This information is useful, as a low COV between Dynamic/Static data indicates that the length of pile estimated to be necessary using a static method will be similar to the length driven when using a dynamic formula. A low COV between Dynamic/Static data does not give any indication as to whether the predicted pile capacities agree with the actual pile capacities.

Based on the performance of the different methods across subcategories, the IDOT Static method appears to offer the best agreement with dynamic formulae. The Dynamic/Driven data displayed low COV's for all pipe piles and pipe piles in clay, but the COV's were large for any other subcategory. The K-IDOT formula usually displayed some of the lower COV's. Of the dynamic formulae, both the FHWA-Gates and WSDOT formulae tended to agree well with static methods. The amount of scatter tended to be smaller for pipe piles than for H-piles. The COV's were fairly similar for clay and sand.

Based only on data from the Illinois Database, the IDOT Static method, used in combination with either the FHWA-Gates or WSDOT formula, will tend to offer the best agreement across the widest range of pile-driving conditions. However, there is no indication within the Illinois Database of how accurate the IDOT Static, FHWA-Gates or WSDOT methods are. Based on information from the International and Comprehensive Databases, there are some biases for methods such as the K-IDOT and ICP methods. Applying an empirical correction to these and other methods may offer better overall agreement than is exhibited for the uncorrected data.

5.5 CURRENT IDOT PRACTICE

Currently, IDOT uses the IDOT Static method to predict the required length of piles in the field. During pile driving, the FHWA-Gates formula is used to determine when a pile has developed adequate axial capacity. Ideally, the length predicted by the IDOT Static method would agree with the length driven when the FHWA-Gates formula predicted adequate capacity has been developed. Due to the uncertainties involved in pile-driving, this ideal is never achieved. However, the probability that the length of pile driven will be greater than that predicted by the IDOT Static method can be quantified.

The cumulative distribution of the FHWA-Gates/IDOT Static data is plotted in Figure 5.3. The y-axis of the figure indicates the probability that the FHWA-Gates/IDOT Static ratio will be less than or equal to the capacity ratio on the x-axis. The line on the graph is the theoretical distribution for a log-normal distribution of data. Variation of the Illinois Database data from this line indicates that it is not a perfect log-normal distribution. A value of 1 for the capacity ratio corresponds to a cumulative probability of about 30% on the figure. This indicates that there is a 30% probability that the FHWA-Gates/IDOT Static ratio will be less than one for any given pile. In other words, 30% of the time, it can be expected that the length of pile driven in the field will be greater than that predicted by the IDOT Static method. Conversely, 70% of the time, the length of pile driven will be less than that predicted by the IDOT Static method.

The capacity predicted by either formula can be corrected to change this probability. For instance, it may be desired that a majority of the time, the length of pile driven in the field is less than that predicted by the IDOT Static method. Driving piles longer than predicted may require splicing or even acquiring additional piling from off-site. On the other hand, it may also be desirable to correct one of the formulas so that half of the time the length of pile driven is shorter than predicted and half of the time it is longer than predicted. Based on the available data, this would represent a best guess for making the actual and predicted pile lengths agree. A probability of 50% corresponds to a capacity ratio of about 1.3. So, if it was desired that there were a 50% chance that the driven pile length would be longer than that predicted by the

IDOT Static method, it would be necessary to multiply the predicted IDOT Static method capacity by a factor of 1.3.

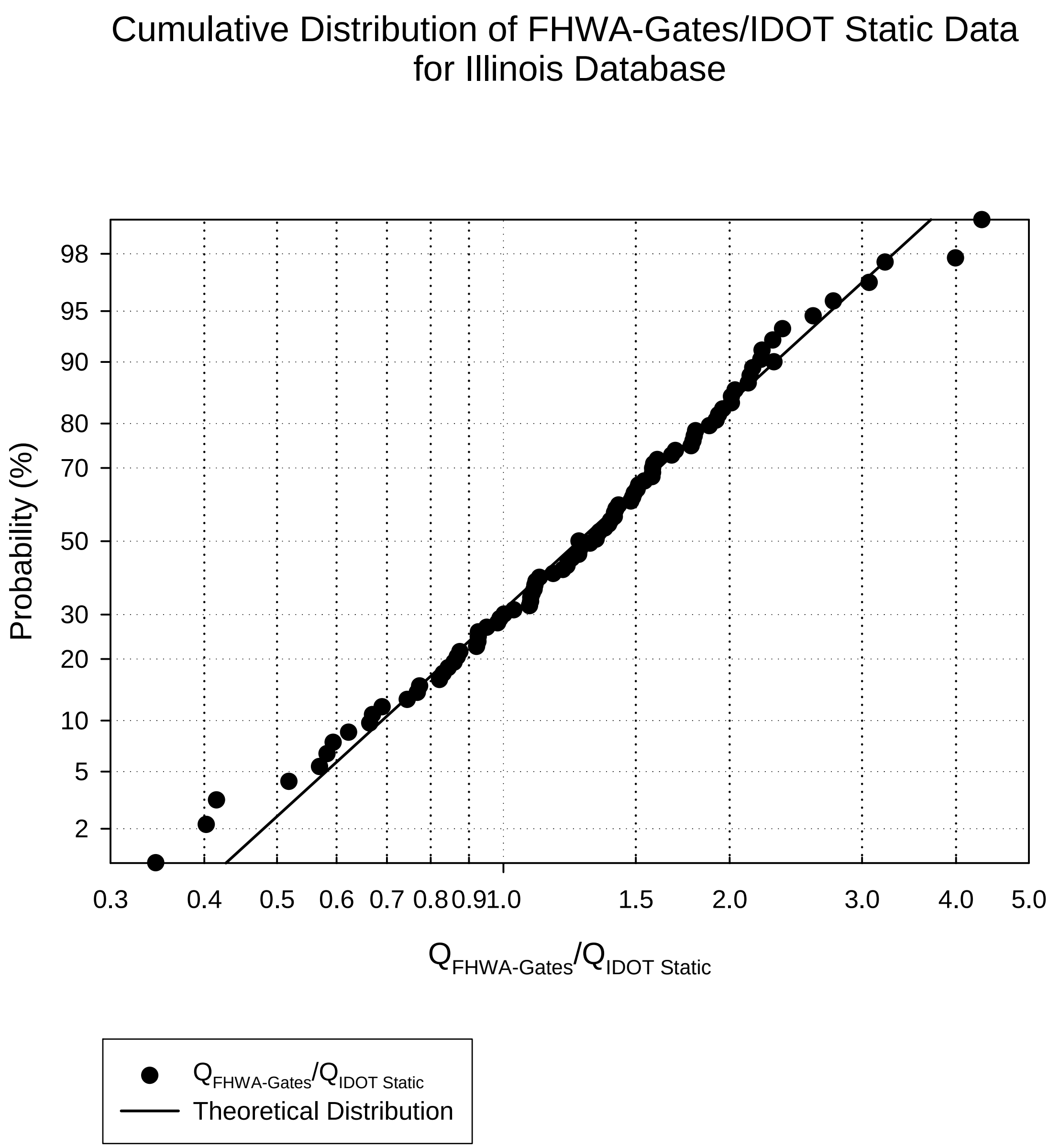

Figure 5.3. Cumulative distribution of FHWA-Gates/IDOT static data, Illinois Database.

CHAPTER 6 IMPROVEMENTS

6.1 INTRODUCTION

Three databases were examined in this study. The International Database consists of 132 piles. Static load test results were available for each pile, as well as sufficient information for determining the pile capacity based on dynamic methods, but there were insufficient data available for determining the pile capacities based on static methods. The Comprehensive Database consists of 26 piles. Static load test results are available for each pile, and sufficient information is available for determining both the static and dynamic pile capacities. The database is small, and caution must be used when attempting to draw any definitive conclusions from only 26 piles. The Illinois Database consists of 92 piles from within the State of Illinois. Sufficient information is available to determine both the static and dynamic capacities of each of the piles. No static load tests were run on the piles, so information on the piles' actual capacity is not available.

6.2 COMPARISONS BETWEEN DATABASES

The different sizes of the databases, along with the different information available for each database, make direct comparison of the different database results difficult. Instead, the following indirect comparisons were used. The International Database provides information on the accuracy and precision of dynamic methods. Based on the results of analyses of the International Database (Chapter 3), it was determined that the FHWA-Gates, FHWA-UI, and WSDOT formulae all predict capacity reasonably accurately and precisely.

The Illinois Database offers information on the agreement between static and dynamic methods, and is also particularly relevant as all of the piles were driven in Illinois. Based on the analysis of this database, the FHWA-Gates, FHWA-UI, and WSDOT formulae agreed well with some of the static methods. These static methods were the IDOT Static method and the K-IDOT method.

The Comprehensive Database contains too few piles from which to draw definitive conclusions. However, because it can be used to examine the accuracy and precision of any static or dynamic method, as well as to quantify the agreement between any two methods, the database is useful for confirming trends seen in the other two databases. The Comprehensive Database suggests that the FHWA-Gates, FHWA-UI, and WSDOT formulae offer good predictions of pile capacity. The database also suggests that the ICP method predicts capacity well. The K-IDOT method and IDOT Static method also performed somewhat well in the Comprehensive Database analyses.

Based on the indirect comparisons between these databases, attention was focused on three dynamic formulae and three dynamic methods. The FHWA-Gates, FHWA-UI, and WSDOT formulae all appear to predict pile capacity fairly accurately and precisely and merit further consideration. The ICP, IDOT Static, and K-IDOT methods also appear to predict capacity fairly accurately and precisely, and they also agree fairly well with the aforementioned dynamic formulae. Empirical correction factors were developed based on these six methods to attempt to further improve the agreement between dynamic and static methods.

6.3 CORRECTION FACTORS

Correction factors were determined for the IDOT Static, K-IDOT, and ICP methods. The dynamic formulae appear to, on the average, predict capacity fairly well without correction factors. Also, while it is possible to correct a dynamic formula for bias with respect to pile type, if both sand and clay layers are present along the sides of the pile, there is no simple way to correct the formula for bias with regard to soil type. With the static methods, it is possible to correct the capacity predictions for any pile for the influence of both sand and clay.

The use of a single overall correction factor, as well as correction factors for only pile type or only soil type were considered. However, it was decided to apply four correction factors to each static method. These corrections are for: H-piles in Sand, H-piles in Clay, Pipe piles in Sand, and Pipe piles in Clay. The corrections were determined as explained below.

For each static method (IDOT Static, K-IDOT, and ICP), the pile capacity derived from sand and the pile capacity derived from clay was determined. These sand and clay capacities were each multiplied by a different correction factor, depending on the pile type. The Dynamic/Corrected Static capacity ratios were then determined. The value of each correction factor was determined by forcing the values of the average capacity ratios to unity for H-piles in Sand, H-piles in Clay, Pipe piles in Sand, and Pipe piles in Clay. As a result, the average capacity ratio for all piles will also approach unity.

One potential problem with determining correction factors in this manner is that the correction factor value could become very large or very small. Limits on the values of the correction factors were applied, as shown in Table 6.1. Different limits were chosen for different static methods based on the Static/SLT analyses from the Comprehensive Database.

Table 6.1. Limits on Correction Factors to Static Methods

	Lower Limit	**Upper Limit**
IDOT Static:	0.5	1.5
K-IDOT:	0.3	1.5
ICP:	0.3	1.5

Correction values were determined for each Dynamic/Static combination (9 total). These values are shown in Table 6.2. Based on these correction factors, corrected statistics were determined for the Dynamic/Static data for both the Illinois Database and Comprehensive Database. The International Database was not analyzed for corrected statistics as insufficient information was available to determine the pile capacity using static methods.

Table 6.2. Correction Factors

	Pipe, Clay	**Pipe, Sand**	**H, Clay**	**H, Sand**
WSDOT/ICP	1.067	0.730	1.277	0.353
FHWA-Gates/ICP	1.178	0.924	1.438	0.461
FHWA-UI/ICP	1.355	0.677	1.226	0.300
WSDOT/IDOT-S	1.174	0.758	1.500	0.724
FHWA-Gates/IDOT-S	1.284	0.955	1.500	1.073
FHWA-UI/IDOT-S	1.500	0.711	1.500	0.500
WSDOT/K-IDOT	1.174	0.758	1.500	0.300
FHWA-Gates/K-IDOT	1.284	0.955	1.500	0.387
FHWA-UI/K-IDOT	1.500	0.711	1.353	0.300

6.3.1 Corrected Illinois Database

Referring to the analyses described in Chapter 5 for the uncorrected Illinois Database, the IDOT Static method offered the best agreement with any dynamic formula, followed by the K-IDOT method, then the ICP method. Generally, the FHWA-Gates formula, then the WSDOT formula, followed by the FHWA-UI formula offered the best agreement with any static method. The average FHWA-Gates/IDOT Static capacity ratio (COV = 0.50), the average WSDOT/IDOT Static capacity ratio (COV = 0.57), then the FHWA-Gates/K-IDOT and FHWA-UI/IDOT Static average capacity ratios (COV = 0.58) had the smallest COV's. Tables 5.1 – 5.9 present the statistics for the uncorrected Dynamic/Static data. Additional information can be found in Appendix D. Selected graphs are presented in Figures 5.1 and 5.2. Additional graphs for the data are presented in Appendix D.

Selected statistics for each Dynamic/Corrected Static capacity ratio are presented in Table 6.3. A more thorough presentation of the statistics can be found in Appendix E. The range in averages was 1.09 to 1.22, indicating that the correction factors brought the average capacity ratios to a value close to unity. The data are presented graphically in Figures 6.1 and 6.2. For the Corrected Illinois Database, the K-IDOT method appears to be the static method that agrees best with the dynamic formulae, both with respect to average and COV. The IDOT Static method appears to offer the second-best agreement, while the ICP method displays the least agreement with dynamic formulae. All of the dynamic formulae performed well when analyzed using the K-IDOT method, the range in Dynamic/K-IDOT COV's is only 0.06, while the range in value of the average capacity ratios is 0.02 (See Table 6.3).

Of the various subcategories, H-piles in Clay tend to overpredict capacity, often by the largest magnitude of any subcategory. Generally, better agreement between dynamic and static methods is seen for pipe piles than for H-piles. Generally, the average capacity ratio for piles in sand is closer to unity than that for piles in clay.

For the FHWA-Gates/Corrected K-IDOT data, there appears to be little bias between soil type for pipe piles. Statistics for the FHWA-Gates/Corrected K-IDOT data, broken down into subcategories are presented in Appendix E. The average capacity ratio for H-piles in clay is larger than the average capacity ratio for H-piles in sand, however the COV is smaller for H-piles in clay. These same general trends are also observed for the WSDOT/K-IDOT data.

The K-IDOT method more closely reflects kinematic soil-pile behavior for a statically loaded pile. After empirical corrections were applied, the method predicted pile capacity more precisely. The average FHWA-Gates/Corrected K-IDOT capacity ratio displayed the smallest scatter with a COV = 0.43. This is followed by the FHWA-Gates/Corrected IDOT Static data (COV = 0.46), and the WSDOT/Corrected K-IDOT and FHWA-UI/Corrected K-IDOT data (COV = 0.49), these data are presented in Table 6.3.

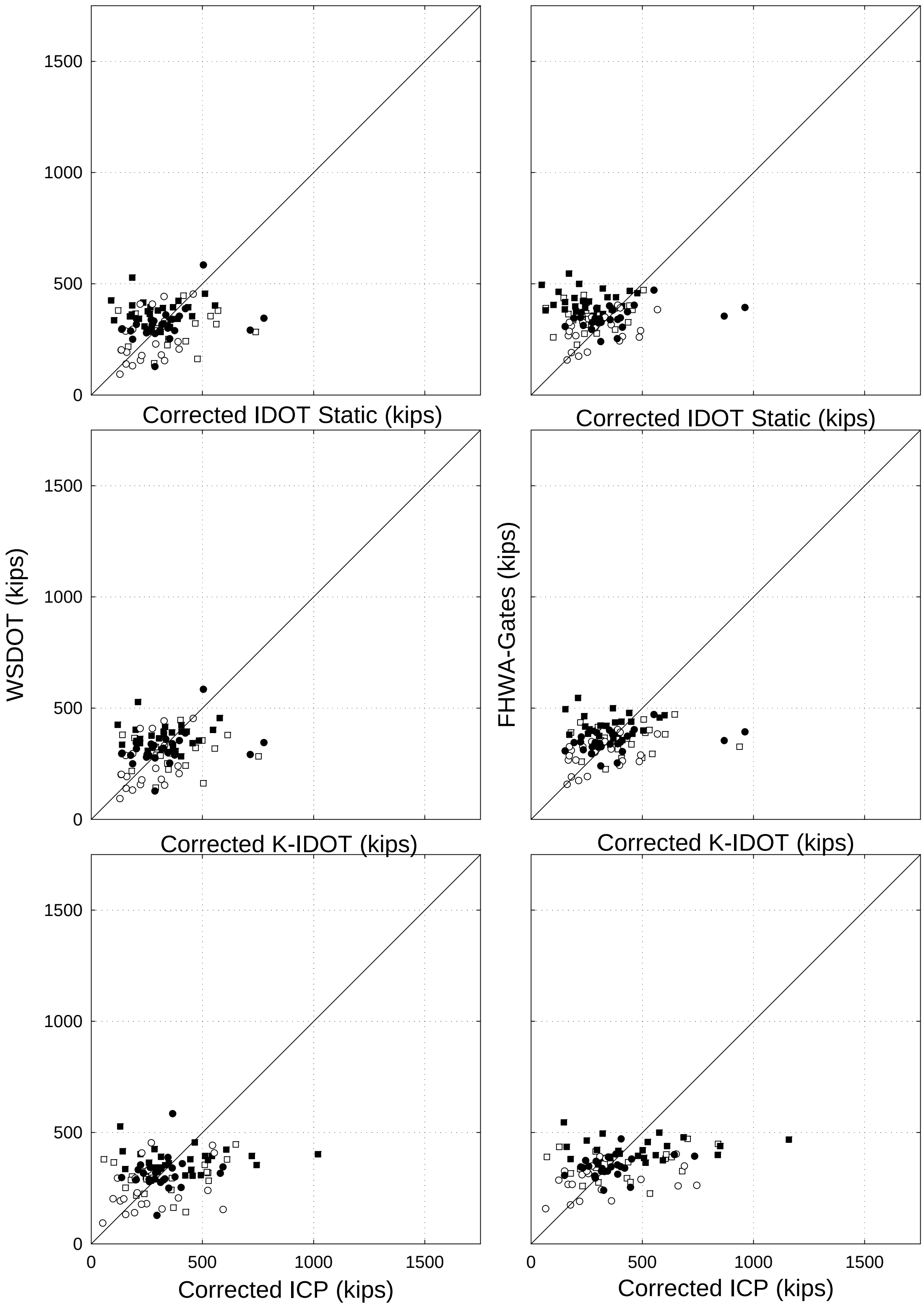

Figure 6.1. Dynamic vs. corrected static capacities for the Illinois Database.

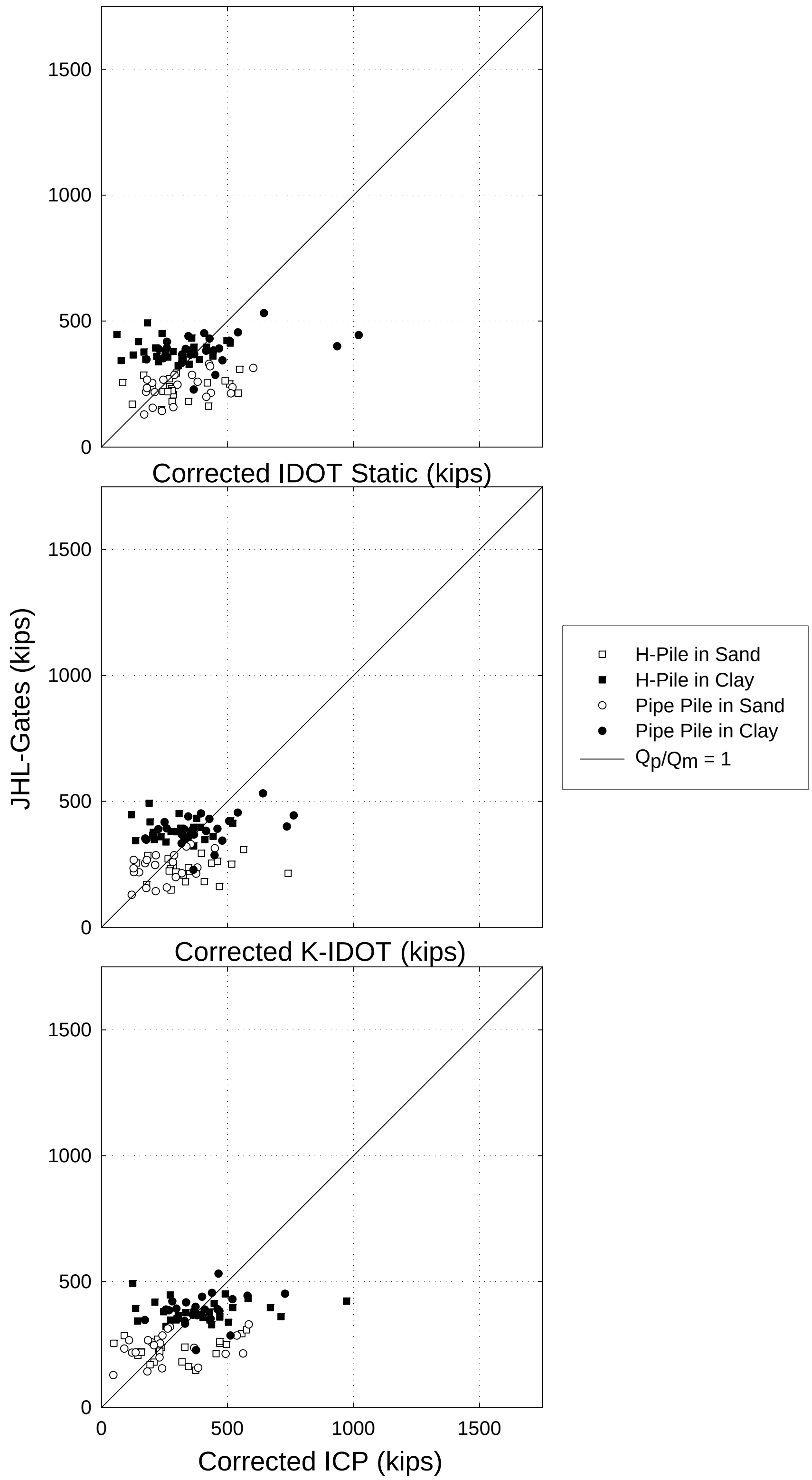

Figure 6.2. Dynamic vs. corrected static capacities for the Illinois Database.

Table 6.3. Statistics for Dynamic vs. Corrected Static Methods, Illinois Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. Corrected IDOT Static	Mean:	1.19	1.16	1.22
	Std. Dev:	0.62	0.54	0.67
	COV:	0.52	0.46	0.55
	r^2:	0.05	0.01	0.08
	n:	92	92	92
vs. Corrected Kinematic IDOT	Mean:	1.11	1.12	1.10
	Std. Dev:	0.54	0.48	0.53
	COV:	0.49	0.43	0.49
	r^2:	0.07	0.05	0.08
	n:	92	92	92
vs. Corrected ICP	Mean:	1.16	1.14	1.13
	Std. Dev:	0.67	0.62	0.63
	COV:	0.58	0.55	0.56
	r^2:	0.09	0.11	0.15
	n:	92	92	92

6.3.2 Corrected Comprehensive Database

Referring to the analyses in Chapter 4 concerning the uncorrected Comprehensive Database, the ICP method appears to offer the best agreement with dynamic formulae. Next is the IDOT Static method, with the K-IDOT method offering the worst agreement with dynamic formulae of the three (as determined based on COV). The Comprehensive Database offers the opportunity to examine the agreement between dynamic and static methods, and to examine the accuracy and precision of each method compared to static load test results.

Based on the Comprehensive Database data, the WSDOT formula agrees very well with static load test results. The FHWA-Gates formula agrees almost as well. The results also indicate that the ICP method is the most precise of the static methods, with the IDOT Static and K-IDOT methods a distant second. These results helped inform the selection of which capacity prediction methods to correct.

Predicted static capacities in the Comprehensive Database were corrected using the correction factors determined from the Illinois Database (Table 6.2). This resulted in the corrected Comprehensive Database statistics shown in Table 6.4. The data are presented graphically in Figures 6.3 and 6.4. The corrected K-IDOT method best agrees with the WSDOT and FHWA-Gates formulae. The next best agreement between these two formulae is seen with the ICP method, then the IDOT Static method (based on COV). The value of the average WSDOT/Corrected K-IDOT capacity ratio COV is 0.58 (Table 6.4), as opposed to COV = 0.84 for the uncorrected average WSDOT/K-IDOT capacity ratio (Table 4.2). The average FHWA-Gates/Corrected K-IDOT capacity ratio COV is 0.62 (Table 6.4), as opposed to COV = 0.87 previously (Table 4.2).

For the subcategories of the WSDOT/Corrected K-IDOT data (presented in Appendix E), there appears to be little bias between pipe piles and H-piles, although there is a slightly stronger tendency to overpredict capacity for pipe piles. The degree of scatter is smaller for H-piles than pipe piles. With regard to soil type, the average capacity ratios are very similar for both piles in sand and piles in clay. More scatter is observed for piles in clay, but there are only 3 data points from which to draw conclusions.

For the subcategories of the FHWA-Gates/Corrected K-IDOT data (presented in Appendix E), there is a tendency to underpredict capacity for both H-piles and pipe piles. The average underprediction for pipe piles is of a larger magnitude and more scatter is observed than for H-piles. For all piles in sand, both the average and COV are very similar to that for all data. There is a tendency to overpredict capacity in clay with a high degree of scatter, but there are only three data points for piles in clay, so no firm conclusions can be drawn from this information.

Table 6.4. Statistics for Dynamic vs. Corrected Static Methods, Comprehensive Database

		WSDOT	FHWA-Gates	FHWA-UI
vs. Corrected IDOT Static	Mean:	1.20	0.94	1.17
	Std. Dev:	0.86	0.72	0.91
	COV:	0.71	0.77	0.78
	r^2:	0.37	0.29	-
	n:	26	23	23
vs. Corrected Kinematic IDOT	Mean:	1.09	0.90	0.96
	Std. Dev:	0.63	0.56	0.62
	COV:	0.58	0.62	0.65
	r^2:	0.27	0.30	-
	n:	26	23	23
vs. Corrected ICP	Mean:	0.94	0.78	0.84
	Std. Dev:	0.60	0.53	0.56
	COV:	0.64	0.67	0.66
	r^2:	0.00	0.00	-
	n:	26	23	23

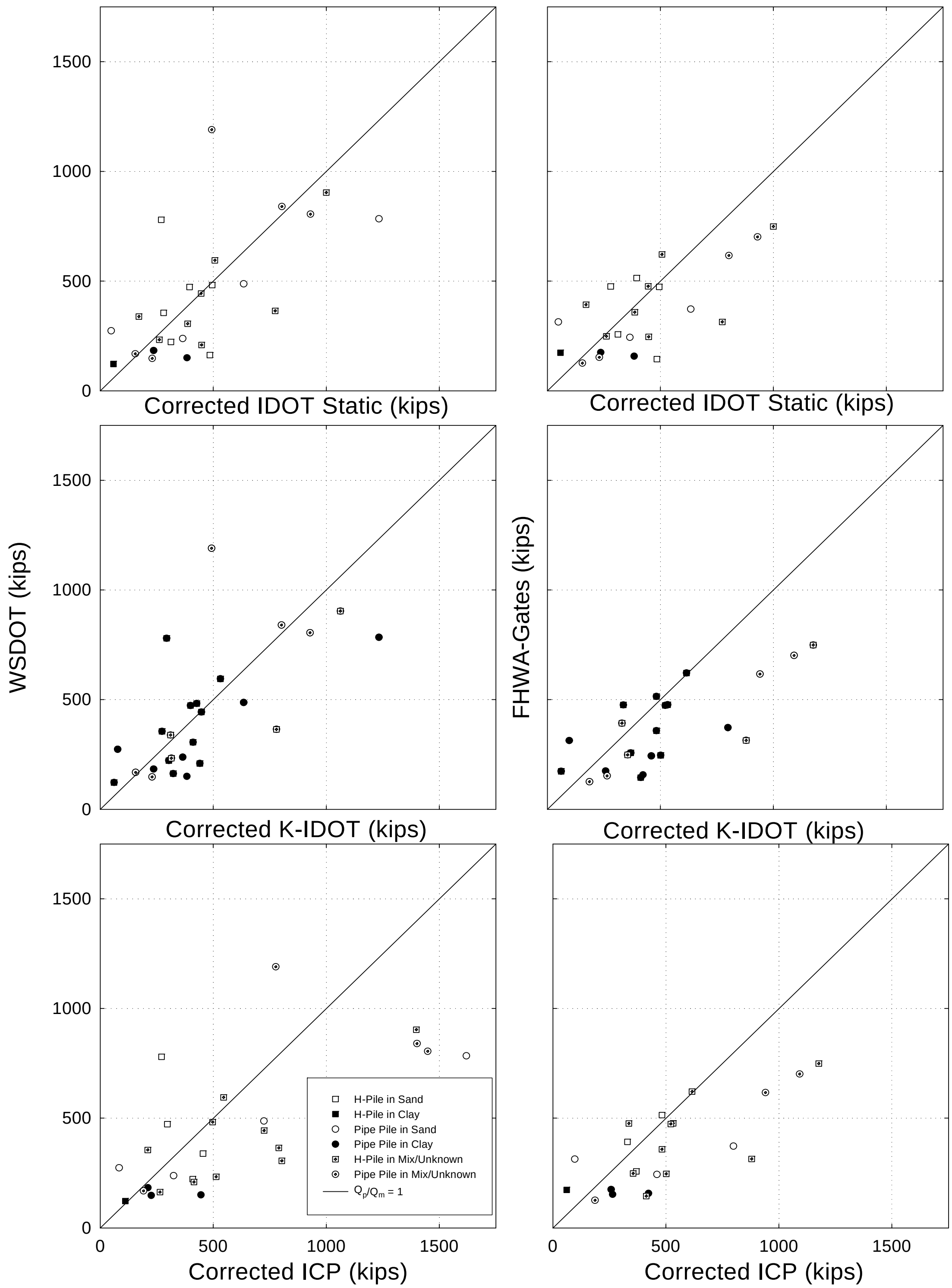

Figure 6.3. Dynamic vs. Corrected Static Capacities for the Comprehensive Database.

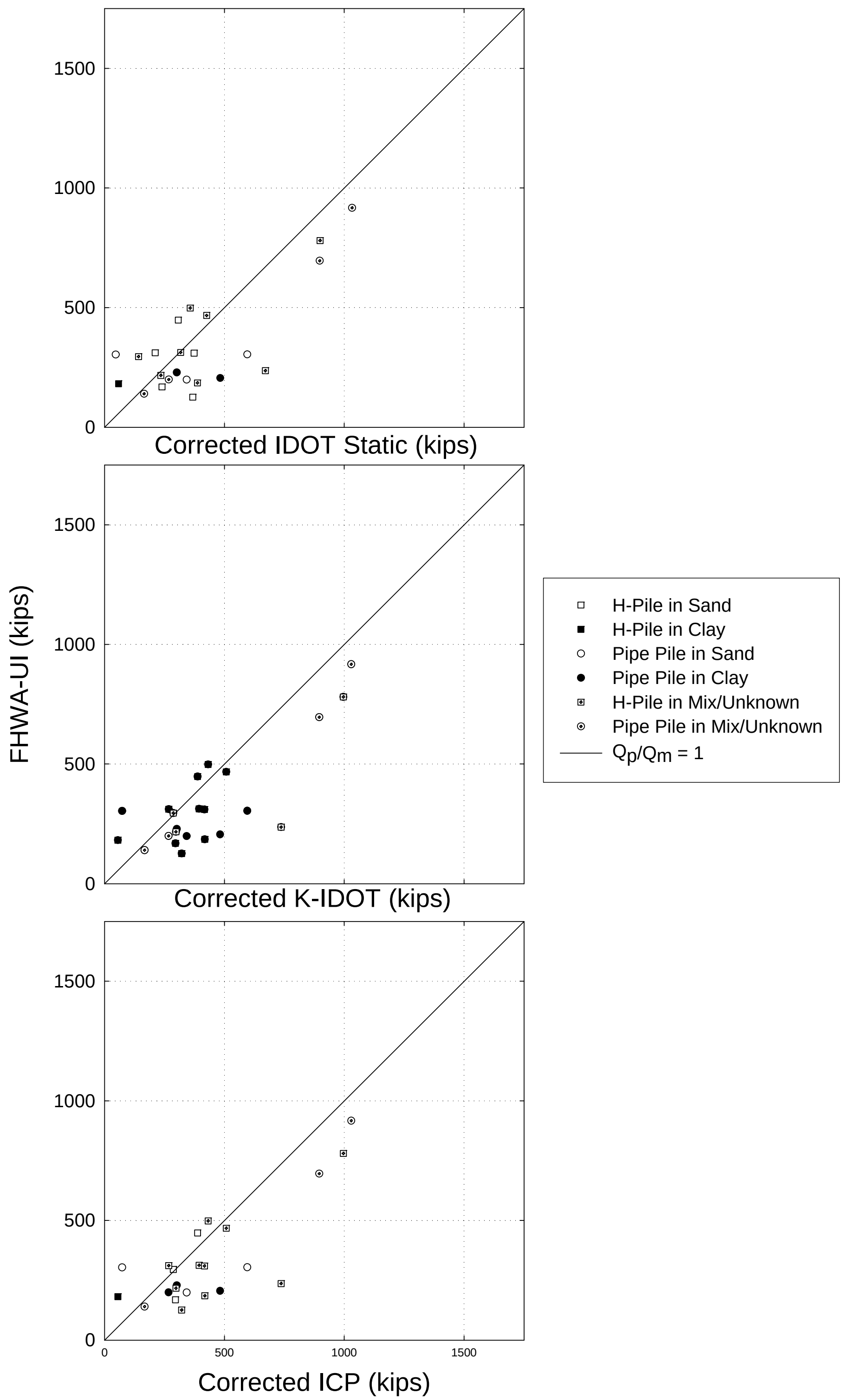

Figure 6.4. Dynamic vs. corrected static capacities for the Comprehensive Database.

6.4 SUMMARY AND RECOMMENDATIONS

The results from analyzing the three databases were considered when developing a course of action for applying empirical correction factors. Because, according to the International and Comprehensive Databases, the dynamic formulae predict capacity reasonably well, it was decided to apply correction factors to the static methods. Based upon data from the three databases, the methods to which correction factors were applied were the ICP method, the K-IDOT method, and the IDOT Static method. Four correction factors were applied to each set of Dynamic/Static data. The corrections were for H-piles in Sand, H-piles in Clay, Pipe Piles in Sand, and Pipe Piles in Clay. The value of these correction factors was determined based on data in the Illinois Database.

After empirical correction factors were applied, the K-IDOT method appears to offer the best agreement with various dynamic formulae. Of the dynamic formulae, both the WSDOT formula and the FHWA-Gates formula appear to agree well with the K-IDOT formula. Both also appear to predict pile capacity fairly accurately and precisely.

The use of the WSDOT formula as a dynamic formula to predict capacity is recommended. The use of the Corrected K-IDOT method is recommended for use as a static method to predict pile capacity, with the following corrections:

Pile, Soil Condition	Correction Factor
Pipe, Clay	1.174
Pipe, Sand	0.758
H-Pile, Clay	1.500
H-Pile, Sand	0.300

These recommendations are based on the following evidence. For the two databases with static load test data (International Database and Comprehensive Database), the WSDOT formula predicted capacity both accurately and precisely. For the International Database the average WSDOT/SLT capacity ratio is 1.14 with a COV = 0.45 (Table 3.1). This was second only to the average FHWA-UI/SLT capacity ratio of 0.97 with a COV = 0.43 (Table 3.1). In the Comprehensive Database, the average WSDOT/SLT capacity ratio is 1.02 with a COV = 0.29 (Table 4.1). This was the smallest COV in the Comprehensive Database. Also, in Long et al. (2009), a tendency for the FHWA-Gates formula to begin to progressively underpredict pile capacity at capacities greater than 750 kips was observed. This tendency was not observed for the same data using the WSDOT formula, as such, the WSDOT formula is considered to be a more robust formula.

The K-IDOT method is recommended for the following reasons. The K-IDOT method better reflects the physical reality of a driven pile. The IDOT Static method assumes a “boxed” pile shaft geometry and assumes the area of steel for the bearing area of an H-pile. This is not kinematically realistic. Based upon data in the Comprehensive Database, the uncorrected K-IDOT method overpredicts pile capacity. When empirical corrections are applied to the K-IDOT method, this tendency is not nearly as strong. Also, when empirically corrected, the K-IDOT method offers the best agreement with dynamic formulae of the three static methods which were empirically corrected.

In the Comprehensive Database, the average WSDOT/Corrected K-IDOT capacity ratio is 1.09 with a COV = 0.58 (Table 6.4), as compared to the average WSDOT/K-IDOT capacity ratio of 0.79 with a COV = 0.84 (Table 4.2). The average WSDOT/SLT capacity ratio for this database is 1.02 with a COV = 0.29 (Table 4.1). The COV of the WSDOT/Corrected K-IDOT data is the smallest COV observed for the Dynamic/Corrected data, while the average is fairly close to unity. In the Illinois Database, the average WSDOT/Corrected K-IDOT capacity ratio is 1.11 with a COV = 0.49 (Table 6.3), as opposed to the average WSDOT/K-IDOT capacity ratio of 0.94 with a COV = 0.63. The lowest COV was seen for the average FHWA-Gates/Corrected K-IDOT capacity ratio of 1.12 with a COV = 0.43 (Table 6.3). Because the difference between the WSDOT/Corrected K-IDOT and FHWA-Gates/Corrected K-IDOT data for the Illinois Database is not large, and due to the previously mentioned factors, the combination of the WSDOT formula and Corrected K-IDOT method is recommended. This is considered a balance between the analyses of the International Database, Comprehensive Database, and Illinois Database, as well as a balance between recommending the most accurate methods (based on static load test results) and those methods which offer the best agreement with each other.

6.5 COMPARISON OF CURRENT METHODS WITH PROPOSED METHODS

Currently, IDOT uses the FHWA-Gates formula and IDOT Static method to predict capacities on-site and during design. Should IDOT wish to continue using these two methods, corrections to the capacity predicted by the IDOT Static method are recommended. These corrections are based on soil type and pile type. Based on the information presented in the previous section, the use of the WSDOT formula along with the corrected K-IDOT method is recommended. The corrections to the K-IDOT method are also based on soil type and pile type. Table 6.5 summarizes the agreement between these three sets of dynamic formulae and static methods along with presenting the recommended correction factors to the predicted static method capacities.

Table 6.5. Statistics and Corrections for Selected Dynamic/static Data

	Average	COV	Pipe Pile in Clay Correction	Pipe Pile in Sand Correction	H-Pile in Clay Correction	H-Pile in Sand Correction
FHWA-Gates/ IDOT Static	1.41	0.51	N/A	N/A	N/A	N/A
FHWA-Gates/ Corr. IDOT Static	1.16	0.46	1.284	0.955	1.500	0.724
WSDOT/ Corr. K-IDOT	1.09	0.58	1.174	0.758	1.500	0.300

In the discussion of the Illinois Database, the cumulative distribution plot of the FHWA-Gates/IDOT Static data was presented (Figure 5.3). The FHWA-Gates/Corrected IDOT Static data and the WSDOT/K-IDOT data are presented in Figures 6.5 and 6.6.

As discussed in Chapter 5, the data for the FHWA-Gates and IDOT Static methods suggest there is a 70% probability that the capacity predicted by the FHWA-Gates formula will be greater than that predicted by the IDOT Static method. In other words, the necessary length of pile predicted by the IDOT Static method is greater than the length necessary according to the FHWA-Gates formula 70% of the time.

The cumulative distribution of the FHWA-Gates/Corrected IDOT Static data indicates that about 60% of the time, the length of pile necessary according to the Corrected IDOT Static method is greater than the length of pile necessary according to the FHWA-Gates method. So, 60% of the time, the length of pile driven in the field will be less than that predicted by the corrected IDOT Static method.

The cumulative distribution of the WSDOT/Corrected K-IDOT data indicates that 50% of the time, the WSDOT formula predicts a capacity greater than the K-IDOT method. This also means that half of the time, the K-IDOT method predicts a capacity greater than the WSDOT formula. It is just as likely that the length of pile driven on-site is longer than predicted necessary as it is that the length of pile driven on-site will be shorter than predicted necessary. The difference in predicted and actual length cannot be determined, only the probability that the length will be longer or shorter than predicted can be determined.

The data associated with the FHWA-Gates formula and IDOT Static method represent the current practice of IDOT. If it is desired to not substantially change current practice, the FHWA-Gates formula in conjunction with a corrected IDOT Static method can be used. The use of the WSDOT formula in conjunction with the K-IDOT method is recommended. The information presented in Table 6.5, along with that presented in Figures 5.3, 6.5 and 6.6 summarizes the agreement between methods and the probability that actual pile length will be longer than predicted pile length. These data allow a comparison between IDOT's current practice and what can be expected if changes are made to the current practice.

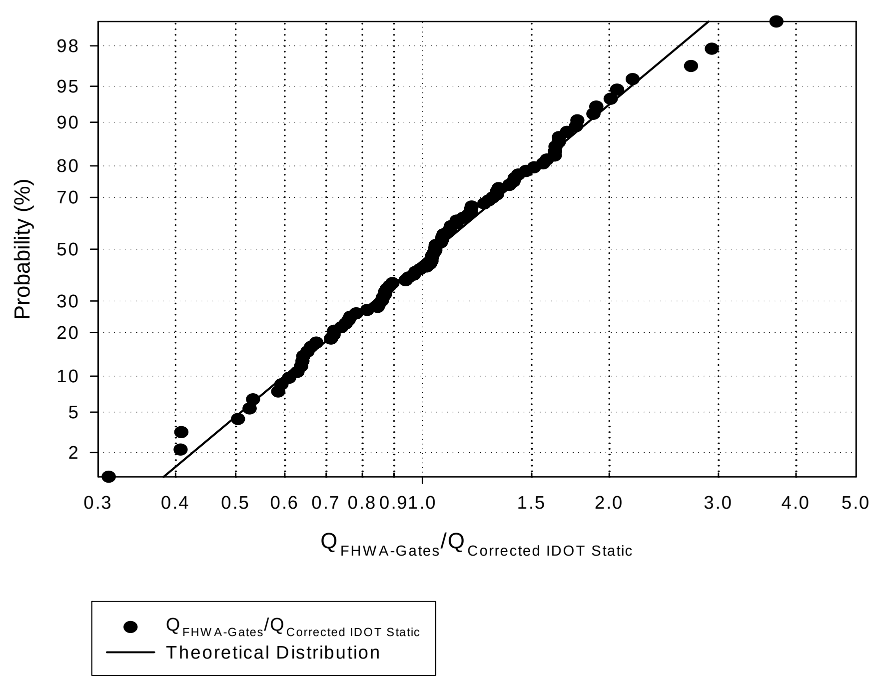

Figure 6.5. Cumulative distribution of FHWA-Gates/Corrected IDOT Static Data, Illinois Database.

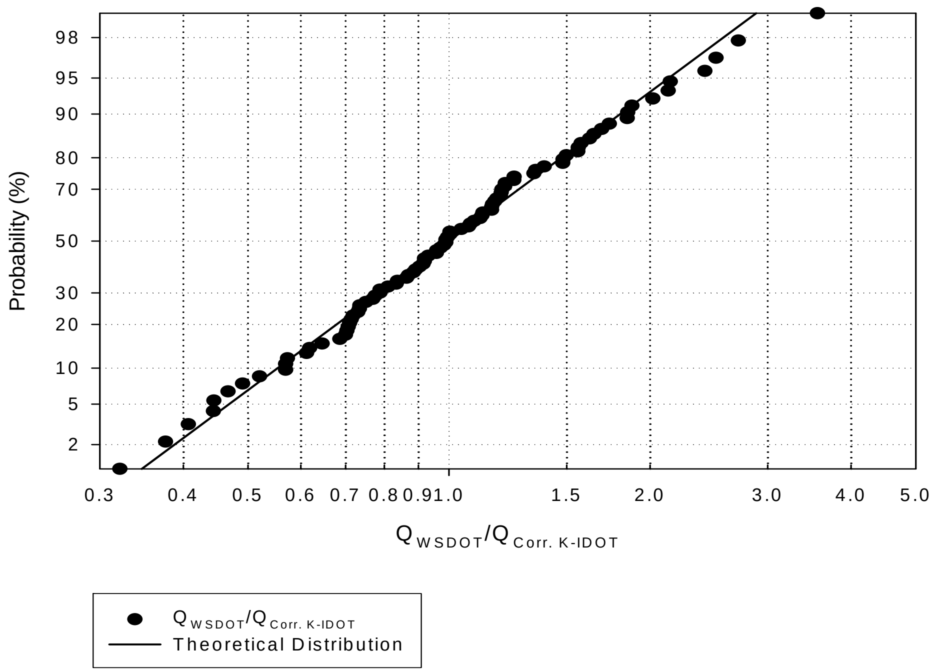

Figure 6.6. Cumulative distribution of WSDOT/Corrected K-IDOT Data, Illinois Database.

CHAPTER 7 RESISTANCE FACTORS FOR PREDICTIVE METHODS

7.1 INTRODUCTION

Three databases have been used to investigate the accuracy and precision of the following methods based on pile behavior during driving: the Engineering News Formula, the FHWA-modified Gates formula, the UI-modified Gates formula, the Washington State DOT formula, and WEAP. Furthermore these same three databases were used to investigate the following methods for predicting static capacity: the current Illinois DOT static method, a UI-modified version of the Illinois DOT static method called the kinematic method, a static method using Tomlinson and Nordlund recommendations and the computer program DRIVEN, and a cone-based method from Imperial College, designated as ICP. Chapters 3 through 5 reviewed the accuracy and precision of these methods, and three dynamic methods (FHWA, FHWA-UI, and WSDOT) were selected for further evaluation. Furthermore, three static methods, the current IDOT static method, the current IDOT static method corrected to optimize agreement with dynamic behavior during driving, and the kinematic static method corrected to optimize agreement with dynamic behavior during driving, were selected for further evaluation. Resistance values are discussed and developed for these methods. The methods investigated represent the combination of static and dynamic methods providing the greatest consistency and agreement in prediction of pile capacity.

7.2 SUMMARY OF PREDICTIVE METHODS

The bias and coefficient of variation, for each of the predictive methods are summarized below.

n	Bias	COV	Method
132	1.02	0.485	FHWA
132	1.15	0.405	FHWA-UI
132	1.05	0.451	WS-DOT
26	1.11	0.666	S-IDOT - current IDOT static method
26	0.97	0.650	Corrected S-IDOT - “corrected” static method
26	1.09	0.525	Corrected K-IDOT - “corrected” kinematic method

The “accuracy” of a predictive method is associated with the bias value, which is defined as the measured capacity/predicted capacity. Bias values closer to unity do a better job, on the average, of predicting capacity. All methods with bias values unequal to unity can be “corrected” by multiplying the predicted pile capacity by a factor equal to the bias. Thus, it is quite simple to correct all the methods above so that each method, on the average, predicts measured capacity. Accordingly, ranking the efficiency of predictive methods based on mean value (accuracy) is ineffective.

However, the precision with which a method predicts capacity is an effective way to rank methods. A precise method will predict capacity with consistency and the coefficient of variation (COV) is a measure of the precision. Low values of COV are associated with a high degree of precision. Unlike the bias, the COV for a method cannot be improved by multiplying the predicted capacity by a constant. Accordingly, the COV will be used to rank predictive methods (lower COV values are more precise).

The predictive methods listed above are arranged first with three dynamic formulae and then three static methods. All three dynamic formulae exhibit greater precision (smaller values of COV) than the static methods. Accordingly, predictions of capacity based on dynamic formulae should be more precise and lead to more efficient design than capacity predictions based on the static formulae investigated herein. The dynamic formula with the greatest precision is the FHWA-UI, followed by the WSDOT, and then the FHWA. The most precise static method is the corrected K-IDOT, followed by the corrected S-IDOT, followed by the current IDOT-static method. The precision of the corrected K-IDOT method is significantly better than the other two static methods.

7.3 RESISTANCE FACTORS AND RELIABILITY

Load and Resistance Factor Design is being used more frequently for bridge foundations. Two procedures for determining resistance factors follow those outlined in NCHRP 507 and are identified as: 1) the first order second moment method (FOSM), and 2) the first order reliability method (FORM).

7.3.1 First Order Second Moment (FOSM)

The FOSM can be used to determine the resistance factor using the following expression:

$$\phi = \frac{\lambda_R\left(\frac{\gamma_D Q_D}{Q_L} + \gamma_L\right)\sqrt{\left[\frac{\left(1 + COV_{Q_D}^2 + COV_{Q_L}^2\right)}{\left(1 + COV_R^2\right)}\right]}}{\left(\frac{\lambda_{Q_D} Q_D}{Q_L} + \lambda_{Q_L}\right)\exp\left\{\beta_T\sqrt{\ln\left[\left(1 + COV_R^2\right)\left(1 + COV_{Q_D}^2 + COV_{Q_L}^2\right)\right]}\right\}} \quad (7.1)$$

where:

λ_R= bias factor (which is the mean value of Q_M/Q_P) for resistance
COV_{QD} = coefficient of variation for the dead load
COV_{QL} = coefficient of variation for the live load
COV_R = coefficient of variation for the resistance
β_T = target reliability index
γ_D = load factor for dead loads
γ_L = load factor for live loads
Q_D/Q_L = ratio of dead load to live load
λ_{QD}, λ_{QL} = bias factors for dead load and live load

Using values consistent with AASHTO and NCHRP 507, the following values were used for parameters in Eqn 7.1:

λ_R= mean value of Q_P/Q_M as determined from database study
COV_{QD} = 0.1
COV_{QL} = 0.2
COV_R = COV as determined from database study
β_T = target reliability index (generally between 2 and 3.2)
γ_D = 1.25
γ_L = 1.75
Q_D/Q_L = 2.0
λ_{QD} = 1.05
λ_{QL} = 1.15

Values for bias (λ_R) and coefficient of variation (COV_R) for the resistance used in Eqn 7.1 are based on Q_M/Q_P; however all the statistics determined in this report have been for Q_P/Q_M. Accordingly, the bias and COV for Q_P/Q_M values were converted to bias and COV values for Q_M/Q_P and are given in Table 7.1.

Table 7.1 Statistical Parameters and Resistance Factors for the Predictive Methods based on Q_M/Q_P Values using FOSM

Predictive Method	Bias, λ	COV	Resistance Factor, ϕ Using FOSM		Resistance Factor, ϕ Using FORM	
			β_T = 2.33	β_T = 3.0	β_T = 2.33	β_T = 3.0
FHWA	1.02	0.485	0.37	0.27	0.40	0.30
FHWA-UI	1.15	0.405	0.50	0.37	0.55	0.42
WSDOT	1.05	0.451	0.42	0.30	0.45	0.34
S-IDOT	1.11	0.666	0.28	0.18	0.29	0.19
corrected S-IDOT	0.97	0.650	0.25	0.16	0.26	0.18
corrected K-IDOT	1.09	0.525	0.37	0.26	0.40	0.28

Using Eqn. 7.1 with the statistical parameters in Table 7.1, the resistance factor was determined for several values of the Target Reliability Index (β_T). The results are shown in Fig. 7.1 for each of the predictive methods.

NCHRP 507 recommends using a target reliability index (β_T) of 2.33 for driven piling when used in groups of 5 or more piles. A reliability index of 3.0 is recommended for single piles and groups containing 4 or less piles. Table 7.1 provides resistance factors for target reliability values of 2.33 and 3.0 for each of the predictive methods.

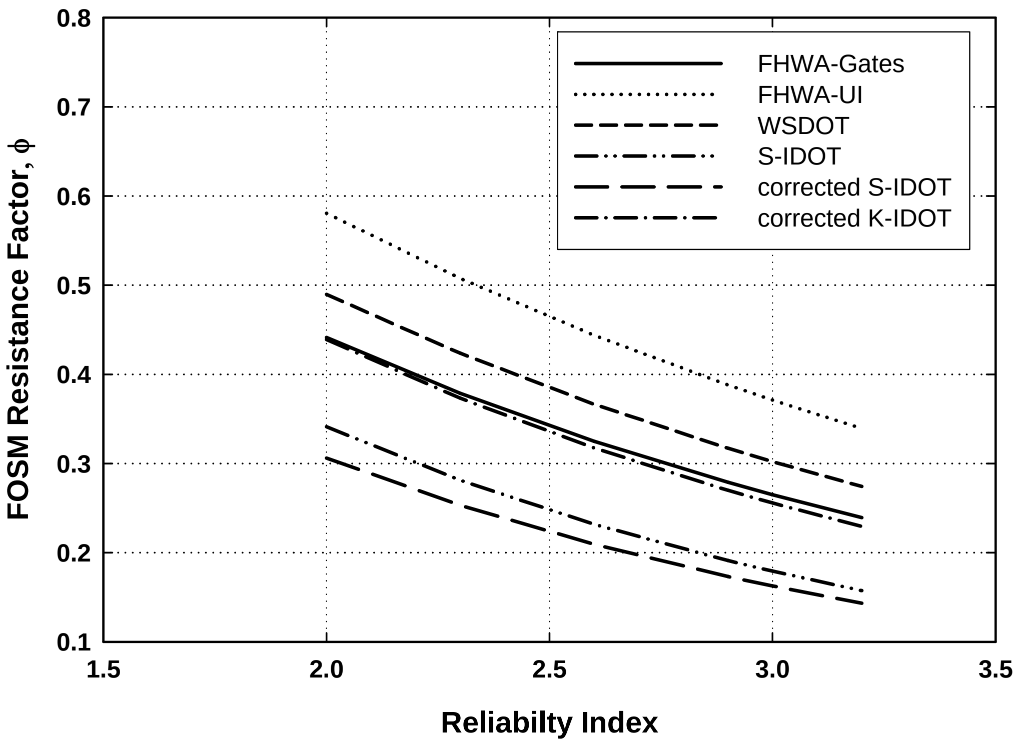

Figure 7.1 Resistance factors versus reliability index for different predictive methods using FOSM.

7.3.2 First Order Reliability Method (FORM)

The Factor of Reliability Method (FORM) provides a more accurate estimate of safety when multiple variables are included, and the variables are not normally distributed, which is the case for the load and resistance values. The method is significantly more complex than Eqn. 7.1, and requires an iterative procedure to determine reliability index based upon an assumed value for the resistance factor.

If the design equation (Eqn. 7.2) is linear and the variables are normally distributed, then the FOSM method is completely adequate. For example, the design equation

$$\phi R_n \geq \gamma_D D_n + \gamma_L L_n \qquad (7.2)$$

where R_n, D_n, and L_n are the calculated values for resistance, dead load and live load, respectively. The performance function, g(x), is:

$$g(x_1, x_2, x_3) = \overline{R} - \overline{D} - \overline{L} \geq 0 \qquad (7.3)$$

Eqn. 7.3 is a linear function. If the parameters $\overline{R}$, $\overline{D}$, and $\overline{L}$ are normally distributed, then the FOSM method estimates reliability accurately. Another way to look at the reliability is by plotting the performance function. A plot for a linear performance function with two parameters would have two axes, (x' and y') and the performance function plots as a line. Any point that plots above the performance function is safe (g()>0) and anything plotting on or above the line is unsafe (or fails). A measure of the minimum safety is thus the shortest distance between the origin to the function g(). If the solution is linear and normally distributed, then the minimum distance is easily calculated as:

$$\beta = \frac{\mu_{\overline{R}} - \mu_{\overline{D}} - \mu_{\overline{L}}}{\sqrt{\sigma_{\overline{R}}^2 + \sigma_{\overline{D}}^2 + \sigma_{\overline{L}}^2}} \tag{7.4}$$

The mean values (μ_R, μ_D, μ_L) can be expressed in terms of ϕ, γ_D, γ_L, λ_R, λ_D, λ_L, and load ratio, Λ (defined as the ratio of live load to dead load). However, the result is that the components of Eqn 7.3 can be expressed in terms of the dead load as:

$$\overline{L} = \left(\frac{\Lambda\lambda_L}{\lambda_D}\right)\overline{D} \tag{7.5}$$

and the resistance can be expressed in terms of dead load as

$$\overline{R} = \left(\frac{\gamma_D}{\lambda_D} + \frac{\Lambda\gamma_L}{\lambda_D}\right)\frac{\lambda_R}{\phi}\overline{D} \tag{7.6}$$

so that the performance function (Eqn 7.3) can be rewritten as

$$g() = \left(\frac{\gamma_D}{\lambda_D} + \frac{\Lambda\gamma_L}{\lambda_D}\right)\frac{\lambda_R}{\phi}\overline{D} - \overline{D} - \left(\frac{\Lambda\lambda_L}{\lambda_D}\right)\overline{D} \geq 0 \tag{7.7}$$

Using D as the metric, the mean values can be expressed as:

$$\mu_{\overline{L}} = \left(\frac{\Lambda\lambda_L}{\lambda_D}\right)\overline{D} \tag{7.8}$$

$$\mu_{\overline{R}} = \left(\frac{\gamma_D}{\lambda_D} + \frac{\Lambda\gamma_L}{\lambda_D}\right)\frac{\lambda_R}{\phi}\overline{D} \tag{7.9}$$

$$\mu_{\overline{D}} = \overline{D} \tag{7.10}$$

However, if the performance function is not linear, and/or the parameters are not normally distributed, then Eqn. 7.4 may not estimate reliability accurately. This is because the estimate of reliability using the FOSM method is based on the mean values of the variables (μ_R, μ_D, μ_L) and this method for estimating the minimum β value is not accurate for non-linear functions. Accordingly, it becomes necessary to estimate the shortest distance by varying the variables R, D, and L until the minimum is found. This procedure requires iterations and is known as the Factor of Reliability Method (FORM). The method is more complex than Eqn 7.4 and requires an iterative six step procedure as follows:

1. Define the appropriate performance function (in our case, it is $g() = \overline{R} - \overline{D} - \overline{L} > 0$ with the mean values of R, D, and L equal to Equations 7.8 through 7.10).
2. Start the first iteration using the initial location for the points R*, D*, and L* to be equal to the initial mean values (μ_R, μ_D, μ_L).
3. The mean and standard deviation for all the non-normal variables must be re-expressed as their "normal distribution" equivalents.
4. Evaluate the partial derivative ($\frac{\partial g}{\partial X_i}$) for each variable, and compute the new direction cosines, α_i for each variable.
5. Solve for the new value of β.
6. Determine the new checking points as x_{new} = normalized mean – $\alpha_i \beta_{normalized} \sigma$. Do this for R, D, and L. Return to step 3 until the value of β converges.

Additional information for the FORM procedure and the theory behind it can be found in the following references: Ang and Tang (1984), Chapter 6, pages 333-365, NCHRP Rpt 343, Appendix A, pages A-17 to A-28, and NCHRP Rpt 507, pages 10-13.

The resistance factors for the FORM method are given in Table 7.1 for target reliability values of 2.33 and 3.0, and they are also shown in Figure 7.2 for a range of target reliability values from 2 to 3.2. The resistance factors for the FORM are slightly higher (approximately 5 to 14 percent higher) than for the FOSM method.

7.4 EFFICIENCY AND RELIABILITY OF THE METHODS

Better predictive methods should predict capacity more accurately and precisely and therefore require less over-design. It is difficult to compare the impact of predictive methods in terms of cost, because pile length and capacity versus depth is very dependent on the specific soil profile. However, it is possible to compare the impact of predictive methods on the excess capacity required to achieve a specific level of reliability.

It is a common misinterpretation to identify more accurate methods with higher values of ϕ. The efficiency of a method cannot be related directly to the resistance factor, ϕ, because ϕ is also affected by the bias of the method (whether it over- or under-predicts capacity on the average). The ratio of the resistance factor to the bias (ϕ/λ) provides a normalized way to compare the efficiency of different methods.

Shown in Figs. 7.3 and 7.4 are plots of efficiency (ϕ/λ) for target reliability values between 2 and 3.2 for the FOSM method and FORM method, respectively. The efficiencies for the FORM method are slightly higher than for the FOSM method.

Figures 7.3 and 7.4, along with Table 7.1 provide a means to compare the efficiency for different methods. For example, compare the efficiency of the FHWA-Gates formula with the FHWA-UI method for a single pile. The efficiency is 0.40 for the FHWA-Gates method at a reliability index of 2.3 whereas the efficiency is 0.48 for the FHWA-UI method. The ratio of 0.48/0.40 equals about 1.2 which means the FHWA-Gates method would require an additional capacity of 20 percent compared to the corrected FHWA-UI for the same level of reliability.

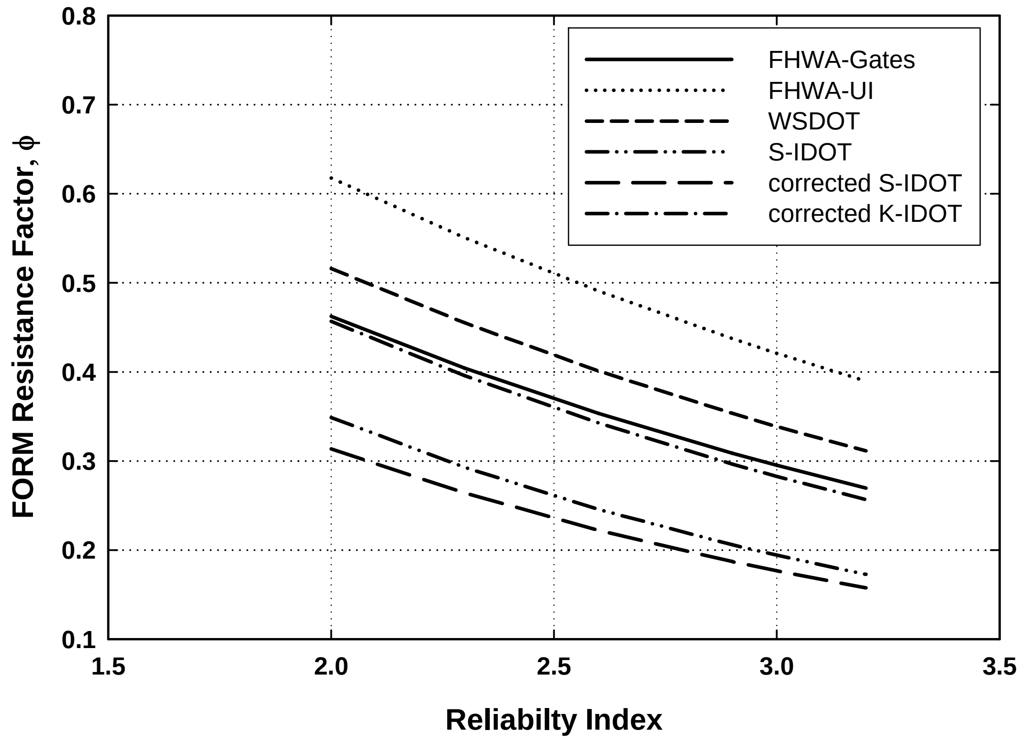

Figure 7.2. Resistance factors versus reliability index for different predictive methods using FORM.

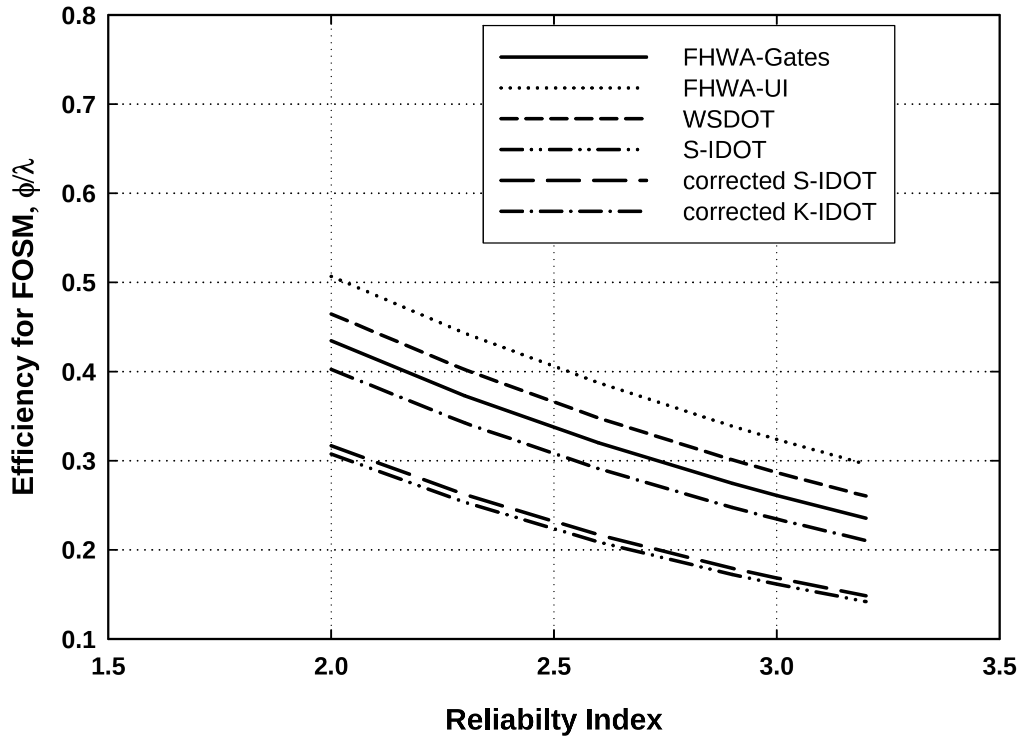

Figure 7.3. Efficiency versus reliability index for different predictive methods using FOSM.

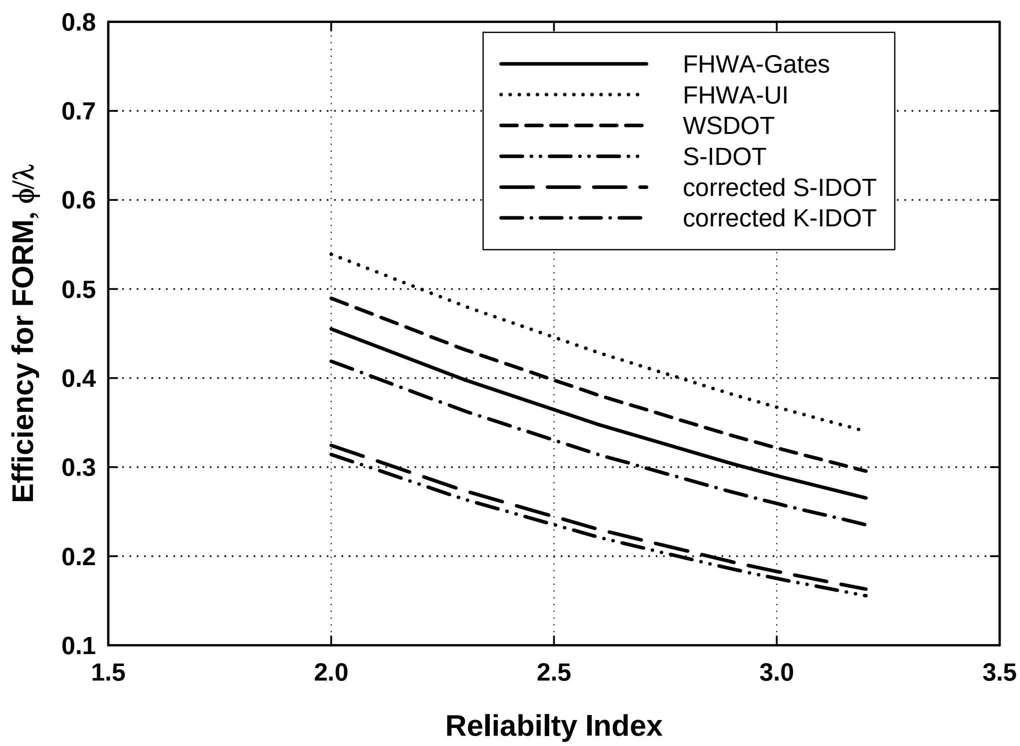

Figure 7.4. Efficiency versus reliability index for different predictive methods using FORM.

7.5 CONSIDERATION OF DISTRIBUTION OF Q_P/Q_M

Several investigators have suggested and observed that the log-normal distribution provides a reasonable overall fit to the cumulative distribution for Q_M/Q_P (Cornell, 1969; Olson and Dennis, 1983; Briaud et al., 1988; Long and Shimel, 1989). Accordingly, all distributions for relating statistical parameters to resistance factors have used a log-normal distribution. However, resistance factors are developed to address extreme cases in which the values of Q_M/Q_P are much smaller than average. Accordingly, it is reasonable to fit the cumulative distribution of the data for the smaller values of Q_M/Q_P rather than fit the distribution for all the data. This section develops resistance factors based on a fit to the extremal data. This procedure is sometimes referred to as fitting the tail of the distribution.

Figure 7.5 exhibits the cumulative distribution of Q_M/Q_P for the WSDOT predictive method using the pile load test data from the International Database. The statistics as given in Table 7.1 (bias = 1.05, COV = 0.451) provide a fit to all the data. The distribution of the data is approximated roughly by the theoretical fit, however, the real distribution appears to be more bi-linear. The theoretical distribution fit to all data indicates a greater probability for small values of Q_M/Q_P than the real data. A second line is shown in Figure 7.5 which results from adjusting the mean and COV to fit the small values of Q_M/Q_P. The result is a significantly better representation of the cumulative distribution at the tail of the distribution. Accordingly, statistics and resistance factors (based on FORM) were re-evaluated for the top 3 predictive methods (FHWA-UI, WSDOT, and FHWA-Gates) and are shown in Table 7.2.

The International Database includes data that were used to develop the WSDOT method. Those data were removed and a smaller database was used to re-evaluate the parameters and estimate resistance factors. The resistance factors are similar, but slightly lower as given in Table 7.3.

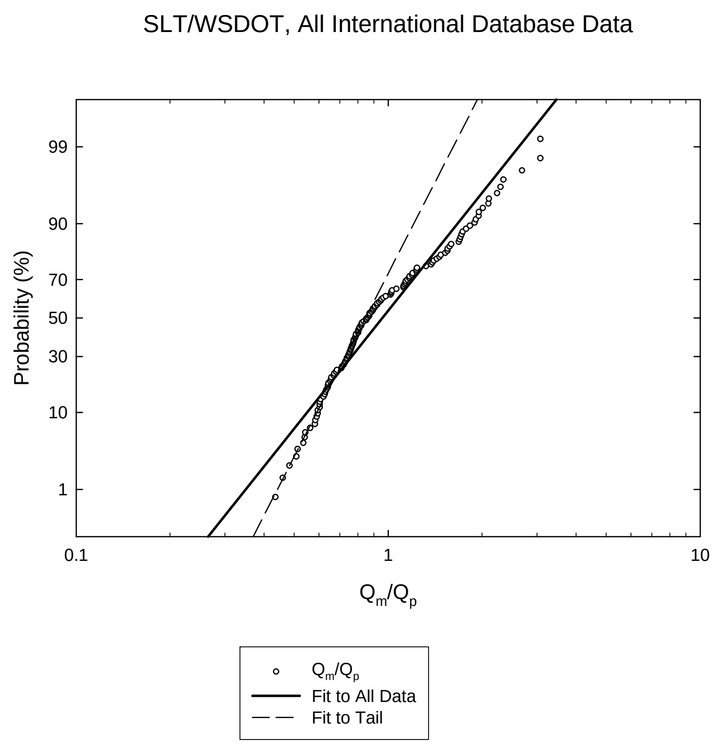

Figure 7.5. Cumulative distribution plot for WSDOT predictive method showing difference between fit to all data and fit to extremal data.

Table 7.2. Statistical Parameters and FORM Resistance Factors for Three Predictive Methods based on Fit of Extremal Data from the International Database

Predictive Method	Bias, λ	COV	ϕ Resistance Factor for FORM and β_T=2.33
FHWA-Gates	0.89	0.34	0.50
FHWI-UI	1.04	0.31	0.63
WSDOT	0.88	0.28	0.56

Table 7.3. Statistical Parameters and FORM Resistance Factors for Three Predictive Methods based on Fit of Extremal Data from the International Database, but Excluding Data from WSDOT

Predictive Method	Bias, λ	COV	ϕ Resistance Factor for FORM and β_T=2.33
FHWA-Gates	0.96	0.41	0.46
FHWI-UI	1.01	0.33	0.59
WSDOT	1.02	0.27	0.54

Based on fits to the extremal portion of the International Database, the following recommendations for β_T = 2.33 are made for the three methods:

Method	ϕ
FHWA-UI	0.61
WSDOT	0.55
FHWA	0.47

These three resistance factors are based on a best fit to the extremal portion of the distribution of Q_M/Q_P. Comparison between the three methods can also be made using the parameter efficiency. Efficiency is a non-dimensional measure of the capacity reduction (ϕ) required to achieve a target reliability divided by how well the method predicts capacity on the average (defined as the average of Q_M/Q_P for all data). Accordingly, calculating and comparing efficiency for fits through the tail of the data require that the value of the resistance factor, ϕ, come from the extremal data, while the average behavior for the method come from the overall fit to the data as givenin Table 7.1. The resulting values of efficiency are 0.61/1.15 = 0.53 for the FHWA-UI method, 0.55/1.05 = 0.52 for the WSDOT method, and 0.47/1.02 = 0.46 for the FHWA method.

7.6 SUMMARY AND CONCLUSIONS

Resistance factors and efficiency of methods were developed and ranked for six predictive methods. The static methods are least efficient while the dynamic methods are more efficient. The predictive methods listed in order of decreasing efficiency are:

FHWA-UI

WSDOT

FHWA

Corrected K-IDOT

Corrected IDOT Static

IDOT Static

Resistance factors determined using the Factor of Reliability Method (FORM) are more accurate and greater than resistance factors determined using the First Order Second Moment method. Resistance factors for reliability index values β_T = 2.33 and 3.0 are provided in Table 7.1 for the FOSM and FORM, respectively.

Moving to the use of the FHWA-UI or the WSDOT method to predict capacity will improve the efficiency and safety of pile foundations driven in Illinois. The use of the corrected K-IDOT will improve the efficiency with which pile lengths are estimated.

More rational resistance factors can be determined by fitting the extremal portions of the cumulative distribution. Recommended resistance factors for a reliability index of 2.33 are 0.61, 0.55, and 0.47 for the FHWA-UI, the WSDOT, and the FHWA-Gates methods, respectively.

CHAPTER 8 SUMMARY AND CONCLUSIONS

Several methods are available for predicting the axial capacity of a pile. These methods are based on soil properties and stratigraphy (static methods), or on the penetration resistance at the end of pile driving (dynamic methods). This study focused on five dynamic methods and five static methods, as discussed in Chapter 2.

Two comparisons were made for evaluating the accuracy and precision of the above methods. The first comparison was between a given method's prediction of capacity and the capacity as measured with a static load test. This comparison allows the accuracy and precision to be quantified with known pile capacity. The second approach compared predictions of capacity based on static properties with predictions of capacity based on dynamic behavior. This comparison provided information on how well the two methods agree with each other and also provides a means to improve the agreement between the two predictions.

Case histories of driven steel piling were collected and sorted into three pile databases to determine how well these static and dynamic methods agree with each other, as well as with static load tests. All piles in the databases are either H-piles, or open- or closed-end steel pipe piles.

The first database, the International Database, compiles the results of several smaller load test databases. The databases include those developed by Flaate (1964), Olson and Flaate (1967), Fragaszy et al. (1988), FHWA (Rausche et al., 1996), Allen (2007), and Paikowsky (NCHRP 507). A total of 132 load tests were collected for this database. Sufficient information is available for each pile so that the pile capacity based on any of the dynamic formulae evaluated can be determined. Sufficient information is not available so that the pile capacity can be estimated based on static methods. The results of a static load test are available for each pile.

The second database, the Comprehensive Database, is comprised of 26 piles gathered for the purposes of this study. The criteria for including a pile in this database included the following: sufficient information must be available so that the pile capacity can be estimated using all of the dynamic formulae evaluated, sufficient information must be available so that the pile capacity can be estimated using all of the static methods evaluated, and the results of a static load test conducted to failure must be available.

The Comprehensive Database is considered an important check on the results of the other two databases as this is the only database for which capacity predictions can be made for every prediction method considered. These predictions can be compared to static load test results.

The Illinois Database consists of pile information provided by IDOT. 92 piles are included in the database and the types of pile are split fairly evenly between H-piles in sand, H-piles in clay, pipe piles in sand, and pipe piles in clay. Sufficient information is available to predict the capacity of a pile based on all static and dynamic methods considered. Static load tests were not conducted on any of the piles.

Based upon the results of the analyses run on these three databases, it was determined that the following methods were the most useful. This determination is based both in terms of actual accuracy and precision and in terms of agreement between static and dynamic methods. The IDOT Static, K-IDOT, and ICP methods are the most promising static methods, while the FHWA-Gates, FHWA-UI, and WSDOT formulae are the most promising dynamic methods. To further refine these results, correction factors were applied to each static method. These correction factors are based on pile type and soil type, and are unique to each method. The proposed corrections are presented in Chapter 6.

Analyses of the agreement between static and dynamic methods were conducted based upon the corrected static method capacities. The WSDOT, FHWA-UI, and the FHWA-Gates formula are all possible recommendations for use as dynamic formula by IDOT. The FHWA-UI method exhibits the smallest COV, and therefore is the most precise of the methods investigated. However, this method was developed using the same load test data that was used to determine the statistics. Accordingly, the method may not exhibit the same degree of precision for a different database. Indeed this is the case. When the FHWA-UI formula was applied to the data in the Comprehensive Database, the WSDOT and FHWA-Gates formulae predicted capacities with greater precision than the FHWA-UI method. The WSDOT dynamic formula performed well for both databases that included static load tests. Therefore, the WSDOT method is moderately preferred over the FHWA-UI and the FHWA-Gates formulae. Recommendations for the resistance factors for use with the WSDOT dynamic formula are as follows: WSDOT - for a target reliability index = 2.33, resistance factor = 0.55.

Methods to predict the static capacity are not as precise as the dynamic formulae discussed above. The most precise static method determined in this study is a modification of the current IDOT static method, called the corrected K-IDOT. The corrected K-IDOT method requires two calculations of static pile capacity, one capacity is calculated as if the soil/pile failure occurs at the contact between the soil and pile, and end bearing is developed only for the steel area. A second capacity is calculated as if failure occurs along an enclosed box around the pile perimeter, and end bearing is developed for the whole enclosed area. The smaller of the two capacities is used. The “corrected” term refers to adjustments made to the method to improve its agreement with dynamic formulae, but these correction factors also show an improvement for predicting static capacity. If the corrected K-IDOT method is used to predict static capacity, the following resistance factor is recommended: for a target reliability index = 2.33, resistance factor = 0.40.

Agreement between capacities predicted with the WSDOT formula and capacities estimated with the corrected K-IDOT method are quantified as the ratio of WSDOT capacity/Corrected K-IDOT capacity. The statistics for this ratio are a mean of 1.11 and a COV of 0.49 (refer to Table 6.3). Figure 6.6 provides a cumulative distribution for the ratio. This cumulative distribution can be used to control the likelihood that piles may be driven to depths greater than estimated. For example, if pile lengths are estimated using the corrected K-IDOT method, and driven with the WSDOT method, then the chance is 50% that driven lengths will be greater than estimated. On the other hand, if the engineer desires a 20% chance that piles will be driven to depths greater than estimated, then the pile’s static capacity should be estimated as (1/0.7), 1.42 times the dynamic capacity.

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APPENDIX A – DEFINITION AND DESCRIPTION OF DYNAMIC AND STATIC METHODS

A.1. ADDITIONAL STATIC METHODS ANALYZED

In addition to those static methods discussed in Chapter 2; Olson's method, Driven, and the Imperial College Pile (ICP) method were also used to estimate pile capacity. While these results were considered in subsequent analyses and in making final recommendations, it was decided that the methods were not promising with regard to improving dynamic/static agreement and are not included in the report itself. For thoroughness, the theory behind Olson's method, Driven, and the ICP method, as well as how they are used to predict pile capacity, is presented in the following.

A.1.1 Olson's Method

Olson's method is based on SPT N-values for coarse-grained soils, and s_u values for fine-grained soils. It was developed using load tests on close-ended pipe piles. The general form of the equation is:

$$Q_u = q_p A_p + f_s A_{sa} \tag{A.1}$$

where Q_u = ultimate pile capacity, q_p = nominal unit end bearing resistance, A_p = area of pile tip, f_s = ultimate skin resistance per unit area of pile shaft segment, and A_{sa} = surface area of pile.

For coarse-grained soils, unit side resistance is determined using:

$$f_s = \sigma'_v K \tan\delta \le f_{s\lim} \tag{A.2}$$

where fs = unit side resistance, σ'_v = vertical effective stress, K = horizontal earth pressure coefficient, tan δ = tangent of pile-soil interface friction angle, and $f_{s\ lim}$ = limiting side resistance. For this study, K = 0.8. δ and $f_{s\ lim}$ are determined based on N_{spt}. Unit end bearing capacity is determined using:

$$q_p = \sigma'_v N_q \le q_{p\lim} \tag{A.3}$$

where q_p = unit end bearing pressure, σ'_v = vertical effective stress, N_q = end bearing capacity factor, and $q_{p\ lim}$ = limiting end bearing pressure. N_q and $q_{p\ lim}$ are determined from N_{spt}.

For fine-grained soils, unit side resistance is determined using:

$$f_s = \alpha s_u \tag{A.4}$$

where f_s = unit side resistance, s_u = average undrained shear strength of the soil along the side of the pile, and α = factor based on s_u. Unit end bearing pressure is determined using:

$$q_p = 9 s_u \tag{A.5}$$

where q_p = unit end bearing pressure and s_u = average undrained shear strength of the soil along the side of the pile.

Values for Olson's granular soil parameters are shown in Figure A-1. For fine-grained soils, α-values can be determined based on Figure A-2.

A.1.2 DRIVEN

Driven is a computer program available through the FHWA. The user inputs a soil profile along with soil properties such as unit weight, friction angle, and undrained shear strength. The pile geometry is also input. Based on these user inputs, Driven estimates the capacity of the pile.

The capacity of a pile in Driven is computed as the sum of the base and side capacities. The base capacity of a pile is estimated based on whether the soil is a sand or clay. If a soil is cohesionless, Driven determines the base capacity using the following formula, after Thurman (1964):

$$Q_b = A_p \sigma_{vo}' \alpha N_q' \quad \text{(A.6)}$$

Where A_p is the area of the base of the pile, σ_{vo}' is the effective vertical stress at the tip of the pile, α is a correction factor based on ϕ and the depth/width ratio of the pile (see Figure A-3), and N_q' is a bearing capacity factor based on ϕ (Figure A-3). There is a maximum value for the unit base resistance which is based on Meyerhof's (1976) recommendations (Figure A-4).

If the tip of the pile bears on a cohesive layer, the base capacity is determined as:

$$Q_b = 9s_u{*}A_p \quad \text{(A.7)}$$

Where s_u is the undrained shear strength of the soil at the pile tip. When H-piles are analyzed, no attempt is made to determine whether the pile is plugged or unplugged. Instead, the conservative approach of using the cross-sectional steel area of the pile is used when determining A_p.

The side capacity of a pile is determined on a layer-by-layer basis, and different formulae are used depending on whether the layer is cohesive or cohesionless. For a cohesionless soil, Driven uses a formula based on Nordlund (1963, 1979). The unit side capacity of the pile is determined by:

$$f_s = K_\delta C_f \, \sigma_{vo}' \sin(\delta) \quad \text{(A.8)}$$

Where δ is the pile-soil interface friction angle, K_δ is the coefficient of lateral earth pressure against the pile, determined as a function of pile size and ϕ (Figure A-5); and C_f is a correction to K_δ when $\phi \neq \delta$ (Figures A-6, A-7). The total side capacity is then determined by integrating f_s along the surface area of the pile.

When determining the surface area of an H-pile, in both cohesive and cohesionless soils, the conservative approach of using the boxed area of the pile is used. There is no maximum value of skin friction applied when computing pile capacity. Thus, at large values of ϕ, the unit side capacity becomes unreasonably large. A maximum value of ϕ =36° is used in this study. This is based on the Driven recommendation that values of ϕ greater than 36° not be used (although it will allow the use of values of ϕ which are greater).

When a cohesive layer is being considered, the unit side resistance is determined using Tomlinson's (1980) α-Method in which

$$f_s = \alpha{*}s_u \quad \text{(A.9)}$$

Where α is an empirical adhesion coefficient (Figure A-8).

A.1.3 ICP METHOD

A.1.3.1 Development

The ICP Method is based on ICP Design Methods for Driven Piles in Sands and Clays (Jardine et al., 2005). This document is a synthesis of research done by Jardine and others, including Chow, Cowley, and Lehane (list not all-inclusive).

Jardine and his colleagues conducted five main phases of research in the development of the method, which consisted of the following:

- Static axial load tests were conducted on heavily-instrumented closed-end pipe pile tests at Canons Park, England. The soil at the site consisted of stiff to very stiff, high plasticity clay. The results of the tests were published by Bond (1989) and Bond and Jardine (1990, 1991).
- Static axial load tests were conducted on heavily-instrumented closed-end pipe pile tests at Labenne (France), Cowden (England), and Bothkennar (England). The soils at these sites were sand, stiff till, and soft clay, respectively. The results of the tests were published by Lehane et al (1993), Lehane and Jardine (1994a,b,c), and Lehane et al (1994).
- Static axial load tests were conducted on instrumented open-ended pipe piles at Pentre, England and Dunkirk, France. The soil at the sites consisted of clay-silts/laminated clays and sand, respectively. The results of the tests were published by Chow (1997) and Chow and Jardine (1996).
- Static axial load tests were conducted on eight full-size open-ended pipe piles at Dunkirk in 1998 and 1999. The results of the tests were published by Jardine and Standing (2000).
- Research for several smaller projects was carried out at Imperial College between 1997 and 2003. A non-comprehensive list includes research into the effect of pile shape by Cowley (1998), research into the soil-pile interface friction angle, and research on different soil conditions by Chow (1997).

A.1.3.2 THEORY

In the ICP Method, the total capacity of a pile, Q, is the sum of the shaft and base capacities.

$$Q = Q_s + Q_b \qquad (A.10)$$

Piles, especially those in clays, can develop larger capacities with time. This increase can sometimes be substantial and take place over an extended period of time. The pile capacity determined using the ICP Method is the expected capacity ten days after the end-of-driving.

A.1.3.2.1 Base capacity of pipe piles in sand

The base capacity of a pile is determined based on soil type. If the pile bears in a sand layer, one set of equations is used. If the pile bears in clay, a different set of equations is used.

In sand, the base capacity of a closed-end pipe pile is the product of the unit end-bearing capacity and the area of the pile.

$$Q_b = q_b A_p \text{ for closed-end pipe piles} \qquad (A.11)$$

The area of the pile is the area of steel at the base of the pile. The unit end-bearing capacity is a function of the CPT tip resistance, q_c, and the diameter of the pile.

$$q_b = q_c[1-0.5\log(D/D_{CPT})] \geq 0.3q_c \text{ for closed-end pipe piles} \quad (A.12)$$

Where D is the diameter of the pile and D_{CPT} is the diameter of the CPT cone, which is 1.4 inches, and q_c is averaged 1.5 diameters above and below the pile tip. The second term in the equation takes into account the effect on capacity due to pile diameter. A lower bound of $q_b = 0.3q_c$ is recommended. This lower limit controls at a pile diameter of about three feet and greater.

When determining the base capacity of an open-ended pipe pile, an attempt is made to determine if a soil plug has formed at the tip of the pile. If both of the following equations are satisfied, the pile is considered to be fully plugged.

$$\text{if } D_{inner}/39.37 < 0.02(D_r - 30), \text{ and} \quad (A.13)$$

$$\text{if } D_{inner}/ D_{CPT} < 0.083q_c/P_a \text{, then the pile is plugged} \quad (A.14)$$

Where D_{inner} is the pile diameter in inches, D_r is the relative density of the sand, and P_a is atmospheric pressure. These criteria are based on the theory that, especially at smaller pile diameters, stress arching can occur, creating a soil plug. As the inner pile diameter increases, these criteria are less likely to be satisfied and the pile will tend to be unplugged.

If Equations (A.13) and (A.14) are satisfied, the pile is considered to be plugged, and it will develop half of the capacity that a closed-end pipe of the same diameter would develop. So, the base capacity becomes

$$Q_b = 0.5*q_b*A_p \text{ for plugged open-ended pipe piles} \quad (A.15)$$

Where q_b is the same as for closed-end pipe piles [Eqn. (A.12)] and A_p is the total base area of the pile. If Equations (A.13) and (A.14) are not both satisfied, the pile is considered to be unplugged. The base capacity is then determined as

$$Q_b = q_cA_s \text{ for unplugged open-ended piles} \quad (A.16)$$

Where A_s is the cross-sectional area of steel of the pile and q_c is the average of the CPT tip resistance measured 1.5 pile diameters above and below the pile tip. This formula does not account for frictional resistance developed on the inside of the pipe pile, and there is no attempt to directly calculate this internal frictional resistance. Instead, Jardine et al. (2005) postulate that the unit end-bearing resistance is less than q_c, and using the value of q_c approximately accounts for the internal frictional resistance.

A.1.3.2.2 Base capacity of pipe piles in clay

For piles bearing in clay, the base capacity is determined in a similar manner to those bearing in sand, with modifications to q_c based on whether the pile is subjected to drained or undrained loading.

For a closed-end pipe pile, the base capacity is

$$Q_b = q_bA_p \text{ for closed-end pipe piles} \quad (A.17)$$

Where $q_b = 0.8q_c$ for undrained loading and $q_b = 1.3q_c$ for drained loading. As with the base capacity in sand, q_c is averaged 1.5 pile diameters above and below the pile tip.

For open-ended piles, a distinction is made between plugged and unplugged piles. If the following empirical equation is satisfied, the pile is considered plugged.

$$D_{inner}/ D_{CPT} + 0.45q_c/P_a < 36 \tag{A.18}$$

If the pile is determined to be fully plugged, the base capacity is determined by

$$Q_b = q_b A_p \text{ for fully plugged open-ended pipe piles} \tag{A.19}$$

Where A_p is the total cross-sectional area at the pile base and $q_b = 0.4q_c$ for undrained loading and $q_b = 0.65q_c$ for drained loading. This is similar to plugged open-ended piles in sand in that the base capacity developed is half the base capacity for a closed-end pipe of the same dimensions. If the pipe is determined to be unplugged, then the base capacity is determined as follows

$$Q_b = q_b A_s \text{ for unplugged open-ended pipe piles} \tag{A.20}$$

Where A_s is the area of steel for the pile tip and $q_b = q_c$ for undrained loading and $q_b = 1.6q_c$ for drained loading. The contribution to pile resistance from internal frictional (side) resistance is implicitly included in the end-bearing estimate of capacity.

A.1.3.2.3 Shaft capacity in sand

The shear strength that develops along the shaft of a pile is determined using the Coulomb equation

$$\tau = \sigma'\tan\phi' \tag{A.21}$$

Where τ is the shear strength (equivalent to unit side resistance) developed, σ' is the effective stress acting on the pile, and ϕ' is the effective stress friction angle (the pile-soil interface friction angle). Determining the unit side resistance of the pile is a matter of determining the stress regime around the pile and the pile-soil interface friction angle. The following is only technically applicable to closed-end pipes.

The following does not technically apply to open-ended pipe piles for two reasons. First, the following discussion does not consider the development of internal frictional resistance. However, recall that when determining the base capacity of an open-ended pipe pile, any internal frictional resistance is implicitly accounted for. The other reason the following discussion does not strictly apply to open-ended pipe piles is the difference in displacement between open- and closed-end pipe piles. This can be addressed by applying a correction to the radius of an open-ended pipe pile, which is discussed later in this section.

When analyzing the shaft capacity of a pile using any static method, the soil along the pile shaft is typically divided into layers based on soil stratigraphy. Jardine et al.'s recommendation is that even for relatively uniform soil profiles, the soil along the pile shaft should be divided into at least 15 layers. The primary reason for this is that Jardine et al. found the unit shaft capacity to be very dependent on the relative tip depth (to be discussed later in this section), so more accurate results can be determined by evaluating frictional capacity at several relative tip depths.

Jardine et al. recommend determining the pile-soil interface friction angle, δ_{cv}, using site-specific soil. Their recommendation is to determine δ_{cv} by testing a soil sample and pile material in either a direct shear or ring shear test. The authors recognize this method is not always feasible or cost-effective. In the absence of site-specific tests, Jardine et al.

recommend a correlation based on the mean particle size, D_{50} (Figure A.9). If this information is also not available, the observed data trend toward $\delta_{cv} = 29°$, and this value is recommended.

The effective stress regime along the pile is considered to consist of two components: the local radial effective stress, σ_{rc}', and the dilatant increase in local radial effective stress during pile loading, $\Delta\sigma_{rd}'$.

$\Delta\sigma_{rd}'$ consists of the stress developed by displacement of individual sand grains and their initial dilatant response to this displacement. $\Delta\sigma_{rd}'$ is determined as follows

$$\Delta\sigma_{rd}' = 2G\Delta r/R \qquad \text{(A.22)}$$

Where G is the shear modulus of the soil, Δr is a measure of the microscopic roughness of the pile, and R is the radius of the pile.

The shear modulus, G, of a material relates its shear stress to shear strain as follows

$$G = \tau/\varepsilon \qquad \text{(A.23)}$$

G is similar to the modulus of elasticity, E, of a material, except when determining G the material is tested in shear, rather than pure tension or compression. G can be estimated for a soil based on q_c and σ_{vo}' using the following empirical equation

$$G = q_c / (A + B\eta - C\eta^2) \qquad \text{(A.24)}$$

Where A = 0.0203, B = 0.00125 and C = 1.216×10^{-6}, η is determined as

$$\eta = q_c / (P_a\sigma_{vo}')^{0.5} \qquad \text{(A.25)}$$

Where P_a is atmospheric pressure (approximately 2117 psf). Equations (A.24) and (A.25) are based on the work of Chow (1997) and Baldi et al (1989) respectively.

Δr is a measure of the roughness of a pile. Once movement of a magnitude Δr has occurred, sand grains are displaced and the sand exhibits dilatant behavior. For steel piles, Jardine et al. specify 6.56×10^{-5} ft as a reasonable value of Δr.

$\Delta\sigma_{rd}'$ is inversely proportional to the radius of the pile. As the radius of a pile decreases, the influence of $\Delta\sigma_{rd}'$ increases.

The other component of effective stress on a pile is the local radial effective stress, σ_{rc}'. The local radial effective stress is determined by

$$\sigma_{rc}' = [0.029q_c(\sigma_{vo}'/P_a)^{0.13}] / (h/R)^{0.38} \qquad \text{(A.26)}$$

The term h/R is the relative tip depth of the soil layer being analyzed. The tip depth, h, is the distance from the soil layer of interest to the tip of the pile (Figure A.10). The tip depth is divided by the pile radius, R, to normalize h with respect to different pile diameters.

The research that resulted in the development of the ICP Method indicated that very high radial stresses develop in the soil directly adjacent to the pile tip during driving. As the pile tip is driven further into the ground past the soil (and h increases), the high radial stresses decay rapidly. Jardine et al. speculate that there are several reasons for this decrease in radial stress with increasing relative tip depth. Two main reasons may be the effect of the cyclic loading the soil is subjected to during pile driving and stress arching around the pile tip.

The influence of h/R in Equation (A.26) is that, all other parameters being equal, a long pile results in a large relative tip depth and results in a lower σ_{rc}' near the ground surface than for a shorter, but otherwise identical pile.

Another important aspect of h is that it approaches zero as the pile tip is approached. As a result the term $(h/R)^{0.38}$ approaches zero, and the value of σ_{rc}' approaches infinity (and thus, results in an infinite pile capacity). Based on their studies, Jardine et al. recommend a minimum value of h/R = 8 when computing σ_{rc}'.

Once the effective stress regime and pile-soil friction angle have been determined, the unit frictional resistance of the shaft, f_s, can be determined as

$$f_s = (\sigma_{rc}' + \Delta\sigma_{rd}')\tan\delta_{cv} \quad \text{(A.27)}$$

Once f_s has been determined for a given layer, the shaft capacity of the layer, Q_i, can be determined by

$$Q_i = f_s(2\pi r)z \quad \text{(A.28)}$$

Where $2\pi r$ is the perimeter of the pile and z is the thickness of the layer. Total shaft capacity, Q_s, is then determined by summing the individual Q_i's.

The above discussion on the shaft capacity of a pile in sand is technically only applicable to closed-end pipe piles. However, the same method can be applied to open-ended pipe piles with only one adjustment. When determining the effective radial stress of a closed-end pipe pile at a given depth, the term h/R is used, where R is the radius of the pile. For an open-ended pipe pile, the term R* is substituted in place of R, and

$$R^* = (R_{outer}^2 - R_{inner}^2)^{0.5} \text{ for an open-ended pipe} \quad \text{(A.29)}$$

Where R_{outer} is the outer radius of the pile and R_{inner} is the inner radius of the pile. The result of this is that R* for an open-ended pipe pile of a given outer diameter is smaller than R for a closed-end pipe pile with the same outer diameter. This correction is made because Jardine et al.'s research indicates that σ_{rc}' reduces more rapidly with relative tip depth for an open-ended pipe pile. Because R* < R, the effective radial stress is reduced.

In summary, for an open-ended pipe pile, when calculating σ_{rc}', replace R with R*, then compute the shaft capacity as you would for a closed-end pipe pile. The same minimum value of h/R* = 8 is recommended.

A.1.3.2.4 Shaft capacity in clay

There are several different methods for determining the static capacity of a pile in clay. One of the more common methods is the α-method, such as Tomlinson (1957) proposed. In this method, the unit shaft resistance is based on the undrained shear strength of the clay, s_u. The undrained shear strength is multiplied by a correction factor, α, which is based on s_u, where α decreases with increasing s_u, and the unit shaft resistance, q_s, is determined by

$$q_s = \alpha\, s_u \quad \text{(A.30)}$$

Where values of α are based on empirical data. Jardine et al. argue against this method for two reasons. First, they argue that pile driving significantly reworks the soil next to a pile. As a result the shear strength of the soil is modified. They argue that because of this, the s_u used to determine an α-value and a unit shaft resistance is not an accurate reflection of the soil conditions immediately surrounding the pile. Their other argument against an α-method is that

s_u is very dependent on the sampling and testing methods used. The sampling method can cause significant disturbance to a soil sample and reduce its undrained shear strength. Also, due to factors such as soil anisotropy, the s_u determined in a direct shear test will be different than that determined in a triaxial test. This makes it difficult to determine the proper value of s_u for calculating pile capacity.

Instead of an α-method, Jardine et al. recommend a procedure similar to their procedure for determining the shaft capacity of a pile in sand. It is also based on the Coulomb equation

$$\tau = \sigma' \tan\phi' \tag{A.31}$$

Jardine et al. recommend a different set of parameters to determine the shaft capacity. Equation (A.31), when applied to clays becomes

$$f_s = \sigma_{rf}' \tan\delta_f = (K_f / K_c)\sigma_{rc}' \tan\delta_f \tag{A.32}$$

Where in the subscripts, r denotes radial, f denotes failure, and c denotes consolidated.

Jardine et al. recommend that the pile-soil interface friction angle be determined using ring shear tests. However, recognizing that this is not always practical, they present two graphs that correlate δ with the plasticity index (PI) of a clay (Figures A.11 and A.12). Two important things should be noted about these graphs. Firstly, there is a significant amount of scatter in the data. Secondly, there is a graph for the peak and ultimate interface friction angle.

The appropriate graph to use depends on properties such as pile length and stiffness. A short rigid pile is more likely to develop a peak-δ along its length. However, with longer piles it is possible that the upper section of the pile will have reached its ultimate δ-value while lower portions of the pile are still mobilizing resistance. The potential for progressive failure in this case can be assessed with the use of t-z curves or a finite element analysis. However, it is possible that the degree of uncertainty in soil properties makes the analytical effort required for these methods impractical. In such cases, the most conservative approach is to assume a peak δ-value for δ_f.

The radial effective stress after consolidation, σ_{rc}', is determined by

$$\sigma_{rc}' = K_c \, \sigma_{vo}' \tag{A.33}$$

Where σ_{vo}' is the original effective vertical stress and K_c is a factor that relates vertical effective stress to radial stress and accounts for the effects of displacements due to pile driving. K_c is determined by

$$K_c = [2.2 + 0.016(OCR) - 0.870\log(S_t)]OCR^{0.42} / (h/R)^{0.20} \tag{A.34}$$

Where OCR is the overconsolidation ratio of the clay, S_t is the sensitivity of the clay and h/R is the relative tip depth. Equations (A.33) and (A.34) are based on the work of Lehane (1992) and Chow (1997) and were determined based on data from the ICP research program.

h/R is the same as for the shaft capacity in sand. A minimum value of h/R = 8 is recommended. Also, as before, this is only strictly applicable to closed-end pipe piles. For open-ended pipe piles, R* (Eqn. A.29) should be used in place of R.

The OCR of a clay is determined by

$$OCR = \sigma_p'/\sigma_{vo}' \tag{A.35}$$

Where σ_p' is the preconsolidation pressure of a clay, which is the highest effective stress to which the soil has been subjected in its history. A clay can become overconsolidated through mechanisms such as loading due to glacial ice or fluctuations in the groundwater table. Typically, in an oedometer test on a clay, a graph of e vs. log-σ_{vo}' is plotted and σ_p' is approximately located at the "break point" of the curve. However, if an oedometer test is not run on the clay, OCR can be correlated to s_u/σ_{vo}' (Figure A-13).

The other parameter on which K_c is dependent is the clay's sensitivity, S_t. Sensitivity is the ratio of the undisturbed undrained shear strength of a soil to the remolded undrained shear strength of the soil. The typical sensitivity for a glacial till is around unity.

The final term in Equation (A.32), K_f / K_c, is a loading factor. σ_{rc}' has been determined in terms of drained conditions. When a pile is loaded, there can be increases in porewater pressures that change the effective stress regime. Jardine et al. determined that σ_{rf}' is typically equal to about 0.8σ_{rc}'. As a result, K_f / K_c is equal to 0.8 to account for the changes in effective stresses during loading.

Once the unit shaft capacity, f_s, has been determined for as many layers as is necessary to account for changes in effective stress, h/R, and other factors; the total shaft capacity can be determined. As with the shaft capacity in sand, the shaft resistance for any given soil layer, Q_i, can be determined using Equation (A.28). The total shaft capacity is then equal to the summation of Q_i over the length of the shaft.

A.1.3.3 Capacity of H-Piles

So far, the procedure for determining both shaft and base capacities of open- and closed- end piles in sand and clay has been discussed. However, it is also common to use H-Piles for deep foundations. To apply the ICP Method, empirical corrections for pile geometry are applied. These corrections are based on the work of Cowley (1998). Cowley assembled a small database of 16 reliable load tests on H-Piles in both sand and clay and focused on corrections that are as simple as possible and which are equally applicable to both sands and clays.

A.1.3.3.1 Shaft capacity of H-Piles

Two corrections to the ICP Method are required for H-Piles. The first addresses what value should be used as the perimeter of the pile when determining its surface area. Cowley recommends that the "boxed" perimeter of the pile, 2*(Depth of Pile + Width of Pile), be used instead of the "unboxed" pile perimeter.

The second correction concerns the value of R to be used when determining the relative tip depth of a given layer. Cowley recommends

$$R^* = (A_b/\pi)^{0.5} \qquad \text{(A.36)}$$

This is the equation for finding the radius of a circle, and in this case the area, A_b, is defined as

$$A_b = A_s + 2X_p(D-2T) \qquad \text{(A.37)}$$

This equation is after De Beer et al. (1979) and A_s is the cross-sectional area of steel, D is the depth of the pile section and T is the flange thickness. X_p is defined as

$$X_p = B/8 \quad \text{if } B/2 < (D-2T) < B \qquad \text{(A.38)}$$

$$X_p = B^2 / [16(D-2T)] \quad \text{if } (D-2T) \geq B \qquad \text{(A.39)}$$

Where B is the flange width and D and T are as defined above. It should be noted that Equation (A.38) applies to all H-pile sections listed in AISC (1989). After these two corrections are applied, the shaft capacity is determined exactly as it would be for a pile of circular cross-section. These two corrections apply to piles in both sand and clay.

A.1.3.3.2 Base Capacity of H-Piles

When determining the base capacity of an H-Pile, it is assumed that the unit base resistance, q_b, is equal to the CPT tip resistance, q_c. The area of the base, A_b, is as determined in Equation (A-37). The base capacity of the pile is then

$$Q_b = q_c A_b \qquad \text{(A.40)}$$

This is applicable to H-Piles in both sand and clay.

A.1.3.4 Final Comments

In the previous sections, the ICP Method for determining the total capacity of a pile has been outlined. The total capacity is broken into two components, that of the base and that of the pile shaft. Depending on whether the soil type is sand or clay, a different set of calculations is applied. Many piles are driven through a soil profile that contains both sands and clays. In this case, the method for clays is applied to clay layers and the method for sands is applied to sand layers. Both methods can be used on the same pile.

A.1.4 DEVELOPMENT OF THE ICP METHOD SPREADSHEET

When applying the ICP Method to determine the capacity of a pile, there are two issues which soon become apparent. The first is that the ICP Method is fairly simple, but it requires several calculations and is thus more suitable for spreadsheets than hand solutions. The other is that the method calls for the use of soil parameters that are not usually determined for routine geotechnical projects, typically for economic reasons.

The first issue can be addressed by automating the ICP Method in a spreadsheet. By doing this, the method requires similar amounts of inputs and application of engineering judgment as is required when performing an analysis with the current IDOT Static Method. The second issue is addressed through correlations to soil properties that are routinely measured during soil explorations. Some of these correlations are published in Jardine et al. (2005) with the caveat that capacity predictions may not be as accurate as if the property itself were measured.

A.1.4.1 Input Page

The ICP Method Spreadsheet developed for use in this report consists of four workbooks, the first one being the Data Input worksheet. In this worksheet, all of the data necessary to compute pile capacity is entered. This includes data on the pile size and the soil stratigraphy. The shaft capacity, base capacity, and total capacity for the pile are also returned on this page. Gray cells require user input, while white cells perform calculations based on user inputs. This spreadsheet is similar in concept to the existing IDOT Static spreadsheet.

The first inputs are the pile size and length. At the top of this page is a list of the different pile types. If the pile is a closed-end pipe (CEP) or open-ended pipe (OEP), additional input on pile size is required. If the pile is an H-Pile, all of the relevant dimensions are automatically assigned using the Lookup Values worksheet. The other pile information input is pile length. It is important to note which units should be used when inputting values.

The other data inputs deal with information on the soil profile, with the exception of two cells. The first of these two cells is the average SPT N-value of the soil 1.5 diameters above and below the pile tip. This value is required to determine the base capacity of the pile, and is a separate input from the SPT N-value of the bearing layer, as the two values are not necessarily the same. The other value is the depth to the groundwater table. This value is required to determine the effective stresses in the ground.

The other inputs define the soil profile. The spreadsheet has space for 50 distinct soil layers. This is considered to be many more layers than necessary to define the soil profile. 50 layers was chosen arbitrarily so that there should never be an issue where it is not possible to input enough soil layers to define the soil profile. For any given soil layer, the following three pieces of information must be input:

1) the thickness of the soil layer
2) the soil type
3) the average N-SPT value of the soil layer

There is a list of soil types to the right of the list of pile types. One of these soil types must be input, any other input will yield an error. If the soil type is "clay," three additional inputs are required. These are the undrained shear strength, s_u, the clay sensitivity, and the pile-soil interface friction angle at failure, δ_f. The latter two values are not determined in typical subsurface explorations. Based on the geology of Illinois, it has been assumed that the clays encountered are glacial tills. Typically, the sensitivity of a glacial till is approximately unity, and Sensitivity = 1 is recommended in the absence of any other information. Jardine et al. recommend determining δ_f based on ring shear tests. To be conservative, it is recommended that estimates of δ_f be based on the ultimate interface friction angle (Figure A-12) rather than the peak interface friction angle (Figure A-11). δ_f decreases with increasing plasticity index (PI) of the clay. Often, the only indication of a clay's PI is whether it is classified as high-plasticity (CH) or low-plasticity (CL) using the Unified Soil Classification System (USCS). Based loosely on Casagrande's plasticity chart, a CH soil was considered to have a PI of 25%, while a CL soil was considered to have a PI of 15% for the purposes of analyses in this report.

The other cells in the worksheet return values based on other inputs. "Depth to Top of Layer" and "Depth to Bottom of Layer" are the depth to the top and bottom of a given layer, respectively. "N1 60" is the N-value of a layer corrected for overburden pressure. This value is used to estimate the unit weight of a soil based on recommendations in the FHWA Driven Pile Manual (FHWA, 1998) as shown in Figure A-13. If the actual unit weight of a soil is known, it can be input into the "Unit Weight" column. Using the actual unit weight, if it is known, would be more accurate, but the error associated with correlating the unit weight is relatively small. "qc" is the estimated CPT tip resistance of the soil layer. The ICP method uses q_c to determine pile capacity. CPT tests are not always performed in subsurface investigations. Instead, based on N and the soil type, q_c is determined based on a correlation published by Burland and Burbidge (1985) (Figure A-14). Eight load tests in this study include information on SPT and CPT tests. By performing a Jardine analysis based on both CPT and SPT values, it was determined that the error associated with using the Burland and Burbidge correlation is negligible. In the ICP Method, R* is a modification to the pile radius required for open-ended and H-Piles. If the pile is a closed-end pipe, R* = R. In the upper right of the worksheet are the calculated shaft capacity, base capacity, and total capacity of the pile.

A.1.4.2 Lookup Values

This worksheet contains all the values that the spreadsheet looks up. Anytime the "vlookup( )" function is used in the spreadsheet, this is the sheet it refers to. The first lookup table is all of the dimensions for an H-Pile. Columns B through G are from the AISC manual.

X_p, A_b, and R* are determined based on empirical correlations recommended by Jardine et al. (2005).

The next table is for computing the unit weight of a soil based on $N_{1\,(60)}$. The relationships are based on those published in the FHWA Driven Pile Manual (Figure A-13). The unit weights are necessary to calculate the effective vertical stresses in any given soil layer.

The third table is used to calculate q_c based on N and the soil type. Burland and Burbidge (1985) published a correlation between q_c/N and D_{50} (Figure A-14). Information on D_{50} is not available in all subsurface investigations, but Burland and Burbidge also give a range of D_{50} for different soil types. The correlations in the table are based on those particle size ranges. The correlation was published in units of MPa, and the third column converts units from MPa to psf. There is also a column titled q_c/N correction. In the early stages of developing the Jardine Method Spreadsheet, the possibility of error associated with this correlation was considered. In the end, it was decided that no correction should be applied. The option to do so remains coded into the spreadsheet if future studies show it would be appropriate, but the default value of 1 should be kept unless further evidence suggests otherwise.

The final table is for calculating the relative density of a sand based on $N_{1\,(60)}$. This is only necessary when determining if an open-ended pipe pile's base is fully plugged. The correlation is published in the FHWA Driven Pile Manual (Figure A-14).

A.1.4.3 Side Capacity Calculations

This worksheet determines the capacity of a pile on a foot-by-foot basis, based on the data from the Data Input worksheet. Jardine et al. (2005) recommend any pile should be divided into at least 15 discrete layers because of the h/R term used in calculating side capacity. Since the spreadsheet can perform a large number of computations, it was decided the easiest way to cope with this requirement would be to calculate capacity at every one foot interval. The worksheet is arbitrarily set up to determine the capacity of a pile up to 500 feet long. This is considered much longer than is necessary, but the large number was chosen to avoid any problems where the pile was longer than the spreadsheet was set up to calculate.

<u>A.1.4.3.1 Midlayer σ_{vo}'</u>

This column calculates the effective vertical stress at the middle of each layer. This is based on the unit weights immediately to the left of this column as well as the groundwater table depth input in the Data Input worksheet.

<u>A.1.4.3.2 η and G</u>

These columns calculate the parameters necessary to determine the change in effective radial stress during loading. η is calculated using an empirical correlation developed by Chow (1997). It is a function of q_c and σ_{vo}'. G is the shear modulus of the soil, it is an empirical relationship developed by Baldi et al. (1989). G is a function of q_c and η.

<u>A.1.4.3.3 $\Delta\sigma_{rd}$'</u>

The change in effective radial stress during loading is a function of η and G. The unit side resistance is calculated based on the Coulomb equation. $\Delta\sigma_{rd}$' is one of the components of the effective stress in the Coulomb equation.

A.1.4.3.4 h/R*

h/R* is the effective tip depth. It is a measure of how far a given soil layer is from the tip of the pile, normalized with respect to the radius of the pile. It is one of the values necessary to calculate σ_{rc}'.

A.1.4.3.5 s_u, sensitivity, and δ_f

These parameters are exactly as entered in the Data Input worksheet. They are reproduced here for ease of setting up the equations to calculate σ_{rc}'.

A.1.4.3.6 OCR

OCR, the overconsolidation ratio, is calculated for every clay layer. OCR is calculated based on a correlation with s_u/σ_{vo}'. This correlation is calculated using an equation determined from Figure A-15. Near the ground surface, the low σ_{vo}' leads to a very large OCR. This was deemed unrealistic, and OCR is limited to a maximum value of 12.

A.1.4.3.7 σ_{rc}'

Depending on whether a soil layer is a sand or clay, σ_{rc}' is calculated based on different parameters. If the soil is a sand, σ_{rc}' is a function of q_c, σ_{vo}', and h/R*. If the soil is a clay, σ_{rc}' is a function of OCR, Sensitivity, h/R*, and σ_{vo}'.

A.1.4.3.8 f_s

As stated, f_s is based on the Coulomb equation. After σ_{rc}' and $\Delta\sigma_{rd}$' have been determined, along with the pile-soil interface friction angle, f_s is calculated.

A.1.4.3.9 Cumulative Q

Based on f_s and the surface area of the pile, Q is calculated for each layer. This column shows the cumulative capacity developed along the pile's length.

A.1.4.4 Tip Capacity Calculations

This final worksheet calculates the base capacity of the pile. The first six rows in the first column are copied directly from the Data Input worksheet. q_b is the unit base resistance of the pile. In cohesive soils it is a certain percent of q_c, depending on whether the loading is drained or undrained. The assumption of undrained loading gives the more conservative value, and it has been assumed in this spreadsheet. For a cohesionless soil, q_b is a function of q_c, and a scale effect based on pile diameter is also incorporated. As pile diameter increases, q_b is a smaller and smaller fraction of q_c. Cohesive base area is calculated for ease of setting up the base capacity equation, the normal formula for area is used.

On the right side of the worksheet, the criteria for an open-ended pipe pile being plugged or unplugged at its base are included. The criteria are slightly different depending on whether the bearing layer is cohesive or cohesionless. Note that for a cohesionless open-ended pile, both criteria must be satisfied for the pile to be considered plugged. Whether a pile is plugged or unplugged affects both q_b and the base area.

Once q_b and the proper base area have been determined, the bottom cell calculates the base capacity of the pile.

A.1.4.5 Final Comments

Although the ICP Method can be tedious in the number of calculations it requires, the process can be greatly simplified by using a spreadsheet. Using the ICP Method Spreadsheet, approximately the same amount of effort is required as for the IDOT Method. To determine a pile's capacity, input is only required in the Data Input worksheet. The pile capacity is also output in the Data Input worksheet. Extra commentary has been provided for the other worksheets to provide background into how the spreadsheet was made and the reasoning behind the setup of the spreadsheet.

A.2 ADDITIONAL DYNAMIC METHODS STUDIED

In addition to those dynamic methods discussed in Chapter 2, the EN-IDOT formula and WEAP were also used to estimate pile capacity. While these results were considered in subsequent analyses and in making final recommendations, it was decided that the methods were not promising with regard to improving dynamic/static agreement. For thoroughness, the theory behind the EN-IDOT formula and WEAP, as well as how they are used to predict pile capacity, is presented in the following.

A.2.1 IDOT-Modified Engineering News Formula (EN-IDOT)

The EN formula, developed by Wellington (1892) is expressed as:

$$Q_u = \frac{WH}{s+c} \tag{A.41}$$

Where Q_u = the ultimate static pile capacity, W = weight of hammer, H = drop of hammer, s = pile penetration for the last blow and c is a constant (with units of length). Specific values for c depend on the hammer type and may also depend upon the ratio of the weight of the pile to the weight of the hammer ram.

Before 2005, the Illinois Department of Transportation used the following to determine the allowable bearing capacity of a pile:

$$P = \frac{2WH}{s+c} \tag{A.42}$$

Where P = the allowable bearing capacity in kips, W = weight of the hammer in pounds, H = drop of the hammer in feet, s = pile penetration for the last blow and c = 0.1 inches for air/steam hammers.

There is a built-in factor of safety = 6 in the EN-IDOT formula, which means the EN-IDOT formula predicts an allowable capacity instead of an ultimate capacity. The reader should be aware that various forms of this equation exist and should inspect carefully the equation and units for the formula and the FS implicit in the formula.

A.2.2 WAVE EQUATION ANALYSIS

Wave equation analyses use the one-dimensional wave equation to estimate pile stresses and pile capacity during driving (Goble and Rausche, 1986). Isaacs (1931) first suggested that a one-dimensional wave equation analysis can model the hammer-pile-soil system more accurately than dynamic formulae based on Newtonian mechanics.

Wave equation analyses model the pile hammer, pile, and soil resistance as a discrete set of masses, springs, and viscous dashpots. A finite difference method is used to model the stress-wave through the hammer-pile-soil system. The basic wave equation is:

$$E_p \frac{\partial^2 u}{\partial x^2} - \frac{S_p}{A_p} f_s = \rho_b \frac{\partial^2 u}{\partial t^2} \tag{A.43}$$

Where E_p= modulus of elasticity of the pile, u = axial displacement of the pile, x = distance along axis of pile, S_p = pile circumference, A_p = pile area, f_s = frictional stress along the pile, ρ_b = unit density of the pile material, and t = time.

Wave equation analyses may be conducted before piles are driven to assess the behavior expected for the hammer-pile selection. Wave equation analyses provide a rational means to evaluate the effect of changes in pile properties or pile driving systems on pile driving behavior and driving stresses (FHWA, 1995). Furthermore, better estimates of pile capacity and pile behavior have been reported if the field measurement of energy delivered to the pile is used as a direct input into the analyses (FHWA, 1995).

Soil Type	Range in N Values	δ (deg)	f_{lim} (kPa)	N_q	q_{lim} (MPa)
Gravel	0-4	(20)	(70)	(12)	(3)
	5-10	(25)	(85)	(20)	(5)
	11-30	(30	(100)	(40)	(10)
	Over 30	(35)	(120)	(60)	(12.5)
Sand/gravel	0-4	(20)	(70)	(12)	(3)
	5-10	(25)	(85)	(20)	(5)
	11-30	(30	(100)	(40)	(10)
	Over 30	(35)	(120)	(60)	(12.5)
Sand	0-4	(20)	(50)	(50)	(2)
	5-10	30	55	120	6
	11-30	35	95	120	9.5
	31-50	40	130	120	9.5
	51-100	40	165	130	10
	Over 100	40	190	220	26.5
Sand/silt	0-4	10	(50)	(10)	(0.5)
	5-10	10	(50)	(20)	(2)
	11-30	15	(70)	50	5.5
	31-50	20	100	100	8
	51-100	(30)	(100)	(100)	(10)
	Over 100	(34)	(100)	(100)	(10)
Silt	0-4	(10)	(50)	(10)	(2)
	5-10	15	(50)	(10)	(2)
	11-30	20	(70)	(10)	(2)
	31-50	20	(70)	(12)	(3)
	Over 50	(25)	(70)	(12)	(3)
Numbers in parentheses were not used in the analyses.					

Figure A-1. Values used for Olson's method.

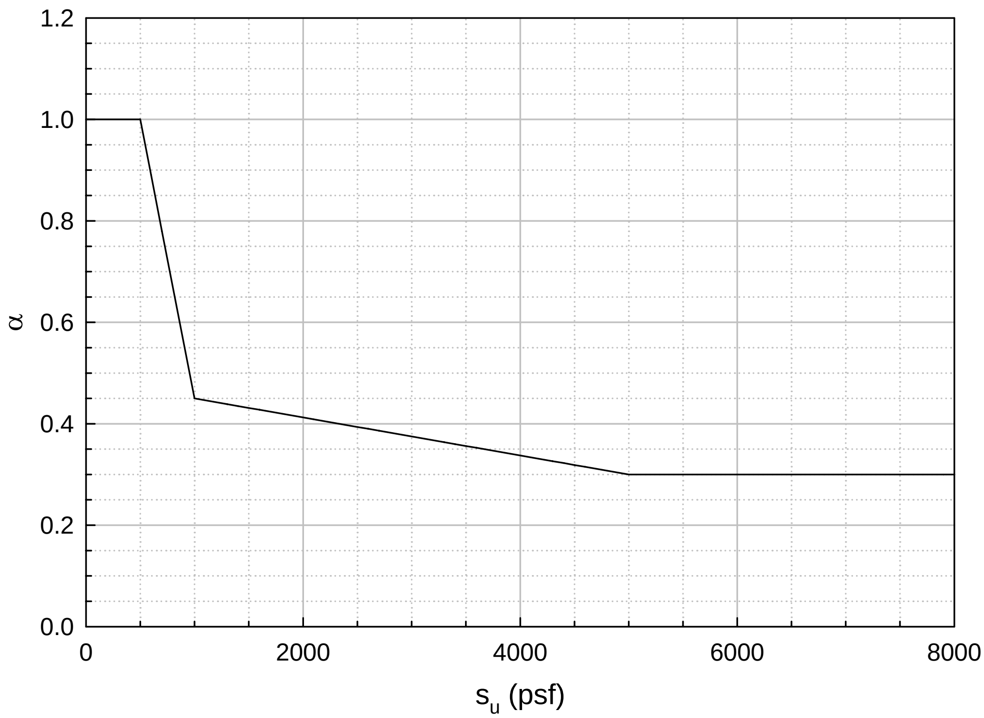
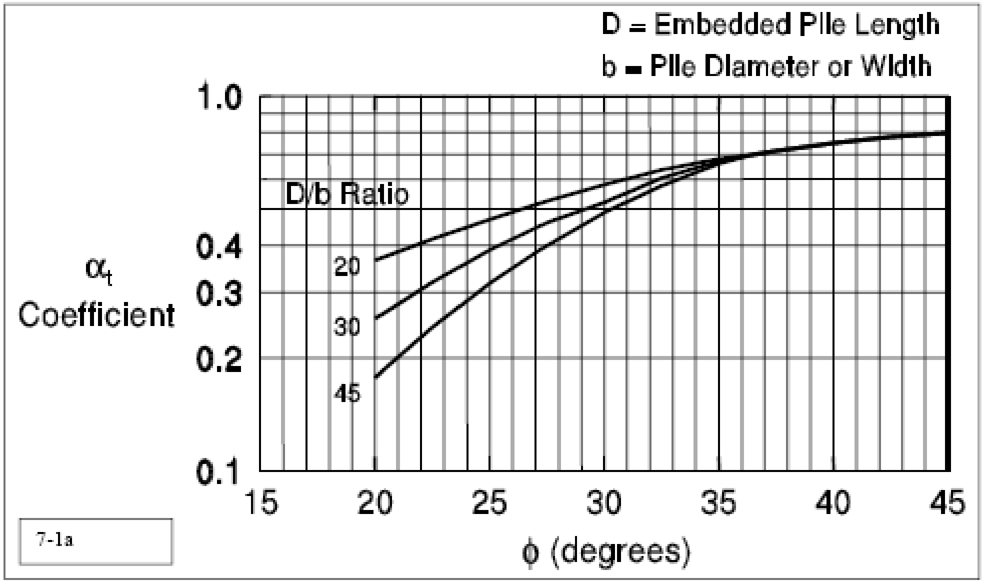


Figure A-2. Values of α for Olson's method.



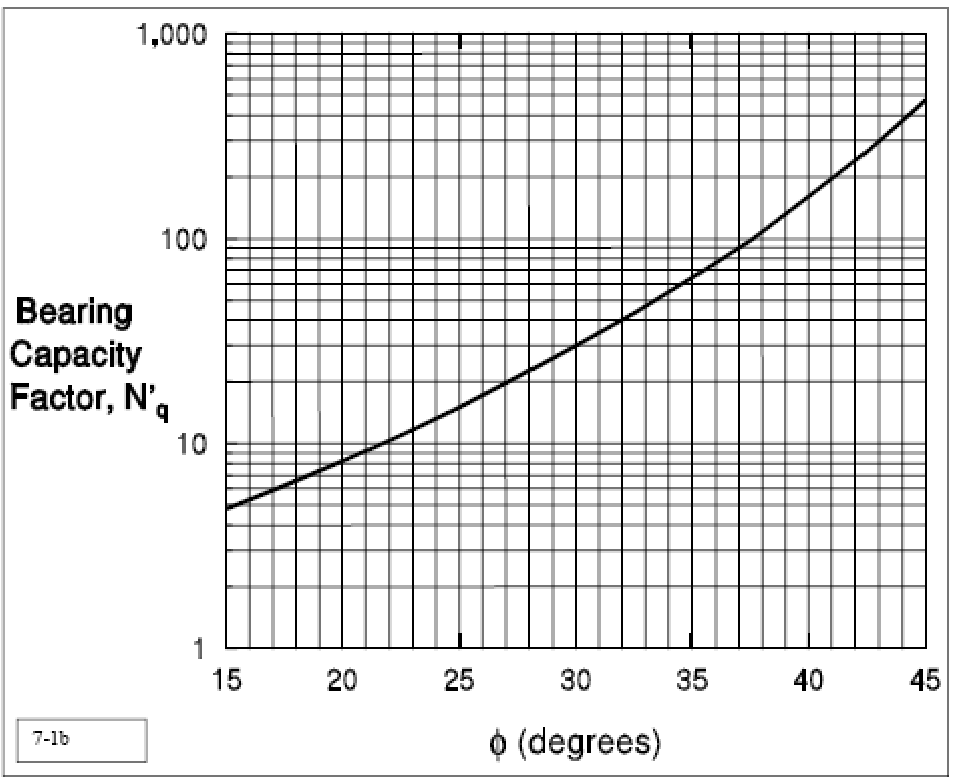


Figure 7-1. Chart for Estimating α_t Coefficient and Bearing Capacity Factor N'_q (Chart modified from Bowles, 1977).

Figure A-3. Charts for determining α_t and N_q' for Driven (Driven Manual).

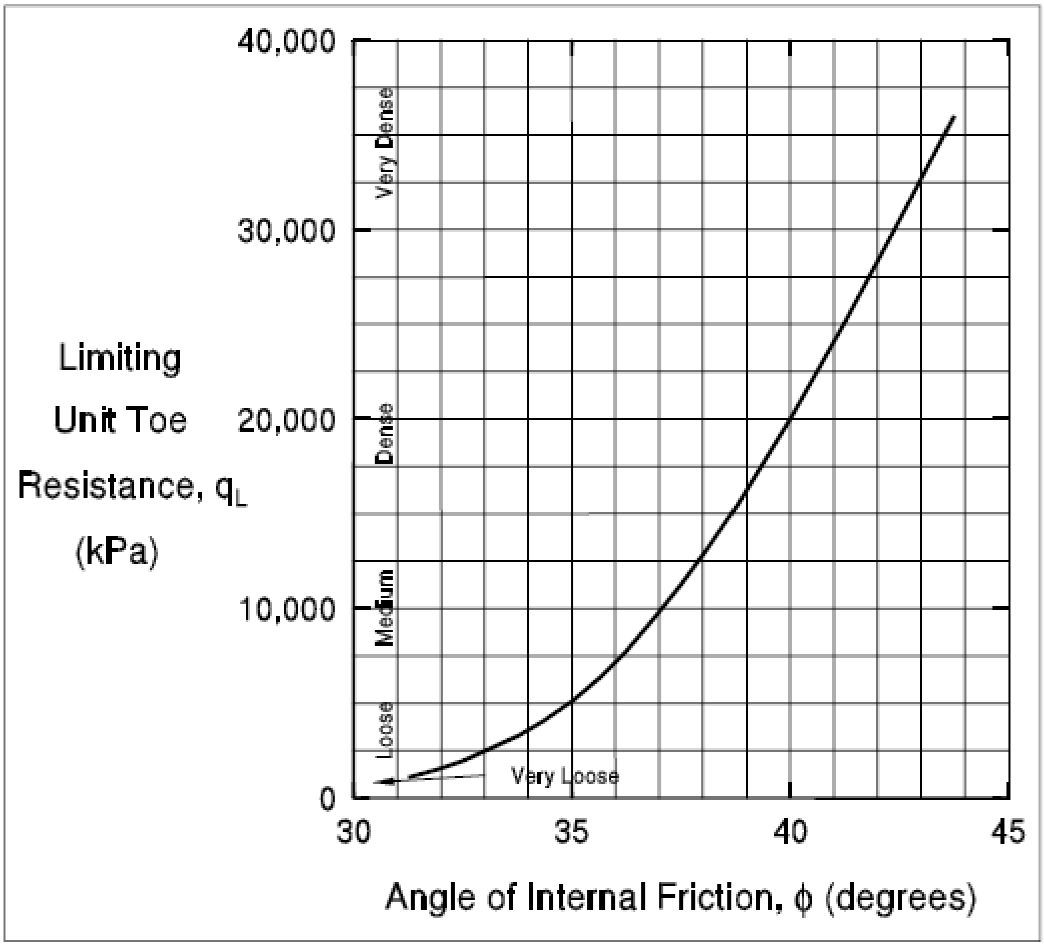


Figure 7-2. Relationship Between Maximum Unit Pile Toe Resistance and Friction Angle for Cohesionless Soils (after Meyerhof, 1976).

Figure A-4. Limiting values of unit base capacity for Driven.

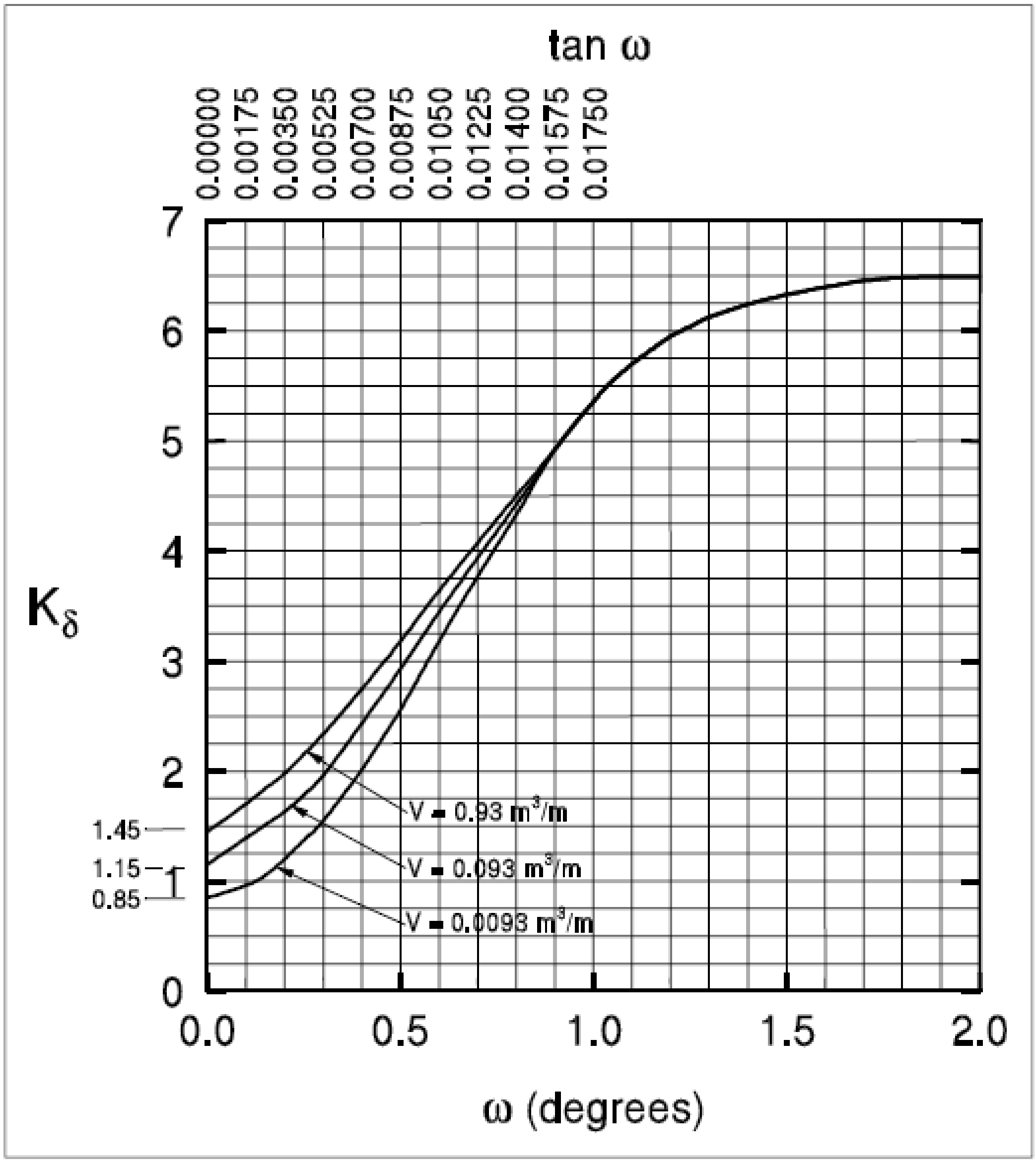


Figure 7-6. Design curves for evaluating K_δ for piles when $\phi = 30°$ (after Norlund 1979).

*Note that this applies only to soil where ϕ = 30°, other charts are available for different values of ϕ, and ω is the taper of the pile (ω = 0 for straight piles).

Figure A-5. Design Curves for determining K_δ (Driven Manual).

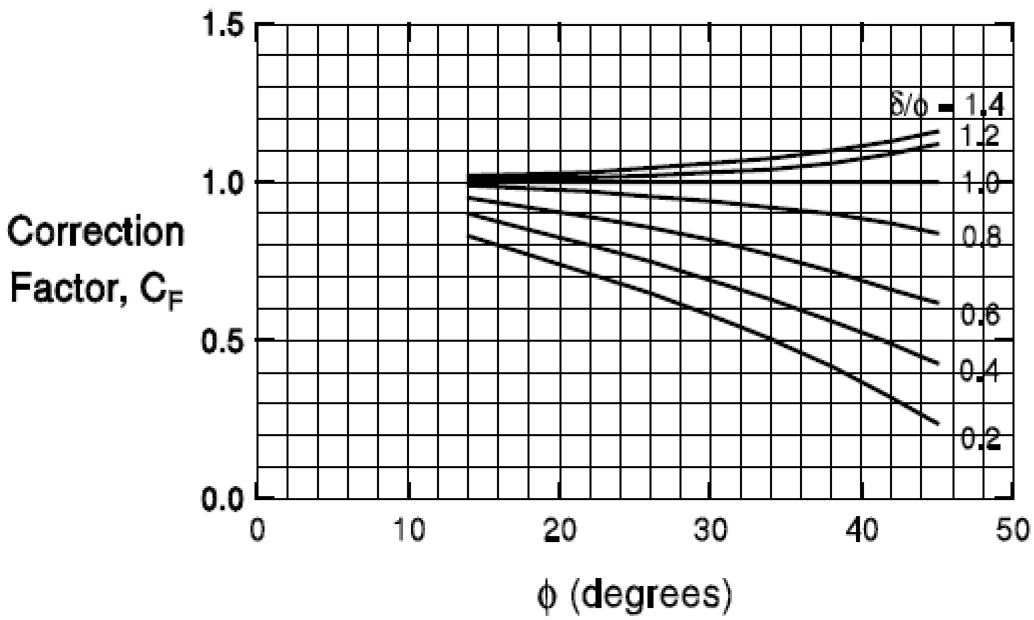


Figure 7-9. Correction factor for K_s when $\delta \neq \phi$ (after Norlund 1979).

Figure A-6. Correction Factor for $\delta \neq \phi$ (Driven Manual).

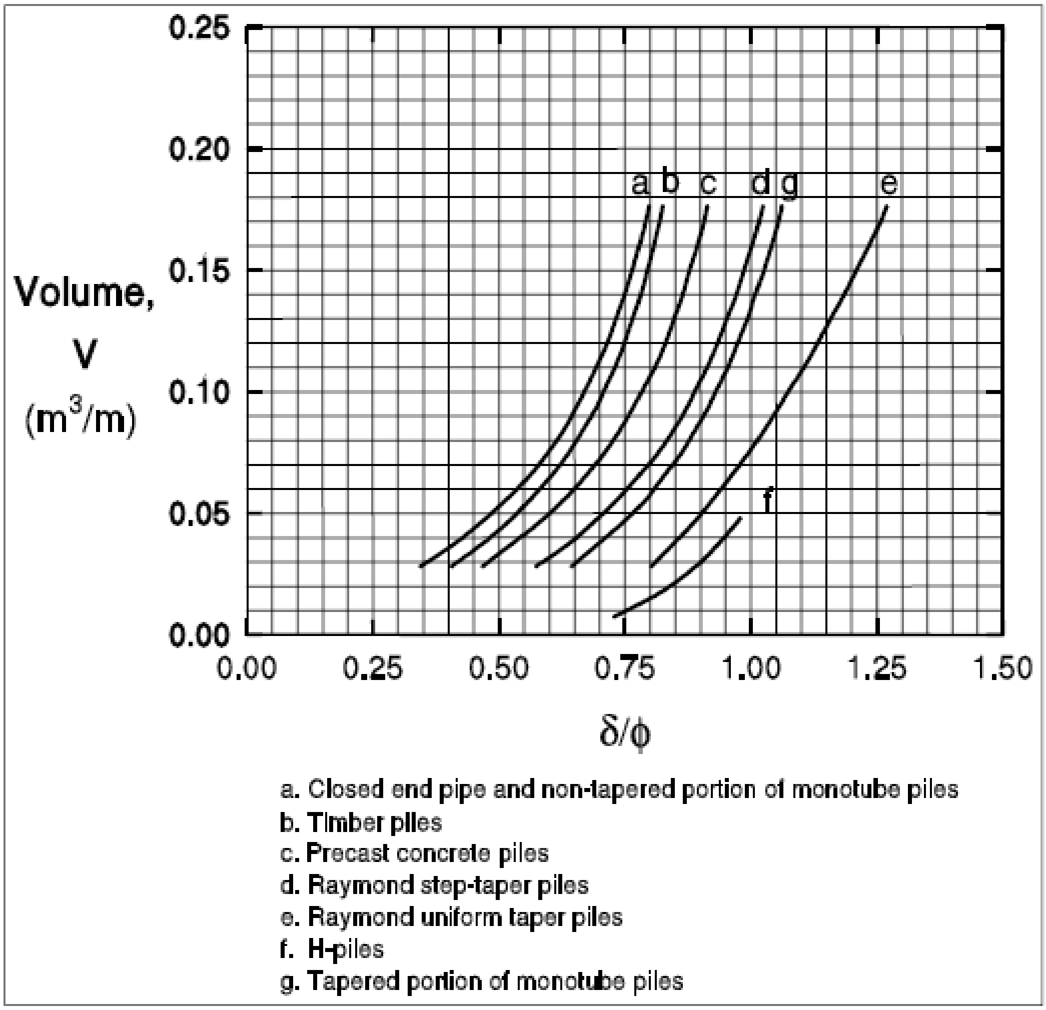


Figure 7-10. Relation of δ / ϕ and pile displacement, V, for various types of piles (after Norlund 1979).

Figure A-7. Chart for determining δ (Driven Manual).

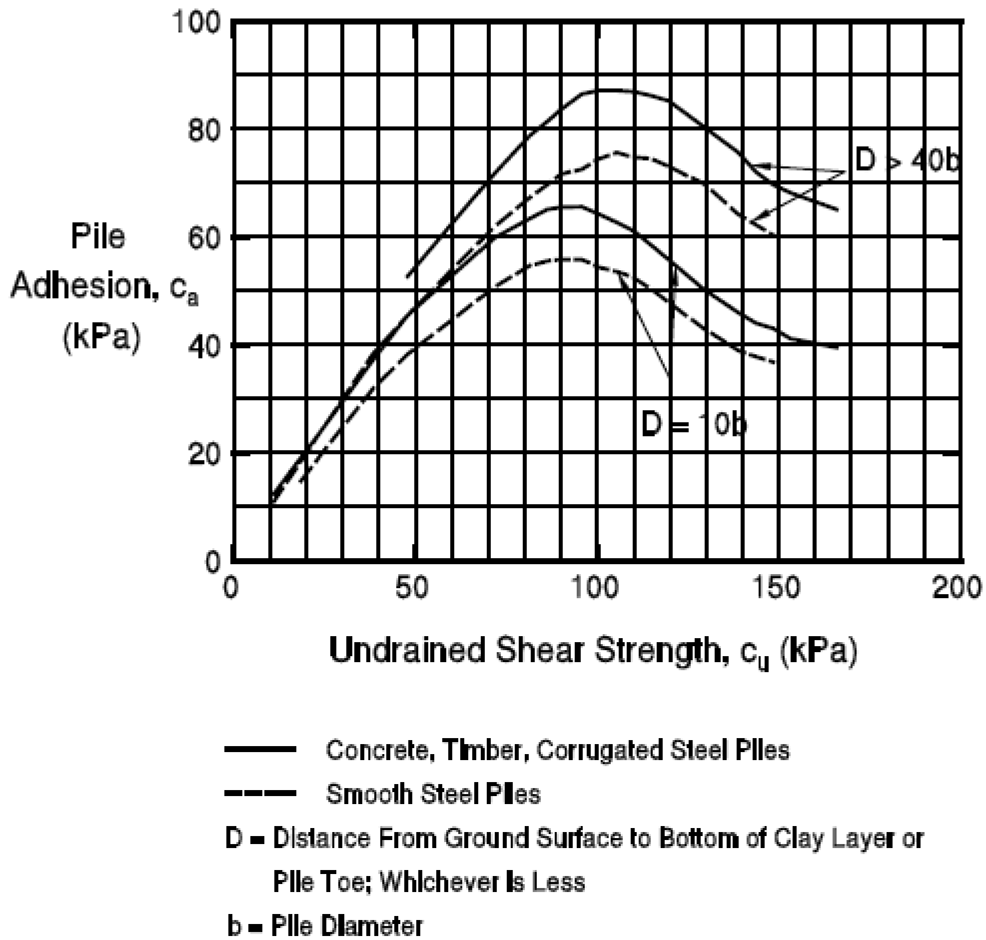


Figure 7-3. Adhesion Values for Piles in Cohesive Soils (after Tomlinson, 1979).

Figure A-8. Adhesion values for Tomlinson's α-method (1979) (Driven Manual).

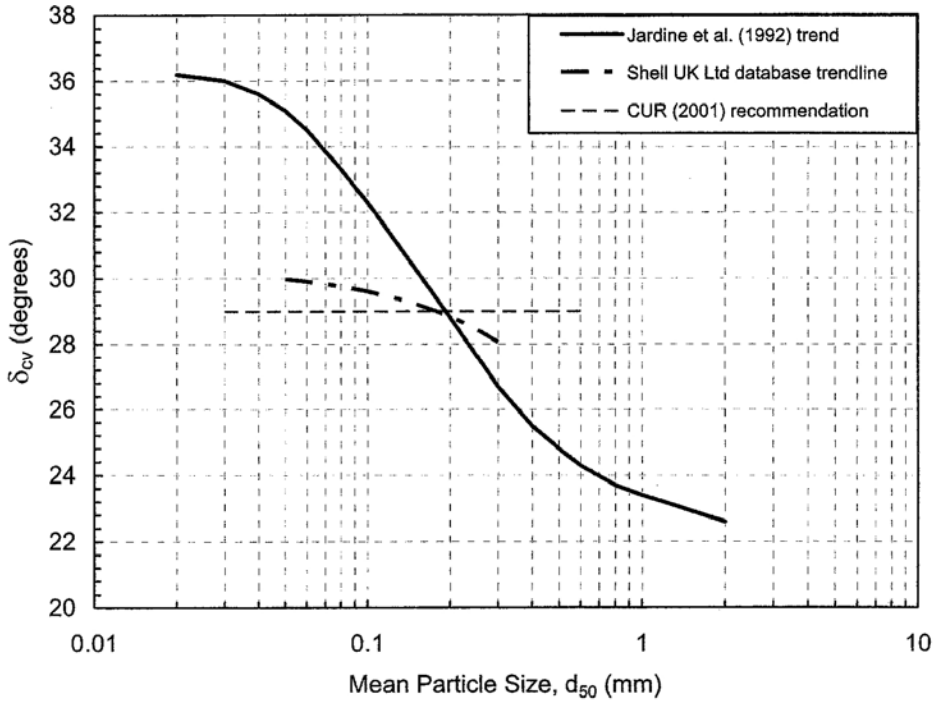


Figure A-9. Chart for determining δ_{cv} for a sand.

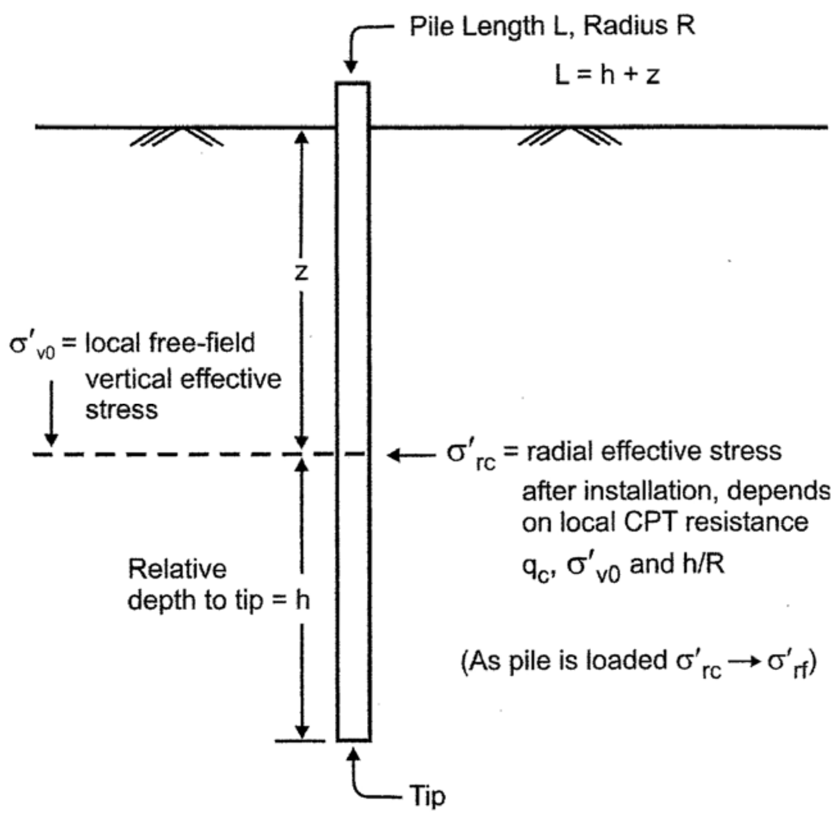


Figure A-10. Illustration of h.

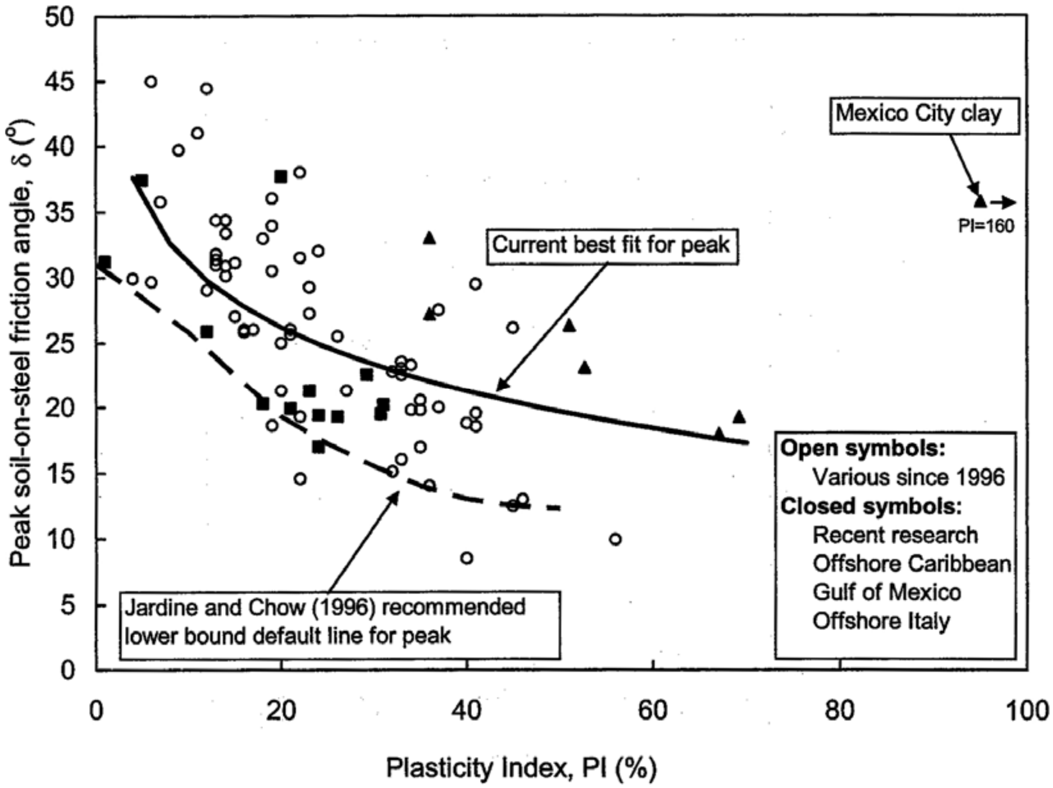


Figure A-11. Chart for determining peak δ for clays.

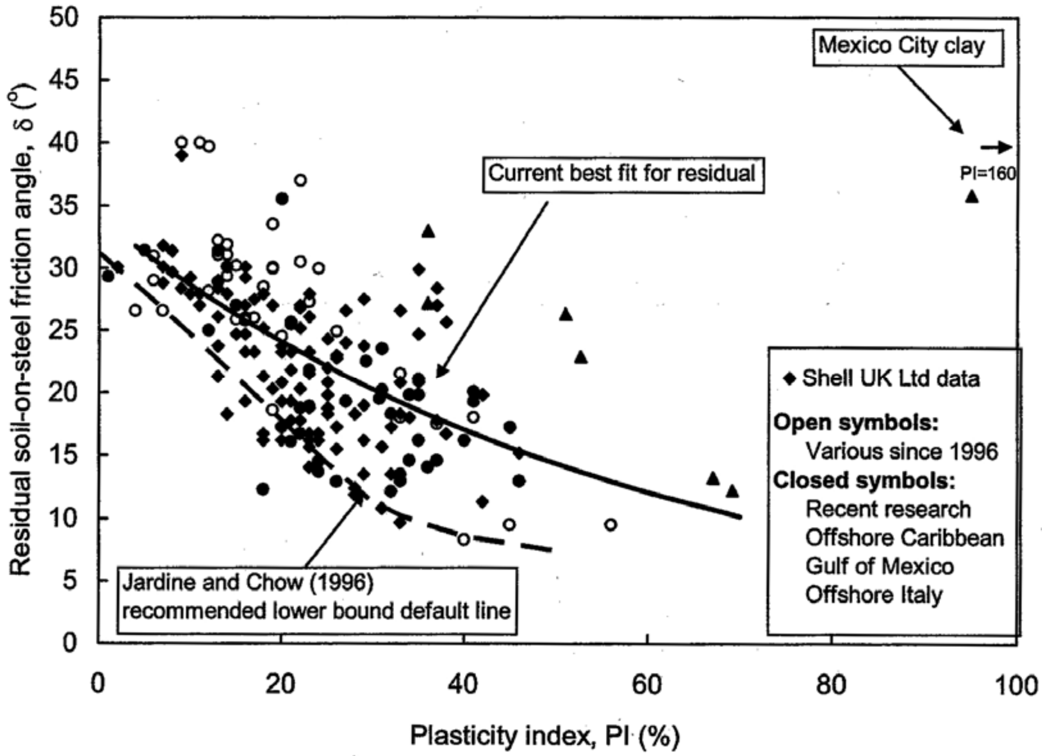


Figure A-12. Chart for determining ultimate δ for clays.

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TABLE 4-5 EMPIRICAL VALUES FOR Φ, D_r, AND UNIT WEIGHT OF GRANULAR SOILS BASED ON CORRECTED N' (after Bowles, 1977)					
Description	Very Loose	Loose	Medium	Dense	Very Dense
Relative density D_r	0 - 0.15	0.15 - 0.35	0.35 - 0.65	0.65 - 0.85	0.85 - 1.00
Corrected standard penetration no. N'	0 to 4	4 to 10	10 to 30	30 to 50	50+
Approximate angle of internal friction ϕ *	25 - 30°	27 - 32°	30 - 35°	35 - 40°	38 - 43°
Approximate range of moist unit weight (γ) kN/m^3	11.0 - 15.7	14.1 - 18.1	17.3 - 20.4	17.3 - 22.0	20.4 - 23.6

Correlations may be unreliable in soils containing gravel. See discussion in Section 9.5 of Chapter 9.

*** Use larger values for granular material with 5% or less fine sand and silt.**

Figure A-13. FHWA Table for determining unit weight based on $N_{1(60)}$.

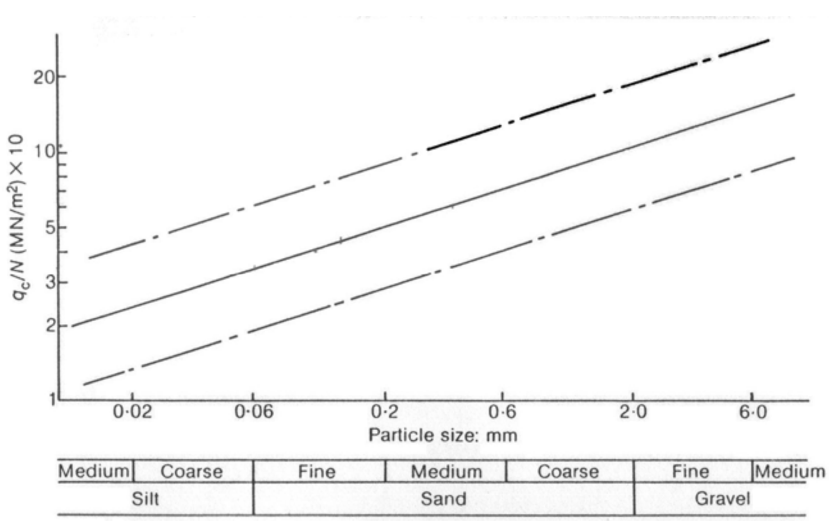

Figure A-14. Chart for estimating q_c based on soil type.

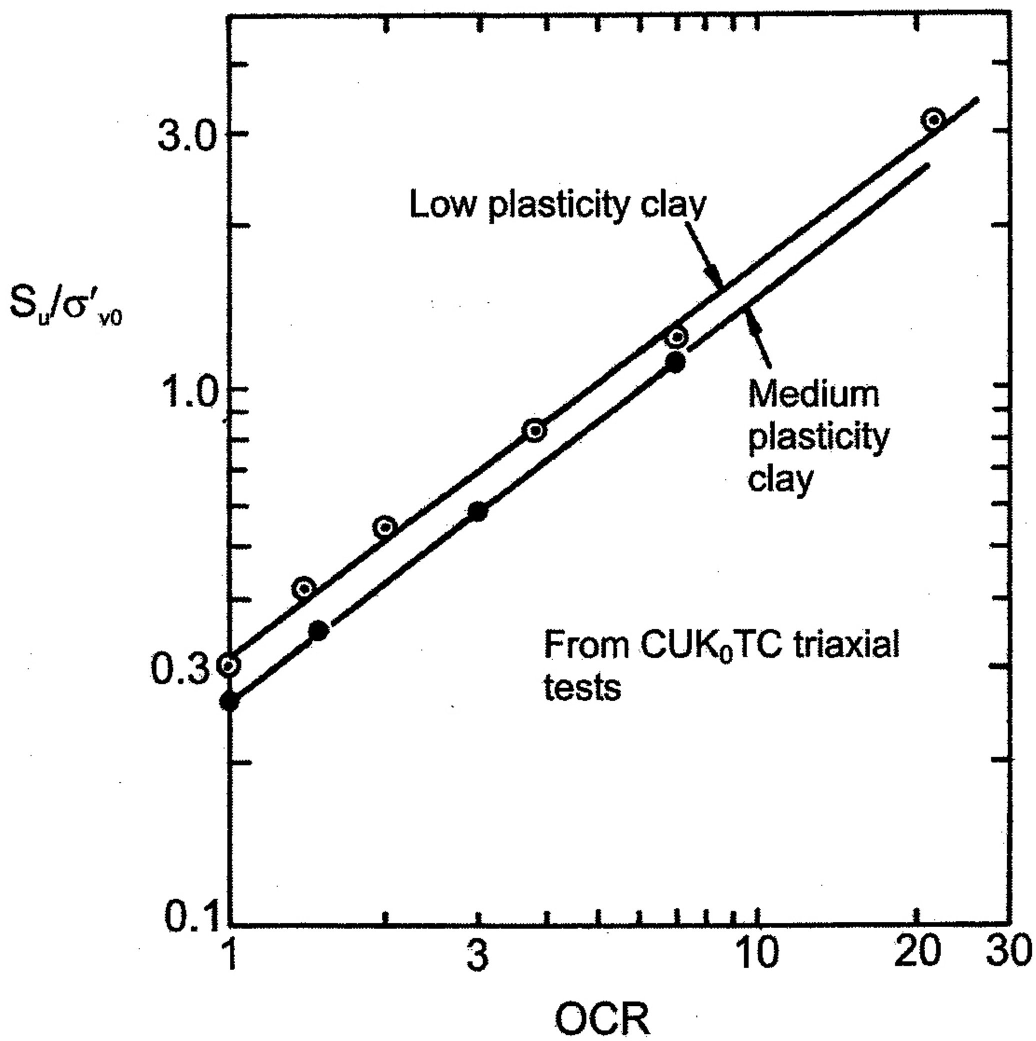

Figure A-15. Figure for determining the OCR of a clay.

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APPENDIX B – ADDITIONAL INFORMATION REGARDING THE INTERNATIONAL DATABASE

B.1 PILE DATABASES

In Tables B.1 – B.4, detailed information for each pile in the International Database is presented. The piles are grouped according to the study from which they were gathered.

B.2 ADDITIONAL DYNAMIC ANALYSES

The results of the following analyses are discussed in the body of the report and these results were considered when making recommendations. However, it was decided that these formulae were not particulary promising, given the goal of increasing dynamic/static agreement. The results of the EN-IDOT/SLT and WEAP/SLT analyses are presented below.

B.2.1 EN-IDOT vs. SLT

The average EN-IDOT/SLT capacity ratio is 0.71 with a COV = 0.87. The statistics for the EN-IDOT/SLT data are presented in Table B.5. The table is set up so that the data for all of the piles is in the bottom right-hand corner of the table. The rest of the statistics presented are for various subcategories of the data, such as H-piles in Clay or Pipe Piles in All Soil types. The data are plotted in Figure B.1. A 45° line on the figure represents perfect agreement between the two methods. The EN-IDOT/SLT data's capacity ratio of 0.71 indicates that the EN-IDOT formula underpredicts capacity (a capacity ratio of one indicates perfect agreement). The EN-IDOT predicted capacity is an allowable capacity, it includes a F.S. = 6. Because an allowable capacity is predicted, it would be expected that the average capacity ratio is less than unity. The capacities predicted by all other formulae in this study are ultimate capacities. The difference between an allowable and ultimate capacity should be considered when comparing the EN-IDOT capacities to any other predicted capacities. The COV of 0.87 indicates a large degree of scatter, the most displayed in the International Database by any formula.

H-piles in Sand have an average capacity ratio close to unity, but there is quite a bit of scatter associated with this average. Pipe Piles in Clay show the greatest bias towards underpredicting pile capacity. H-piles in Clay display the smallest amount of scatter (COV = 0.23), but there are only five H-piles in clay from which to draw conclusions.

B.2.2 WEAP vs. SLT

The average WEAP/SLT capacity ratio is 0.64 with a COV = 0.63. Statistics for the WEAP/SLT data are presented in Table B.6. The data are graphed in Figure B.2. The average capacity ratio of 0.64 is the largest underprediction of capacity displayed by any of the predictive methods for the International Database. The degree of scatter is fairly large, smaller only than that of the EN-IDOT/SLT data.

The majority of piles analyzed using WEAP were driven into mixed soils. There is insufficient data to draw any conclusions about WEAP's bias in sand or clay. Some conclusions about pile type can be drawn. WEAP displays a slightly stronger tendency to underpredict capacity for Pipe Piles than H-piles. There is some difference in degree of scatter between the pile types, but the COV for both pile types is large.

WEAP does not appear to display much bias with respect to pile type. There is insufficient data to draw any conclusions about any bias WEAP may show with respect to soil type.

B.3 DISCUSSION

The following is a discussion of some of the more detailed analyses conducted for the Dynamic/SLT data, which were considered when making recommendations. A more general discussion of the following results is presented in the body of the report.

B.3.1 FHWA-Gates

Detailed results for the FHWA-Gates/SLT data are presented in Table B.7, and the data are graphed in Figure B.3. While there are only five H-piles in Clay from which to draw conclusions, the FHWA-Gates formula appears to exhibit low scatter in these conditions. The FHWA-Gates formula exhibits the most scatter for Pipe Piles in Clay. In clay, the FHWA-Gates formula tends to overpredict capacity for H-piles and underpredict it for Pipe Piles. In Sand, the FHWA-Gates formula displays the same trend observed in the EN-IDOT formula, that the average overprediction in H-piles is greater than that for Pipe Piles. More scatter is observed in the data for Pipe Piles than for H-piles. The FHWA-Gates formula appears to display some bias, both with respect to pile type and with respect to soil type.

B.3.2 FHWA-UI

Detailed results for the FHWA-UI/SLT data are presented in Table B.8, and the data are graphed in Figure B.4. While there are only five piles from which to draw conclusions, the FHWA-UI formula predicts capacity with the smallest amount of scatter of any of the subcategories for H-piles in Clay. The average capacity ratio of this subcategory is the largest however. This trend was also observed for the FHWA-Gates data. The FHWA-UI formula appears to predict capacity well in sand, regardless of pile type, with a relatively small amount of scatter. In clay, there is a tendency to overpredict capacity for H-piles and underpredict it for pipe piles.

Overall, the FHWA-UI formula predicts capacity well with the smallest amount of scatter of any formula analyzed using the International Database. The method does not appear to display significant bias due to pile type. The method performs well in sand, but appears to be biased with respect to pile type in clay. However, there are fewer data points in clay from which to draw conclusions, compared to other subcategories.

B.3.3 WSDOT

Detailed results for the FHWA-Gates/SLT data are presented in Table B.9, and the data are graphed in Figure B.4. Within the subcategories of the WSDOT/SLT data, the WSDOT formula displays a tendency to overpredict capacity in sand by about 17%. This is comparable to the overprediction for all data, and the degrees of scatter are similar. As was observed for both the FHWA-UI and FHWA-Gates formulae, the smallest amount of scatter of any subcategory is for H-piles in Clay. This subcategory also displays the largest bias (Average = 1.30). There is a tendency to underpredict capacity for Pipe Piles in Clay, this is the only subcategory which displayed that trend.

B.3.4 Overall

The WSDOT formula has a tendency to overpredict capacity with a fairly small degree of scatter. It appears to be more accurate and precise than the FHWA-Gates formula, but less so than the FHWA-UI formula. The formula predicts capacity well in sand, while there is a greater amount of scatter and bias in clays.

Looking only at the FHWA-Gates, FHWA-UI, and WSDOT formulae, one trend appears to be that in sand, the formulae do not appear very sensitive to pile type, with the tendency being to overpredict capacity (or in the case of the FHWA-UI formula, predict capacities very similar to those of static load tests). The degree of scatter in sand appears to be comparable to that of all data. In clay, the tendency seems to be to underpredict capacity for pipe piles and overpredict capacity for H-piles. Pipe Piles in clay display the largest amount of scatter of any subcategory, while H-piles in clay display the smallest amount of scatter. It is worth noting that there are few piles in clay from which to draw conclusions.

Table B.1 Load Test Data Used by Flaate (1964), and by Olson and Flaate (1967)

LTN	Pile Type	Measured Capacity (kips)	Hammer Type	Predicted Capacities		
				Q_{EN} (kips)	$Q_{FHWA\text{-}Gates}$ (kips)	Q_{WsDOT} (kips)
1. s26	H	280	steam/double	129	392	272
2. s27	H	300	steam/double	143	434	295
3. s28	H	280	steam/double	146	441	299
4. s29	H	180	steam/double	107	336	241
5. s30	H	160	steam/double	110	344	245
6. s31	Pipe	300	steam/single	103	336	218
7. s32	Pipe	240	steam/single	100	329	214
8. s33	HP	198	steam/single	46	187	101
9. s36	H	580	steam/single	104	332	307
10. s37	pipe	570	steam/single	121	363	329
11. s38	H	270	steam/single	76	272	264
12. s39	pipe	700	steam/single	183	474	407
13. s40	pipe	630	steam/single	155	424	372
14. s41	pipe	600	steam/single	173	455	394
15. s42	pipe	720	steam/single	263	668	545
16. s43	monotube	340	steam/single	125	414	257
17. s44	monotube	286	steam/single	130	441	270
18. s45	pipe	516	steam/single	130	441	270
19. s46	pipe	614	steam/single	263	668	545
20. s47	pipe	346	steam/single	86	296	281
21. s48	pipe	924	steam/single	263	668	545
22. s49	H	88	steam/single	67	243	172
23. s50	H	126	steam/single	68	247	174
24. s51	H	110	steam/single	43	179	139
25. s52	H	84	steam/single	38	162	131
26. s53	H	54	steam/single	30	135	118
27. s54	H	108	steam/single	50	200	150
28. s55	H	120	steam/single	54	209	155

Table B.2 Load Test Data from Fragaszy et al. (1988)

LTN	Pile Type	Measured Capacity (kips)	Predicted Capacities		
			$Q_{EN\text{-}Wisc}$ (kips)	$Q_{FHWA\text{-}Gates}$ (kips)	Q_{WsDOT} (kips)
1. HP-3	Steel H Pile	284	105	332	246
2. HP-4	Steel H Pile	158	25	114	107
3. HP-5	Steel H Pile	244	102	326	280
4. HP-6	Steel H Pile	364	81	279	216
5. HP-7	Steel H Pile	298	75	265	208
6. CP-4	Closed Steel Pipe Pile	494	241	562	522
7. CP-6	Closed Steel Pipe Pile	246	144	407	334
8. OP-3	Open Steel Pipe Pile	424	124	372	372
9. OP-4	Open Steel Pipe Pile	450	253	568	635
10. FP-1	Concrete Filled Steel Pipe Pile	290	125	371	301
11. FP-2	Concrete Filled Steel Pipe Pile	158	43	182	186
12. FP-3	Concrete Filled Steel Pipe Pile	600	200	506	429
13. FP-6	Concrete Filled Steel Pipe Pile	244	111	344	283
14. FP-7	Concrete Filled Steel Pipe Pile	442	187	479	551
15. FP-8	Concrete Filled Steel Pipe Pile	522	374	734	793
16. FP-9	Concrete Filled Steel Pipe Pile	338	194	489	560

Table B.3. Piles in the International Database from FHWA, Developed by Rausche, et al. (1996)

Pile No.	Pile Type	Soil Type	Static Load Test Capacity (kips)	EN-IDOT Capacity (kips)	FHWA-Gates Capacity (kips)	FHWA-UI Capacity (kips)	WSDOT Capacity (kips)	WEAP Capacity (kips)
1	CEP	Clay	109	19	71	93	97	-
2	CEP	Clay	114	19	71	93	97	-
3	CEP	Mix	158	110	289	315	222	107
4	CEP	Clay	287	150	374	422	376	180
5	H-Pile	Clay	296	294	554	500	680	-
6	H-Pile	Clay	306	169	397	358	397	185
7	H-Pile	Mix	308	197	416	363	380	215
8	H-Pile	Mix	313	149	394	343	493	110
9	CEP	Mix	347	105	282	308	218	194
10	CEP	Mix	375	211	436	410	414	360
11	CEP	Mix	380	31	121	131	162	66
12	CEP	Mix	380	50	191	208	214	175
13	CEP	Mix	470	419	613	668	524	410
14	H-Pile	Clay	474	324	582	525	722	-
15	CEP	Sand	497	90	270	223	236	180
16	H-Pile	Mix	509	174	395	297	367	370
17	H-Pile	Clay	575	518	724	653	913	-
18	H-Pile	Mix	576	900	962	839	1062	596
19	CEP	Mix	580	81	269	293	297	300
20	CEP	Mix	600	55	204	222	223	180
21	CEP	Mix	600	415	647	608	783	420
22	H-Pile	Mix	618	95	287	250	499	100
23	H-Pile	Mix	635	404	615	537	646	600
24	CEP	Mix	656	490	685	747	578	623
25	CEP	Mix	657	50	191	208	214	120
26	CEP	Mix	659	631	774	735	799	540
27	CEP	Mix	660	264	485	456	452	580

Table B.4. Piles in the International Database from Allen (2005)

Pile	Pile Type	Soil Type	Static Load Test Capacity (kips)	EN-IDOT Capacity (kips)	FHWA-Gates Capacity (kips)	FHWA-UI Capacity (kips)	WSDOT Capacity (kips)
1	CEP	Sand	104	63	206	195	153
2	CEP	Mix	647	632	775	845	800
3	CEP	Mix	504	274	517	564	564
4	H-Pile	Mix	315	45	176	154	203
5	H-Pile	Mix	214	59	215	188	232
6	CEP	Mix	237	97	292	319	289
7	CEP	Clay	364	50	190	249	213
8	CEP	Clay	656	50	190	249	213
9	CEP	Clay	372	31	121	158	162
10	CEP	Clay	554	68	237	310	248
11	OEP	Mix	586	327	575	639	675
12	H-Pile	Mix	318	149	394	344	494
13	CEP	Clay	476	90	270	354	237
14	H-Pile	Mix	416	231	478	417	528
15	H-Pile	Mix	448	286	527	460	572
16	CEP	Mix	400	231	478	521	528
17	CEP	Mix	737	247	450	491	351
18	H-Pile	Sand	313	220	417	316	294
19	H-Pile	Clay	300	211	456	412	497
20	CEP	Clay	280	190	433	489	474
21	CEP	Mix	650	318	542	510	545
22	CEP	Sand	557	667	831	680	1154
23	CEP	Mix	420	162	418	393	564
24	CEP	Sand	447	178	439	359	588
25	CEP	Sand	340	167	425	347	572
26	CEP	Sand	340	217	453	371	462
27	CEP	Sand	376	226	461	377	469
28	H-Pile	Sand	315	102	273	179	200
29	H-Pile	Sand	313	71	224	146	171
30	OEP	Mix	533	556	723	693	679
31	CEP	Mix	477	470	678	637	791
32	CEP	Mix	490	673	833	783	783
33	H-Pile	Sand	350	327	540	353	386
34	H-Pile	Sand	570	507	687	450	617
35	H-Pile	Sand	475	350	571	374	407
36	OEP	Sand	655	192	469	391	784
37	OEP	Sand	745	485	725	605	1021
38	CEP	Clay	684	207	464	523	555
39	CEP	Mix	740	148	391	367	478

40	CEP	Sand	310	156	375	257	356

Table B.4 (Cont'd.). Piles in the International Database from Allen (2005)

41	CEP	Sand	160	81	265	182	269
42	CEP	Sand	480	485	668	459	598
43	CEP	Sand	296	260	480	330	441
44	CEP	Sand	326	432	623	428	560
45	CEP	Sand	530	485	668	459	598
46	CEP	Sand	320	485	668	459	598
47	CEP	Sand	390	372	573	394	518
48	CEP	Mix	440	361	602	475	708
49	CEP	Mix	486	361	602	475	708
50	CEP	Mix	490	433	654	516	765
51	CEP	Mix	660	597	758	599	879
52	CEP	Mix	420	411	638	504	748
53	CEP	Mix	386	427	650	513	760
54	CEP	Mix	560	713	829	655	959
55	H-Pile	Sand	397	315	519	285	388
56	H-Pile	Sand	550	396	621	341	459
57	H-Pile	Sand	570	485	668	367	598
58	H-Pile	Sand	310	302	505	278	379
59	H-Pile	Sand	330	315	519	285	388
60	H-Pile	Sand	272	385	605	333	448
61	H-Pile	Sand	300	385	605	333	448
62	H-Pile	Sand	390	624	811	446	722
63	H-Pile	Sand	500	544	723	397	645
64	H-Pile	Mix	223	121	322	242	288

Table B.5. Statistics for the Average EN-IDOT/SLT Capacity Ratios.

		Clay	Sand	All Soil
Pipe Piles	Average:	0.25	0.64	0.63
	Std. Dev:	0.20	0.35	0.54
	COV:	0.82	0.55	0.87
	r^2:	0.12	0.15	0.17
	n:	10	27	80
H-Piles	Average:	0.77	1.05	0.83
	Std. Dev:	0.18	0.87	0.69
	COV:	0.23	0.82	0.82
	r^2:	0.80	0.26	0.25
	n:	5	30	52
All Piles	Average:	0.45	0.84	0.71
	Std. Dev:	0.50	0.61	0.61
	COV:	1.12	0.73	0.87
	r^2:	0.10	0.18	0.19
	n:	15	57	132

Table B.6. Statistics for the Average WEAP/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	Average:	0.63	0.36	0.62
	Std. Dev:	-	-	0.38
	COV:	-	-	0.61
	r^2:	-	-	0.36
	n:	1	1	15
H-Piles	Average:	0.60	-	0.69
	Std. Dev:	-	-	0.50
	COV:	-	-	0.73
	r^2:	-	-	0.35
	n:	1	-	7
All Piles	Average:	0.62	0.36	0.64
	Std. Dev:	0.02	-	0.41
	COV:	0.03	-	0.63
	r^2:	1.00	-	0.35
	n:	2	1	22

Table B.7. Statistics for the Average FHWA-Gates/SLT Capacity Ratios.

		Clay	Sand	All Soil
Pipe Piles	Average:	0.70	1.20	1.09
	Std. Dev:	0.40	0.46	0.54
	COV:	0.57	0.38	0.50
	r^2:	0.20	0.27	0.22
	n:	10	27	80
H-Piles	Average:	1.44	1.41	1.39
	Std. Dev:	0.26	0.55	0.55
	COV:	0.18	0.39	0.39
	r^2:	0.76	0.58	0.49
	n:	5	30	52
All Piles	Average:	0.96	1.39	1.22
	Std. Dev:	0.63	0.56	0.59
	COV:	0.66	0.41	0.49
	r^2:	0.13	0.43	0.31
	n:	15	57	132

Table B.8. Statistics for the Average FHWA-UI/SLT Capacity Ratios.

		Clay	Sand	All Soil
Pipe Piles	Average:	0.85	0.97	1.02
	Std. Dev:	0.43	0.31	0.42
	COV:	0.51	0.32	0.42
	r^2:	0.26	0.50	0.29
	n:	10	27	80
H-Piles	Average:	1.30	1.01	1.02
	Std. Dev:	0.24	0.37	0.39
	COV:	0.18	0.36	0.38
	r^2:	0.76	0.61	0.48
	n:	5	30	52
All Piles	Average:	1.01	1.00	1.02
	Std. Dev:	0.50	0.36	0.41

	COV:	0.50	0.36	0.41
	r^2:	0.22	0.63	0.42
	n:	15	57	132

Table B.9. Statistics for the Average WSDOT/SLT Capacity Ratios.

		Clay	**Sand**	**All Soil**
Pipe Piles	Average:	0.79	1.15	1.12
	Std. Dev:	0.44	0.52	0.56
	COV:	0.56	0.45	0.50
	r^2:	0.21	0.25	0.21
	n:	10	27	80
H-Piles	Average:	1.69	1.17	1.21
	Std. Dev:	0.36	0.49	0.46
	COV:	0.21	0.42	0.38
	r^2:	0.71	0.61	0.55
	n:	5	30	52
All Piles	Average:	1.11	1.17	1.14
	Std. Dev:	0.73	0.49	0.51
	COV:	0.66	0.42	0.45
	r^2:	0.13	0.45	0.35
	n:	15	57	132

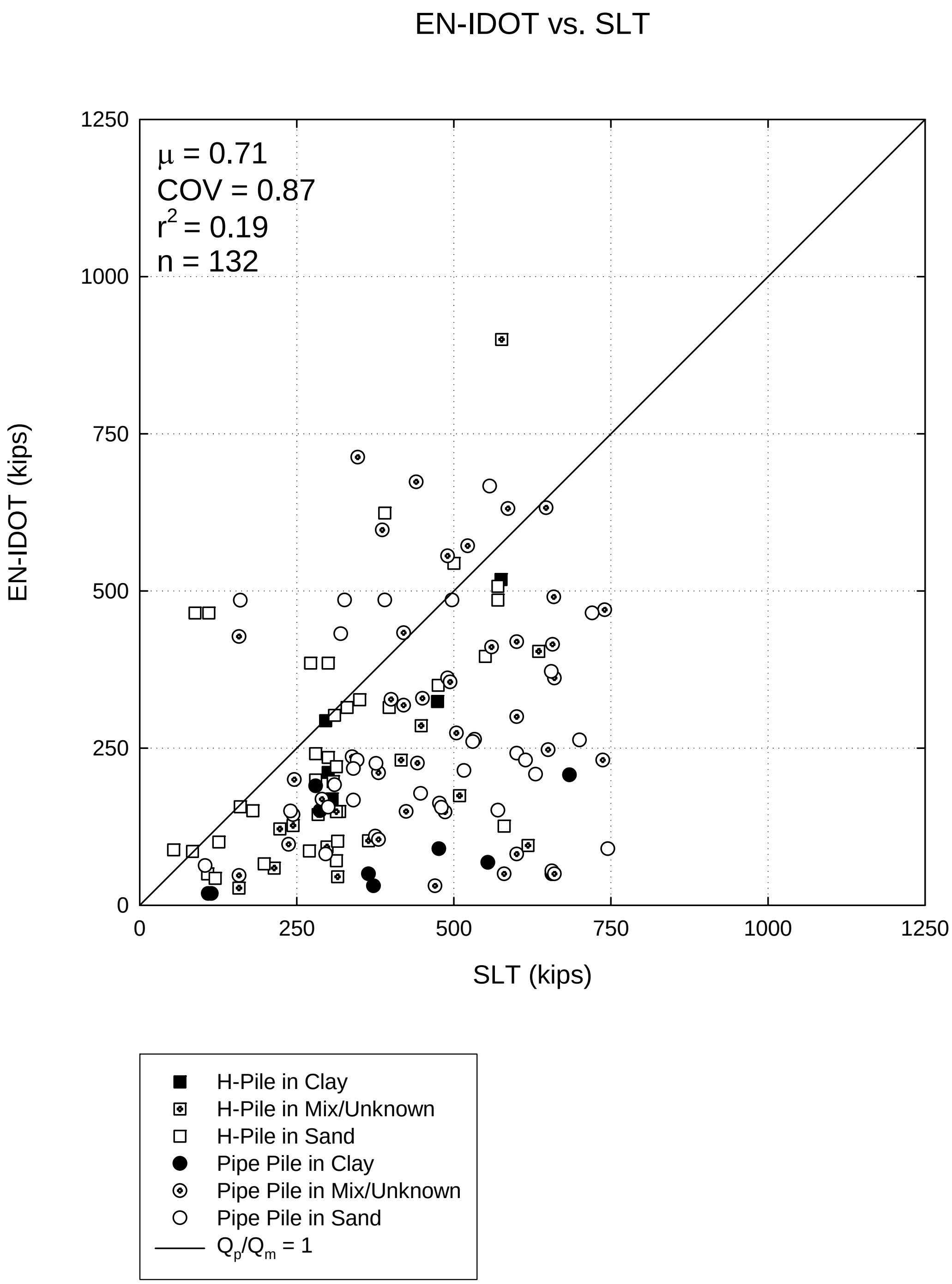

Figure B.1. EN-IDOT vs. SLT, International Database.

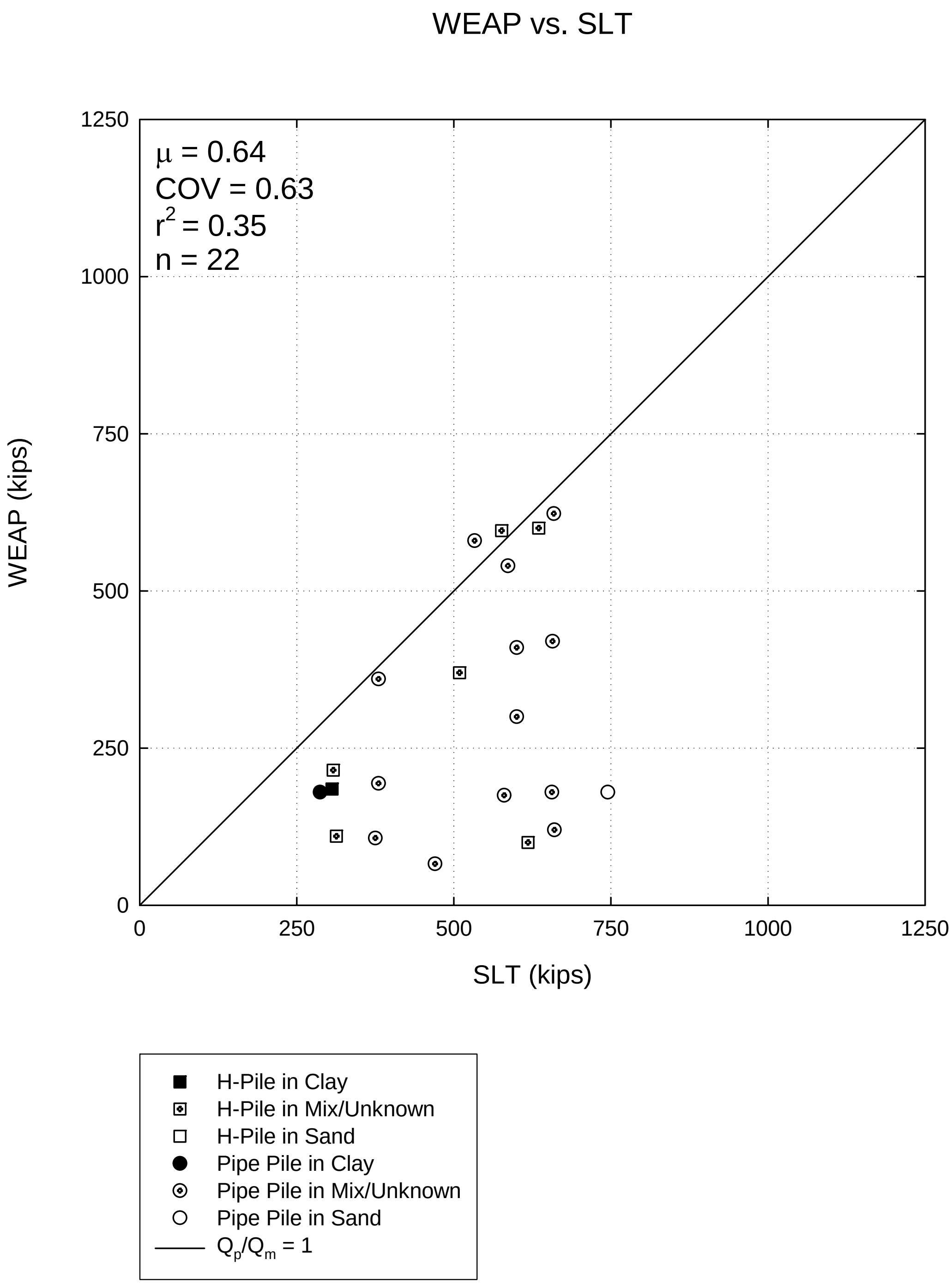

Figure B.2. WEAP vs. SLT, International Database.

FHWA-Gates vs. SLT

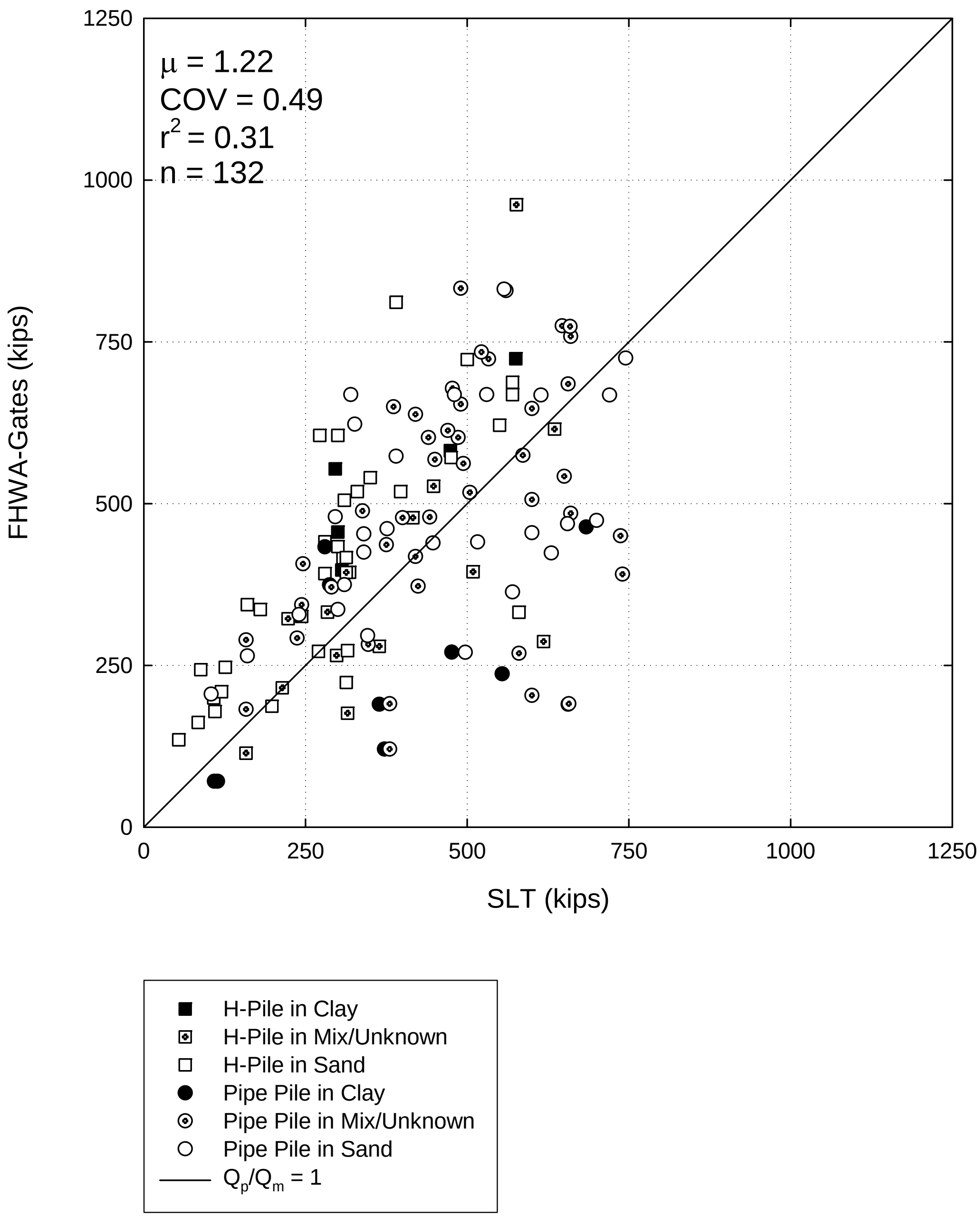

Figure B.3. FHWA-Gates vs. SLT, International Database.

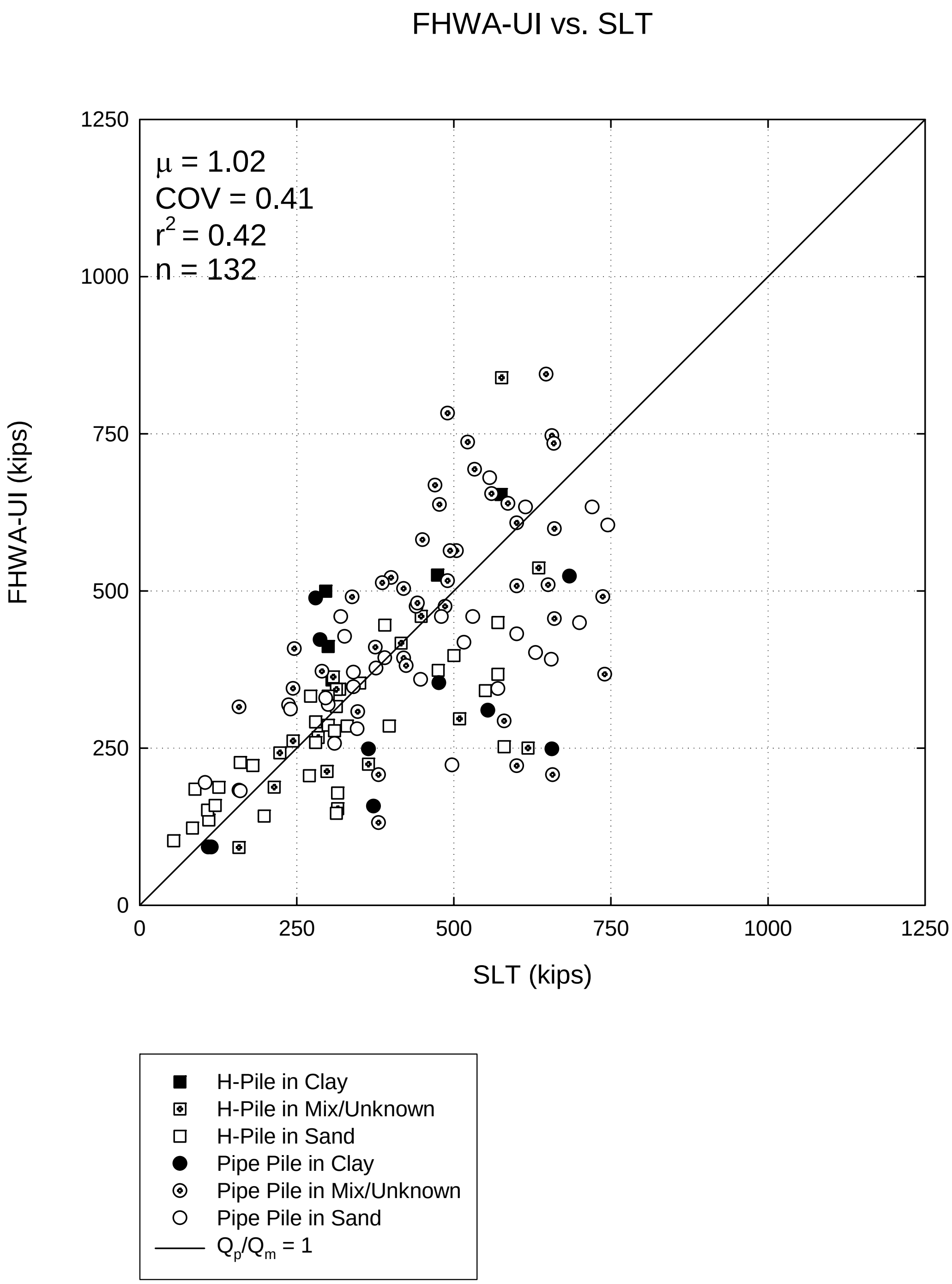

Figure B.4. FHWA-UI vs. SLT, International Database.

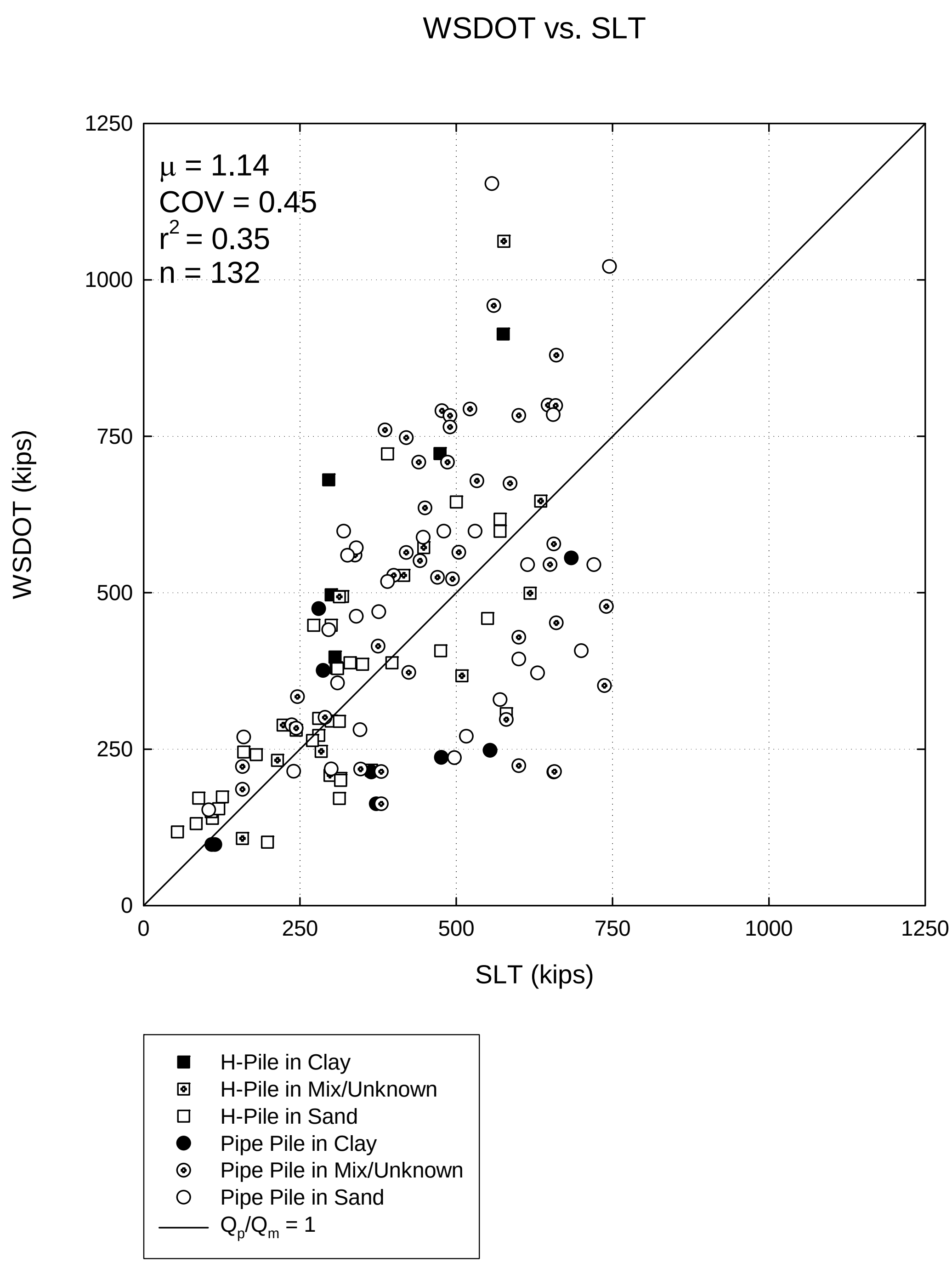

Figure B.5. WSDOT vs. SLT, International Database.

APPENDIX C – ADDITIONAL INFORMATION REGARDING THE COMPREHENSIVE DATABASE

C.1 PILE DATABASE

In Table C.1, detailed information for each pile in the Comprehensive Database is presented. The piles are grouped according to the study from which they were gathered. Of the 26 piles that make up the Comprehensive Database, 15 are H-piles and 11 are pipe piles. The length of the piles ranges from 38 feet to 136 feet with an average length of 103 feet. The H-pile sections range from HP10x42 to HP14x89. The diameter of the pipe piles ranges from 12.75 inches to 18 inches. Some of the piles were driven into only sandy or clayey materials, but the majority were driven through a mixture of the two.

C.2 ADDITIONAL DYNAMIC ANALYSES

The results of the following analyses are discussed in the body of the report and these results were considered when making recommendations. However, it was decided that these formulae were not particularly promising, given the goal of increasing dynamic/static agreement. The results of the EN-IDOT/SLT and WEAP/SLT analyses are presented below.

C.2.1 EN-IDOT/SLT

The average EN-IDOT/SLT capacity ratio is 0.47 with a COV = 0.56. Statistics for the data, broken down into several subcategories, are presented in Table C.2. Figure C.1 is a plot of the data. A F.S. = 6 is built into the EN-IDOT formula, yielding an estimated allowable pile capacity. The other dynamic formulae are not associated with a FS and provide ultimate capacity predictions. The average capacity ratio of 0.47 indicates the formula underpredicts pile capacity by about half. The COV = 0.56 indicates a large degree of scatter within the data.

There is a limited amount of data from which to draw conclusions about any of the subcategories of the data. But, based on the available data, the formula does not appear to be biased with regard to pile type. The average capacity ratios for pipe piles and H-piles are similar. The formula appears to more greatly underpredict capacity in clay, while the underprediction is not of as great a magnitude in sand. There is a greater amount of scatter in the clay data.

C.2.2 WEAP/SLT

The average WEAP/SLT capacity ratio is 0.65 with a COV = 0.40. The data, broken into subcategories, are presented in Table C.3. The data are plotted in Figure C.2. The average WEAP/SLT capacity ratio indicates that WEAP tends to underpredict pile capacity by a fair amount. There is a moderate amount of scatter in the data, similar to that displayed by the FHWA-UI formula.

WEAP appears to have some bias with respect to pile type. The method more greatly underpredicts the capacity of H-piles. There is also more scatter in the data for H-piles than for pipe piles. The method appears to be fairly insensitive to soil type, with average capacity ratios that are almost identical across sand, clay, and mixed soils. There does appear to be a smaller amount of scatter associated with capacity predictions in sand.

C.3 ADDITIONAL STATIC ANALYSES

The results of the following analyses are discussed in the body of the report and these results were considered when making recommendations. However, it was decided that these methods were not particulary promising, given the goal of increasing dynamic/static agreement. The results of the Olson/SLT and DRIVEN/SLT analyses are presented below.

C.3.1 OLSON/SLT

The average Olson/SLT capacity ratio is 1.33, with a COV = 0.70. The statistics for this data, broken into subcategories, are presented in Table C.4, and the data are graphed in Figure C.3. The average capacity ratio indicates that Olson's method tends to overpredict pile capacity by about 30%. The COV of 0.70 indicates that Olson's method predicts capacity with an appreciable amount of scatter.

Olson's method does not appear to be very biased with regard to pile type. The average capacity ratios for both H-piles and pipe piles are similar. There is a smaller amount of scatter present in the H-pile data. Olson's method was developed using data from load tests on pipe piles, and its applicability to H-piles could be questioned. Based on the results of the relatively small Comprehensive Database, the method seems to predict capacity at a similar accuracy for both H-piles and pipe piles. Olson's method does appear to display a fairly large amount of bias with respect to soil type. The method underpredicts capacity in clay, and overpredicts it in sand. The overprediction in sand is by a fairly large amount (Q_{Olson}/Q_{SLT} = 1.72). The capacity predictions in sand also have a large amount of scatter associated with them (COV = 1.05).

C.3.2 DRIVEN/SLT

The average Driven/SLT capacity ratio is 1.30 with a COV = 0.92. Further statistics for the data are presented in Table C.5, and the data are plotted in Figure C.4. Driven tends to overpredict capacity in piles by about 30%. However, these capacity predictions are associated with a very large amount of scatter. The COV of 0.92 is the greatest overall amount of scatter associated with any of the methods analyzed using the Comprehensive Database.

Driven appears to be slightly biased with respect to pile type. The method tends to overpredict the capacity of pipe piles to a greater degree than it overpredicts the capacity of H-piles. There is appreciable scatter associated with both pile types. Driven displays significant bias between soil types. The method tends to slightly underpredict capacity in clay, while it overpredicts capacity in sand by a considerable amount, with significant scatter in the data.

C.4 DISCUSSION

The following is a discussion of some of the more detailed analyses conducted for the data, which were considered when making recommendations. A more general discussion of the following results are presented in the body of the report.

C.4.1 FHWA-Gates/SLT

Detailed results for the FHWA-Gates/SLT data are presented in Table C.6, and the data are graphed in Figure C.5. The FHWA-Gates formula appears to slightly overpredict the capacity of pipe piles. It does so with a small amount of scatter (COV = 0.22). The FHWA-Gates formula does not appear biased towards an underprediction or overprediction of capacity for H-piles, but it does display slightly more scatter than for pipe piles. The FHWA-Gates formula appears to predict capacity very well in sand, with statistics very similar to those for all piles. The formula appears to tend to overpredict the capacity of piles in clay, with more scatter than for other categories.

C.4.2 FHWA-UI/SLT

Detailed results for the FHWA-UI/SLT data are presented in Table C.7, and the data are graphed in Figure C.6. There does appear to be some bias in the formula with respect to pile type. The FHWA-UI formula tends to overpredict capacity for pipe piles and underpredict capacity for H-piles. There is a smaller COV associated with pipe piles (COV = 0.24) than with

H-piles (COV = 0.45). There also appears to be a tendency for the FHWA-UI formula to overpredict pile capacity in clay and to underpredict it in sand. The scatter in clay is smaller than the scatter in sand.

C.4.3 WSDOT/SLT

Detailed results for the WSDOT/SLT data are presented in Table C.8, and the data are graphed in Figure C.7. Within the subcategories of the WSDOT/SLT data, there appears to be a trend to overpredict the capacity of pipe piles and underpredict the capcity of H-piles. There is a similar amount of scatter for the different pile categories. The average capacity ratio for both sand and clay is similar, as is the degree of scatter.

C.4.4 ICP/SLT

Detailed results for the ICP/SLT data are presented in Table C.9, and the data are graphed in Figure C.8. The ICP method appears to be somewhat biased with regard to pile type. The ICP method tends to overpredict capacity by a greater magnitude for pipe piles than it does for H-piles. The method has an appreciably smaller amount of scatter in its predictions of H-pile capacity than for pipe pile predictions. The method also appears to have some bias with respect to soil type. The ICP method tends to overpredict capacity by a smaller amount in clay than in sand. The degree of scatter is smaller in clay than in sand.

C.4.5 IDOT Static/SLT

Detailed results for the IDOT Static/SLT data are presented in Table C.10, and the data are graphed in Figure C.9. The IDOT Static method displays some bias between pile types. The method overpredicts capacity to a greater degree for pipe piles than for H-piles. The COV for the pipe pile data (COV = 0.73) is also larger than the COV for the H-pile data (COV = 0.62). It is difficult to draw conclusions about the bias of the IDOT Static method with respect to soil type. Looking only at piles classified as deriving most of their capacity (>80%) from only sand or only clay, it appears that there is little bias between soil types. The average capacity ratio in either sand or clay is about 1.58. However, the overall average capacity ratio of 1.30 indicates that for piles that were classified as being in mixed soil, the average capacity ratio is closer to unity. Capacity predictions in mixed soil are a combination of capacity predictions for clay and sand layers, and it would be expected that for piles in mixed soil, the average capacity ratio should be between that of sands and clays. This is not the case for the Comprehensive Database. There are only 3 piles driven into clay in the Comprehensive Database, and a significant amount of scatter is associated with the capacity predictions for those piles. Due to this, only limited conclusions about the IDOT Static method and a soil type bias can be drawn.

C.4.6. K-IDOT/SLT

Detailed results for the K-IDOT/SLT data are presented in Table C.11, and the data are graphed in Figure C.10. The capacity estimates for closed-end pipe piles in sand and clay will be the same for both the K-IDOT and IDOT-S methods. There are two open-ended pipe piles in the database. For one of these piles, the IDOT-S and K-IDOT methods predict a different base capacity. This is noticeable when comparing the pipe piles in sand subcategory between the two methods, but the data for all pipe piles are not significantly affected. There is a much stronger tendency for the K-IDOT method to overpredict capacity in sand than there is in clay. However, the scatter associated with capacity estimates in sand is almost half that associated with capacity estimates in clay.

C.4.7 WSDOT/IDOT Static

Detailed results for the WSDOT/IDOT Static data are presented in Table C.12, and the data are graphed in Figure C.11. The average capacity ratio does not show much bias between pile types. There are similar amounts of scatter for H-piles and pipe piles. The WSDOT formula tends to predict a much higher capacity than the IDOT Static method in clays. The agreement for sands is comparable to that for all data.

C.4.8 WSDOT/K-IDOT

Detailed results for the WSDOT/K-IDOT data are presented in Table C.13, and the data are graphed in Figure C.12. With regard to pile type, the WSDOT formula tends to overpredict capacity for pipe piles and underpredict it for H-piles, relative to the K-IDOT method. In clay, the WSDOT formula tends to predict a much larger capacity than the K-IDOT method, while in sand, the K-IDOT method tends to predict a much larger capacity than the WSDOT method. There are some fairly large COV values within the subcategories that indicate a lot of disagreement between the WSDOT formula and the K-IDOT method.

C.4.9 WSDOT/ICP

Detailed results for the WSDOT/ICP data are presented in Table C.14, and the data are graphed in Figure C.13. There appears to be some bias for pile type between the WSDOT formula and ICP method. The ICP method predicts a larger capacity for both pile types on the average, but the difference between capacity estimates is larger for H-piles than pipe piles. Across soil types, the average capacity ratios are fairly similar, indicating the average WSDOT/ICP capacity ratio is not very sensitive to soil type.

C.4.10 FHWA-Gates/IDOT Static

Detailed results for the FHWA-Gates/IDOT Static data are presented in Table C.15, and the data are graphed in Figure C.14. There appears to be some bias between pile types for the data. The average capacity ratio for pipe piles is 1.02, while that for H-piles is 1.18. Both categories have a degree of scatter comparable to the overall. Based on limited data points, the FHWA-Gates formula tends to predict a much higher capacity than the IDOT Static method in clay. In sand, the FHWA-Gates formula also tends to predict a higher capacity than the IDOT Static method, but not to the extent as in clay. The degree of scatter for both soil types is large.

C.4.11 FHWA-Gates/K-IDOT

Detailed results for the FHWA-Gates/K-IDOT data are presented in Table C.16, and the data are graphed in Figure C.15. With respect to pile type, the Kinematic IDOT method tends to overpredict pile capacity relative to the FHWA-Gates formula to a greater extent in H-piles than in pipe piles. In sand, the Kinematic IDOT method tends to predict a larger capacity than the FHWA-Gates formula with a degree of scatter comparable to that for all data. Although there are a limited amount of data points in clay, the Kinematic IDOT method tends to predict a much smaller capacity than the FHWA-Gates formula. There is a large amount of scatter associated with this data.

C.4.12 FHWA-Gates/ICP

Detailed results for the FHWA-Gates/ICP data are presented in Table C.17, and the data are graphed in Figure C.16. The average FHWA-Gates/ICP capacity ratio does appear to be slightly sensitive to pile type. The average capacity ratio is a little lower for H-piles than pipe piles, but the difference is not large. The degree of scatter for H-piles and pipe piles is similar to that for all data. The average capacity ratios for clay and sand are also fairly similar.

The ICP method predicts a greater capacity than the FHWA-Gates formula in sand, and the ICP method predicts a smaller capacity than the FHWA-Gates formula in clay.

C.4.13 FHWA-UI/IDOT Static

Detailed results for the FHWA-UI/IDOT Static data are presented in Table C.18, and the data are graphed in Figure C.17. The average FHWA-UI/IDOT Static capacity ratio does not appear to be very sensitive to pile type. The average capacity ratios and scatter are very similar for H-piles and pipe piles. There is limited data available for piles in clay. Based on this limited data, it appears that IDOT Static predicts a much smaller capacity in clays than the FHWA-UI formula. The agreement between the average capacity ratios of the two methods is good for sand. However, there is a significant amount of scatter in each soil subcategory.

C.4.14 FHWA-UI/K-IDOT

Detailed results for the FHWA-UI/K-IDOT data are presented in Table C.19, and the data are graphed in Figure C.18. There appears to be bias with regard to pile type for the FHWA-UI/Kinematic IDOT data. The Kinematic IDOT method predicts a larger capacity than the FHWA-UI formula for H-piles. The opposite trend is observed for the average FHWA-UI/IDOT Static capacity ratio in pipe piles. Based on the assumptions of the K-IDOT method, this is to be expected. There are few data points to draw conclusions from in clayey soils. Acknowledging this, the K-IDOT method tends to predict a much smaller capacity in clays than the FHWA-UI formula, and the K-IDOT method tends to predict a much larger capacity than the FHWA-UI formula in sand.

C.4.15 FHWA-UI/ICP

Detailed results for the FHWA-UI/ICP data are presented in Table C.20, and the data are graphed in Figure C.19. With regard to pile type, the ICP method tends to predict a higher capacity than the FHWA-UI formula for both H-piles and pipe piles. The average capacity ratio is closer to unity for pipe piles. Looking at the limited data available for piles in clay, it appears that the ICP method tends to predict a smaller capacity than the FHWA-UI formula. In sand, the opposite is true, the ICP method tends to predict a larger capacity than the FHWA-UI formula.

Table C.1. Piles in the Comprehensive Database

Pile Number	Pile Type	Soil Type	Pile Length (ft)	Location
1	HP12x53	Mix	104	Dubuque, IA
2	HP14x89	Mix	131	Dubuque, IA
4	HP14x89	Sand	104.3	Dubuque, IA
5	18" x 0.625" CEP	Sand	155	Dubuque, IA
7	14" x 0.50" CEP	Sand	125.9	Dubuque, IA
8	14" x 0.25" CEP	Sand	66.7	Dubuque, IA
9	HP12x53	Mix	41.3	Tioga River, PA
12	HP10x42	Mix	72	Baltimore, MD
13	HP10x42	Sand	73	Baltimore, MD
15	HP14x89	Mix	80	Mobile County, AL
16	HP14x89	Mix	100	Mobile County, AL
17	10" OEP	Sand	48	Mobile, AL
18	14" OEP	Mix	71	New Orleans, LA
19	HP14x73	Mix	136	Arrowhead Bridge, WI
20	16" x 0.219" CEP	Mix	122	Arrowhead Bridge, WI
24	14" x 0.438" CEP	Mix	103.5	Marquette Interchange, WI
27	12.75" x 0.375" CEP	Mix	130	Marquette Interchange, WI
28	HP12x53	Sand	37.9	Jacksonville, IL
29	HP12x53	Mix	84.3	Peoria, IL
30	12.75" x 0.75" CEP	Clay	45	Lemoore, CA
31	12.75" x 0.75" CEP	Clay	45	Lemoore, CA
32	HP10x42	Clay	53	Baldwin County, AL
33	HP14x73	Sand	96.1	Hennipen, MN
Finno	HP14x73	Mix	50	Evansville, IL
O'Neill	10.75" CEP	Clay	43	Texas
Laier	HP12x74	Mix	119	Louisiana

Table C.2. Statistics for the Average EN-IDOT/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.24	0.43	0.45
	Std. Dev:	0.07	0.12	0.26
	COV:	0.27	0.27	0.57
	r^2:	0.18	0.93	0.82
	n:	3	4	11
H-Piles	**Average:**	0.60	0.39	0.48
	Std. Dev:	-	0.14	0.27
	COV:	-	0.35	0.57
	r^2:	-	0.46	0.38
	n:	1	4	15
All Piles	**Average:**	0.34	0.40	0.47
	Std. Dev:	0.18	0.12	0.26
	COV:	0.53	0.31	0.56
	r^2:	0.68	0.71	0.62
	n:	4	8	26

Table C.3. Statistics for the Average WEAP/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.55	0.74	0.70
	Std. Dev:	0.22	0.25	0.23
	COV:	0.39	0.34	0.33
	r^2:	0.00	0.94	0.90
	n:	3	4	11
H-Piles	**Average:**	0.90	0.55	0.61
	Std. Dev:	-	0.17	0.28
	COV:	-	0.31	0.45
	r^2:	-	0.84	0.59
	n:	1	4	15
All Piles	**Average:**	0.64	0.65	0.65
	Std. Dev:	0.28	0.22	0.26
	COV:	0.44	0.34	0.40
	r^2:	0.54	0.90	0.77
	n:	4	8	26

Table C.4. Statistics for the Average Olson/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.85	2.39	1.39
	Std. Dev:	0.59	3.08	1.15
	COV:	0.70	1.29	0.82
	r^2:	0.89	0.88	0.48
	n:	3	4	11
H-Piles	**Average:**	0.43	1.32	1.32
	Std. Dev:	-	1.20	0.84
	COV:	-	0.92	0.63
	r^2:	-	0.51	0.24
	n:	1	4	15
All Piles	**Average:**	0.73	1.72	1.33
	Std. Dev:	0.45	1.80	0.93
	COV:	0.62	1.05	0.70
	r^2:	0.03	0.19	0.38
	n:	4	8	26

Table C.5. Statistics for the Average Driven/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.06	2.01	1.38
	Std. Dev:	0.50	3.49	1.20
	COV:	0.47	1.74	0.87
	r^2:	1.00	0.98	0.50
	n:	3	4	11
H-Piles	**Average:**	0.41	1.23	1.27
	Std. Dev:	-	1.82	1.24
	COV:	-	1.49	0.98
	r^2:	-	0.49	0.20
	n:	1	4	15
All Piles	**Average:**	0.91	1.45	1.30
	Std. Dev:	0.55	2.09	1.19
	COV:	0.61	1.44	0.92
	r^2:	0.21	0.21	0.34
	n:	4	8	26

Table C.6. Statistics for the Average FHWA-Gates/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.96	1.22	1.07
	Std. Dev:	0.26	0.23	0.24
	COV:	0.26	0.19	0.22
	r^2:	0.14	0.93	0.89
	n:	3	3	9
H-Piles	**Average:**	1.86	0.81	0.99
	Std. Dev:	-	0.15	0.35
	COV:	-	0.18	0.35
	r^2:	-	0.74	0.53
	n:	1	3	14
All Piles	**Average:**	1.20	1.01	1.02
	Std. Dev:	0.51	0.29	0.31
	COV:	0.43	0.29	0.31
	r^2:	0.37	0.81	0.73
	n:	4	6	23

Table C.7. Statistics for the Average FHWA-UI/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.26	1.09	1.17
	Std. Dev:	0.33	0.32	0.29
	COV:	0.26	0.30	0.24
	r^2:	0.14	0.82	0.70
	n:	3	3	9
H-Piles	**Average:**	1.95	0.62	0.84
	Std. Dev:	-	0.19	0.38
	COV:	-	0.31	0.45
	r^2:	-	0.37	0.39
	n:	1	3	14
All Piles	**Average:**	1.45	0.85	0.97
	Std. Dev:	0.48	0.35	0.42
	COV:	0.33	0.42	0.43
	r^2:	0.19	0.50	0.52
	n:	4	6	23

Table C.8. Statistics for the Average WSDOT/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.96	1.19	1.16
	Std. Dev:	0.27	0.23	0.26
	COV:	0.29	0.19	0.22
	r^2:	0.14	0.82	0.70
	n:	3	4	11
H-Piles	**Average:**	1.31	0.80	0.91
	Std. Dev:	-	0.21	0.26
	COV:	-	0.26	0.29
	r^2:	-	0.37	0.39
	n:	1	4	15
All Piles	**Average:**	1.05	1.00	1.02
	Std. Dev:	0.31	0.32	0.29
	COV:	0.30	0.32	0.29
	r^2:	0.19	0.50	0.52
	n:	4	8	26

Table C.9. Statistics for the Average ICP/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.80	2.33	1.95
	Std. Dev:	1.19	2.28	1.29
	COV:	0.66	0.98	0.66
	r^2:	0.52	0.95	0.59
	n:	3	4	11
H-Piles	**Average:**	0.93	1.64	1.77
	Std. Dev:	-	0.74	0.70
	COV:	-	0.45	0.39
	r^2:	-	0.01	0.52
	n:	1	4	15
All Piles	**Average:**	1.55	1.91	1.85
	Std. Dev:	0.90	1.28	0.94
	COV:	0.58	0.67	0.51
	r^2:	0.05	0.50	0.55
	n:	4	8	26

Table C.10. Statistics for the Average IDOT Static/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.93	2.18	1.57
	Std. Dev:	1.03	2.86	1.14
	COV:	0.53	1.31	0.73
	r^2:	1.00	0.90	0.49
	n:	2	4	11
H-Piles	**Average:**	0.42	1.37	1.13
	Std. Dev:	-	0.97	0.70
	COV:	-	0.71	0.62
	r^2:	-	0.40	0.27
	n:	1	6	15
All Piles	**Average:**	1.56	1.59	1.30
	Std. Dev:	1.69	1.38	0.88
	COV:	1.08	0.87	0.67
	r^2:	0.43	0.30	0.36
	n:	3	10	26

Table C.11. Statistics for the Average Kinematic IDOT/SLT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.93	1.99	1.56
	Std. Dev:	1.03	1.76	0.95
	COV:	0.53	0.88	0.61
	r^2:	1.00	0.91	0.49
	n:	2	4	11
H-Piles	**Average:**	0.42	2.63	2.36
	Std. Dev:	-	1.16	1.65
	COV:	-	0.44	0.70
	r^2:	-	0.09	0.38
	n:	1	10	15
All Piles	**Average:**	1.56	2.44	2.00
	Std. Dev:	1.69	1.45	1.37
	COV:	1.08	0.59	0.68
	r^2:	0.43	0.48	0.41
	n:	3	14	26

Table C.12. Statistics for the Average WSDOT/IDOT Static Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.73	1.56	1.16
	Std. Dev:	0.40	2.28	0.94
	COV:	0.55	1.46	0.81
	r^2:	1.00	0.90	0.39
	n:	2	4	11
H-Piles	**Average:**	3.13	1.08	1.17
	Std. Dev:	-	0.86	0.85
	COV:	-	0.80	0.73
	r^2:	-	0.55	0.30
	n:	1	6	15
All Piles	**Average:**	1.77	1.19	1.16
	Std. Dev:	2.28	1.15	0.86
	COV:	1.29	0.96	0.74
	r^2:	0.25	0.31	0.37
	n:	3	10	26

Table C.13. Statistics for the Average WSDOT/K-IDOT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.73	1.10	1.05
	Std. Dev:	0.40	1.09	0.70
	COV:	0.55	1.00	0.67
	r^2:	1.00	0.91	0.39
	n:	2	4	11
H-Piles	**Average:**	3.13	0.43	0.60
	Std. Dev:	-	0.22	0.49
	COV:	-	0.52	0.81
	r^2:	-	0.17	0.43
	n:	1	10	15
All Piles	**Average:**	1.77	0.58	0.79
	Std. Dev:	2.28	0.43	0.66
	COV:	1.29	0.74	0.84
	r^2:	0.25	0.35	0.27
	n:	3	14	26

Table C.14. Statistics for the Average WSDOT/ICP Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.69	1.04	0.85
	Std. Dev:	0.35	1.14	0.55
	COV:	0.51	1.10	0.65
	r^2:	0.25	0.95	0.53
	n:	3	4	11
H-Piles	**Average:**	1.48	0.69	0.64
	Std. Dev:	-	0.57	0.38
	COV:	-	0.82	0.59
	r^2:	-	0.16	0.35
	n:	1	4	15
All Piles	**Average:**	0.88	0.82	0.72
	Std. Dev:	0.55	0.72	0.46
	COV:	0.62	0.88	0.63
	r^2:	0.08	0.39	0.47
	n:	4	8	26

Table C.15. Statistics for the Average FHWA-Gates/IDOT Static Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.70	2.62	1.02
	Std. Dev:	0.32	6.07	0.85
	COV:	0.46	2.31	0.84
	r^2:	1.00	0.79	0.36
	n:	2	3	9
H-Piles	**Average:**	4.44	0.90	1.18
	Std. Dev:	-	0.68	0.92
	COV:	-	0.75	0.78
	r^2:	-	0.13	0.23
	n:	1	5	14
All Piles	**Average:**	2.42	1.24	1.11
	Std. Dev:	4.15	1.39	0.88
	COV:	1.71	1.12	0.80
	r^2:	0.63	0.12	0.29
	n:	3	8	23

Table C.16. Statistics for the Average FHWA-Gates/Kinematic IDOT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.70	1.61	0.88
	Std. Dev:	0.32	2.43	0.55
	COV:	0.46	1.51	0.63
	r^2:	1.00	0.81	0.36
	n:	2	3	9
H-Piles	**Average:**	4.44	0.41	0.65
	Std. Dev:	-	0.21	0.63
	COV:	-	0.50	0.96
	r^2:	-	0.14	0.34
	n:	1	9	14
All Piles	**Average:**	2.42	0.60	0.74
	Std. Dev:	4.15	0.51	0.64
	COV:	1.71	0.84	0.87
	r^2:	0.63	0.27	0.30
	n:	3	12	23

Table C.17. Statistics for the Average FHWA-Gates/ICP Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.67	1.54	0.78
	Std. Dev:	0.31	2.37	0.57
	COV:	0.46	1.53	0.74
	r^2:	0.14	0.88	0.50
	n:	3	3	9
H-Piles	**Average:**	1.99	0.54	0.65
	Std. Dev:	-	0.34	0.42
	COV:	-	0.62	0.65
	r^2:	-	0.26	0.27
	n:	1	3	14
All Piles	**Average:**	1.05	0.90	0.69
	Std. Dev:	0.82	0.92	0.47
	COV:	0.78	1.03	0.67
	r^2:	0.35	0.30	0.41
	n:	4	6	23

Table C.18. Statistics for the Average FHWA-UI/IDOT Static Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.92	2.60	1.18
	Std. Dev:	0.43	7.09	1.05
	COV:	0.46	2.73	0.88
	r^2:	1.00	0.60	0.27
	n:	2	3	9
H-Piles	**Average:**	4.66	0.71	1.10
	Std. Dev:	-	0.54	1.01
	COV:	-	0.77	0.92
	r^2:	-	0.37	0.28
	n:	1	5	14
All Piles	**Average:**	2.54	1.05	1.12
	Std. Dev:	3.54	1.29	0.97
	COV:	1.40	1.23	0.87
	r^2:	0.30	0.17	0.29
	n:	3	8	23

Table C.19. Statistics for the Average FHWA-UI/Kinematic IDOT Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.92	1.53	1.02
	Std. Dev:	0.43	2.66	0.71
	COV:	0.46	1.74	0.70
	r^2:	1.00	0.62	0.27
	n:	2	3	9
H-Piles	**Average:**	4.66	0.34	0.59
	Std. Dev:	-	0.18	0.63
	COV:	-	0.53	1.08
	r^2:	-	0.23	0.37
	n:	1	9	14
All Piles	**Average:**	2.54	0.51	0.77
	Std. Dev:	3.54	0.47	0.81
	COV:	1.40	0.92	1.05
	r^2:	0.30	0.21	0.18
	n:	3	12	23

Table C.20. Statistics for the Average FHWA-UI/ICP Capacity Ratios

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.88	1.51	0.89
	Std. Dev:	0.41	2.70	0.67
	COV:	0.46	1.79	0.75
	r^2:	0.14	0.72	0.43
	n:	3	3	9
H-Piles	**Average:**	2.08	0.52	0.58
	Std. Dev:	-	0.50	0.45
	COV:	-	0.96	0.77
	r^2:	-	0.37	0.30
	n:	1	3	14
All Piles	**Average:**	1.22	0.85	0.72
	Std. Dev:	0.80	1.10	0.58
	COV:	0.66	1.29	0.81
	r^2:	0.12	0.22	0.38
	n:	4	6	23

EN-IDOT vs. SLT

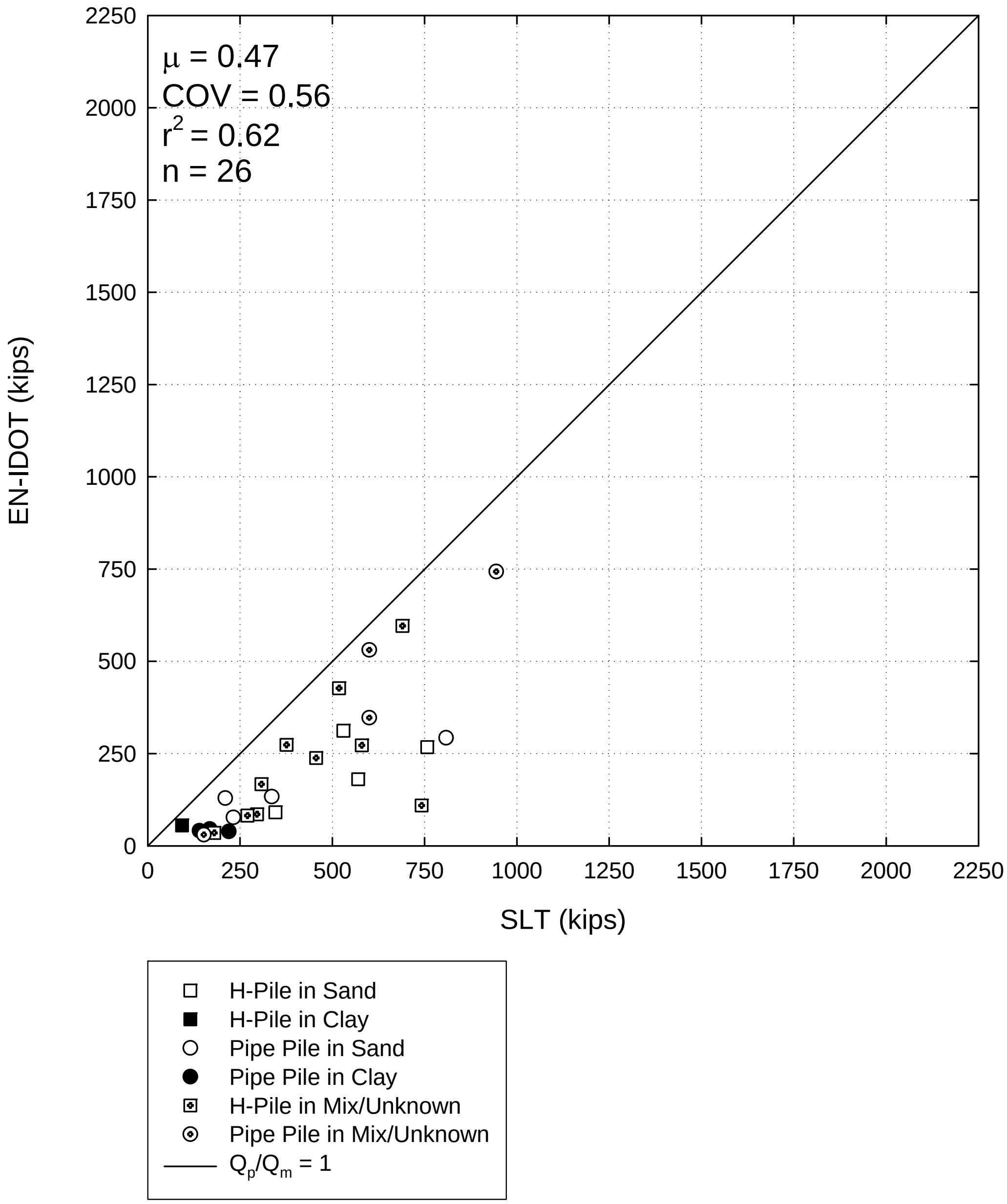

Figure C.1. EN-IDOT vs. SLT, Comprehensive Database.

WEAP vs. SLT

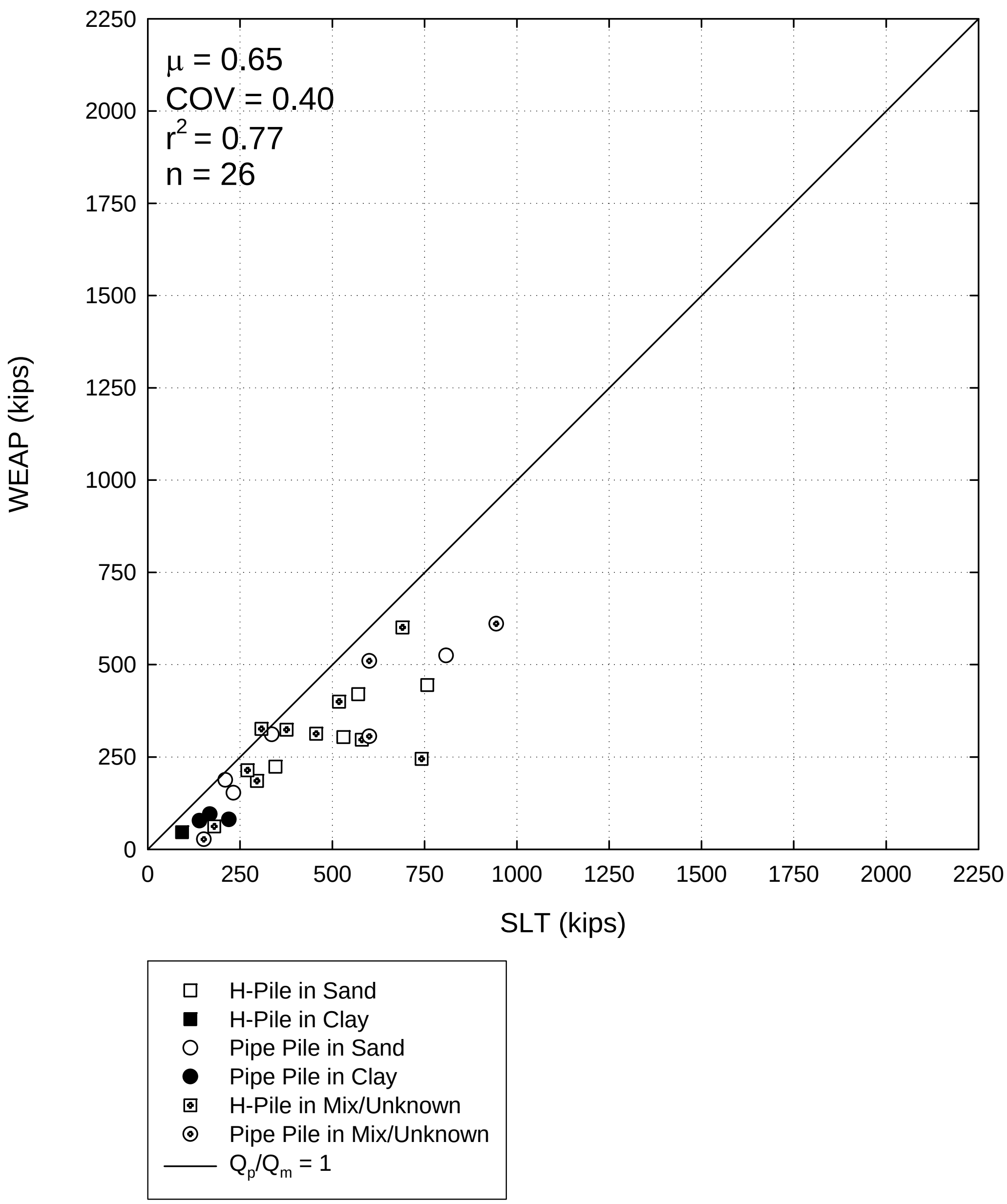

Figure C.2. WEAP vs. SLT, Comprehensive Database.

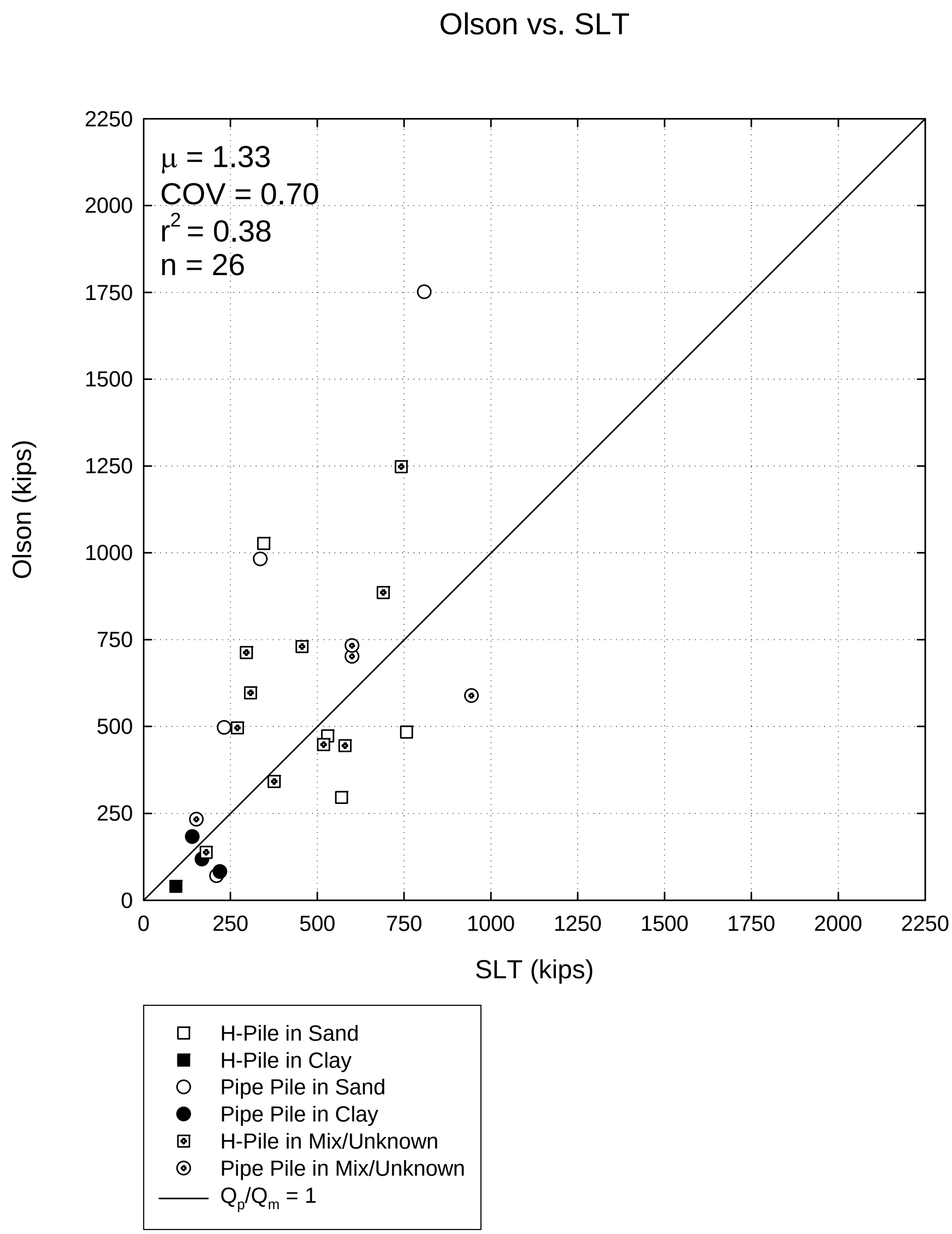

Figure C.3. Olson vs. SLT, Comprehensive Database.

Driven vs. SLT

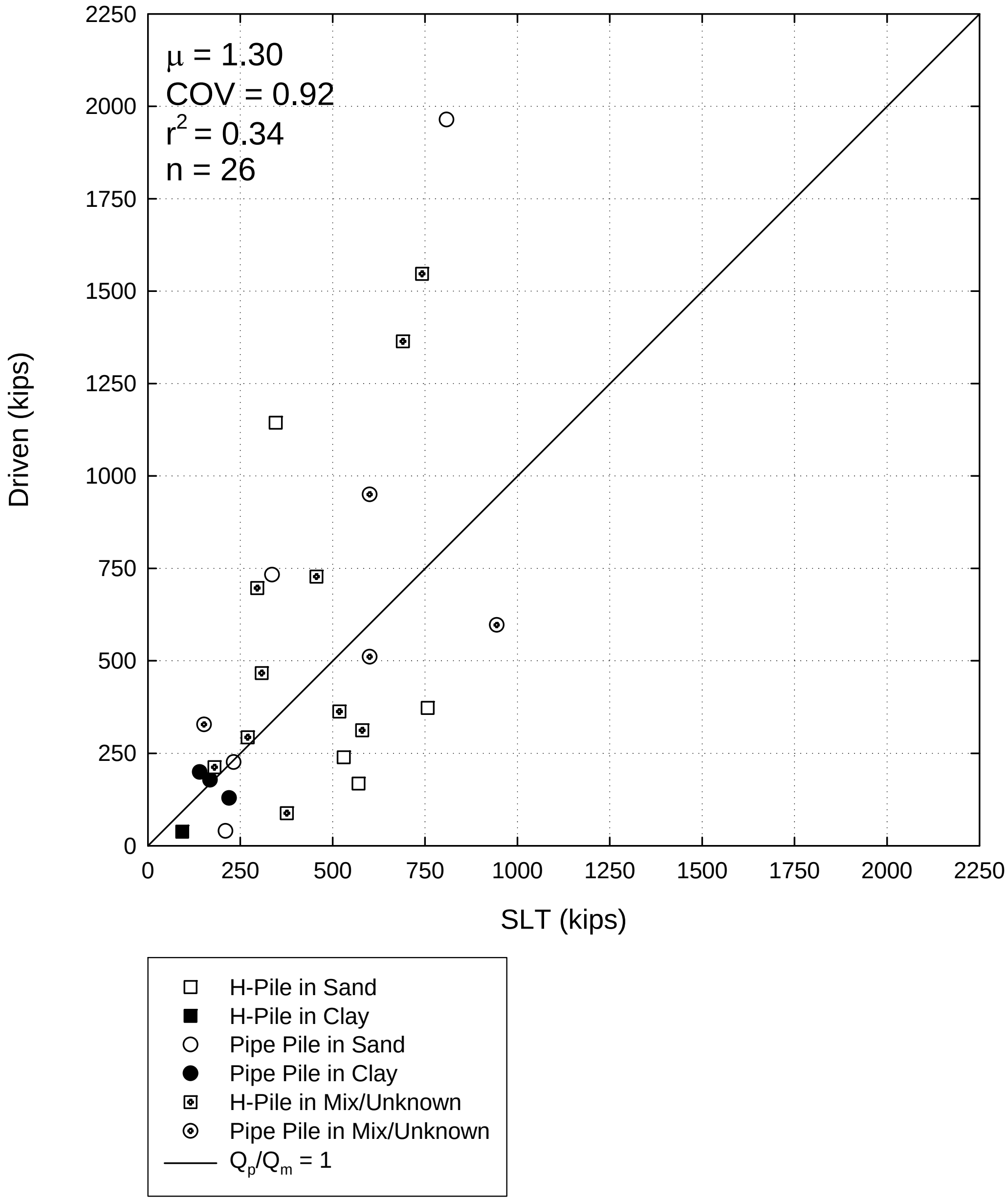

Figure C.4. Driven vs. SLT, Comprehensive Database.

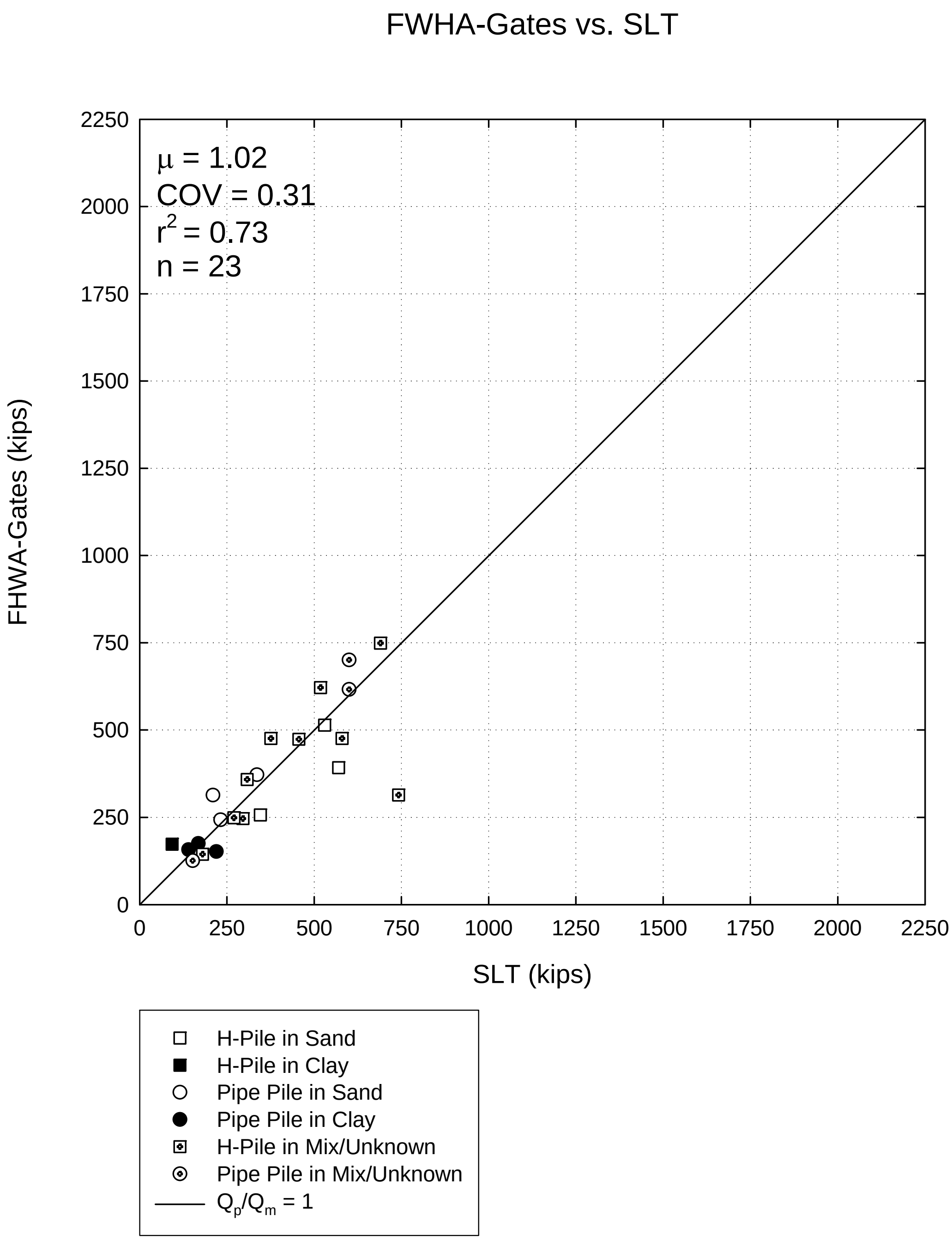

Figure C.5. FHWA-Gates vs. SLT, Comprehensive Database.

FWHA-UI vs. SLT

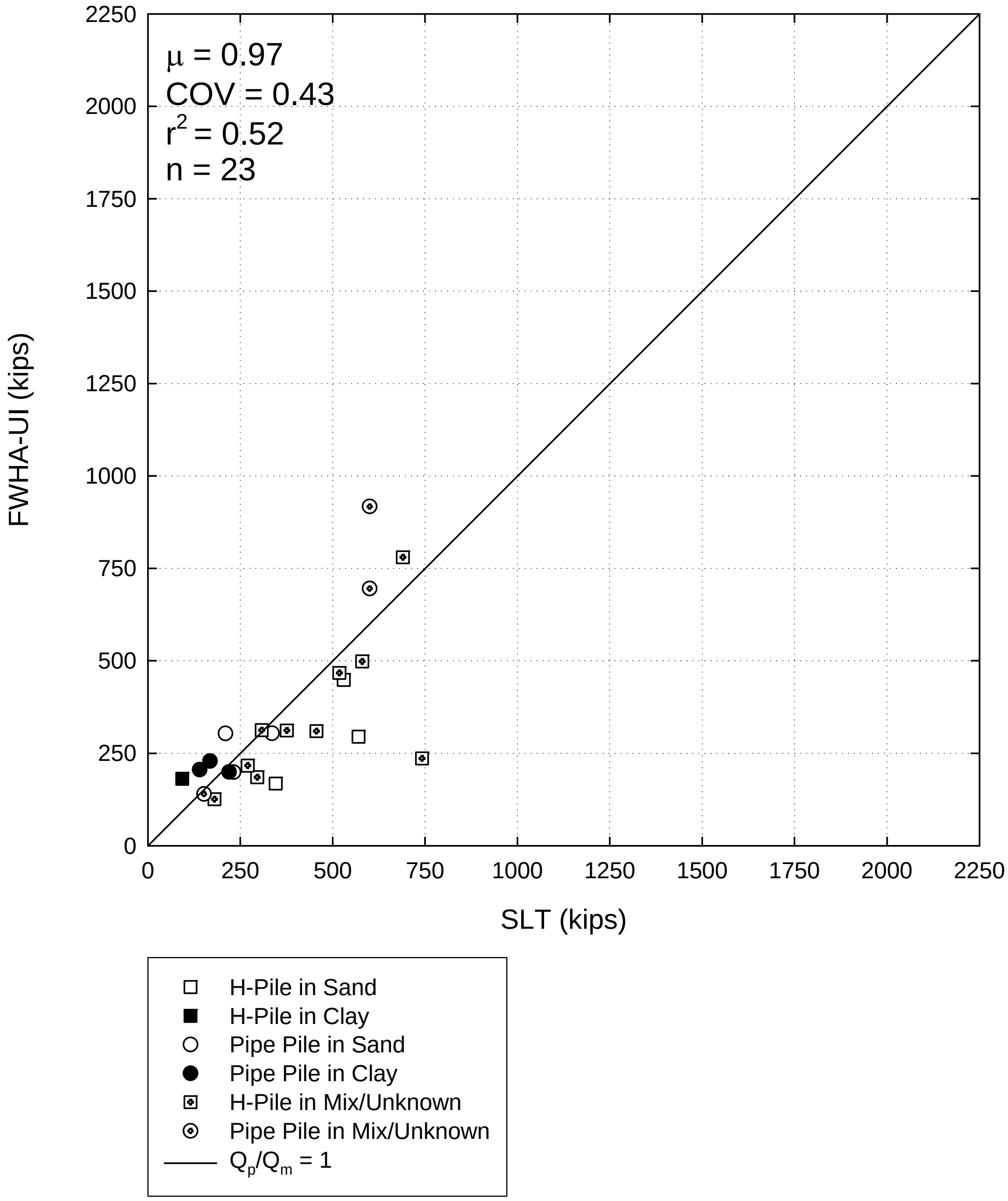

Figure C.6. FHWA-UI vs. SLT, Comprehensive Database.

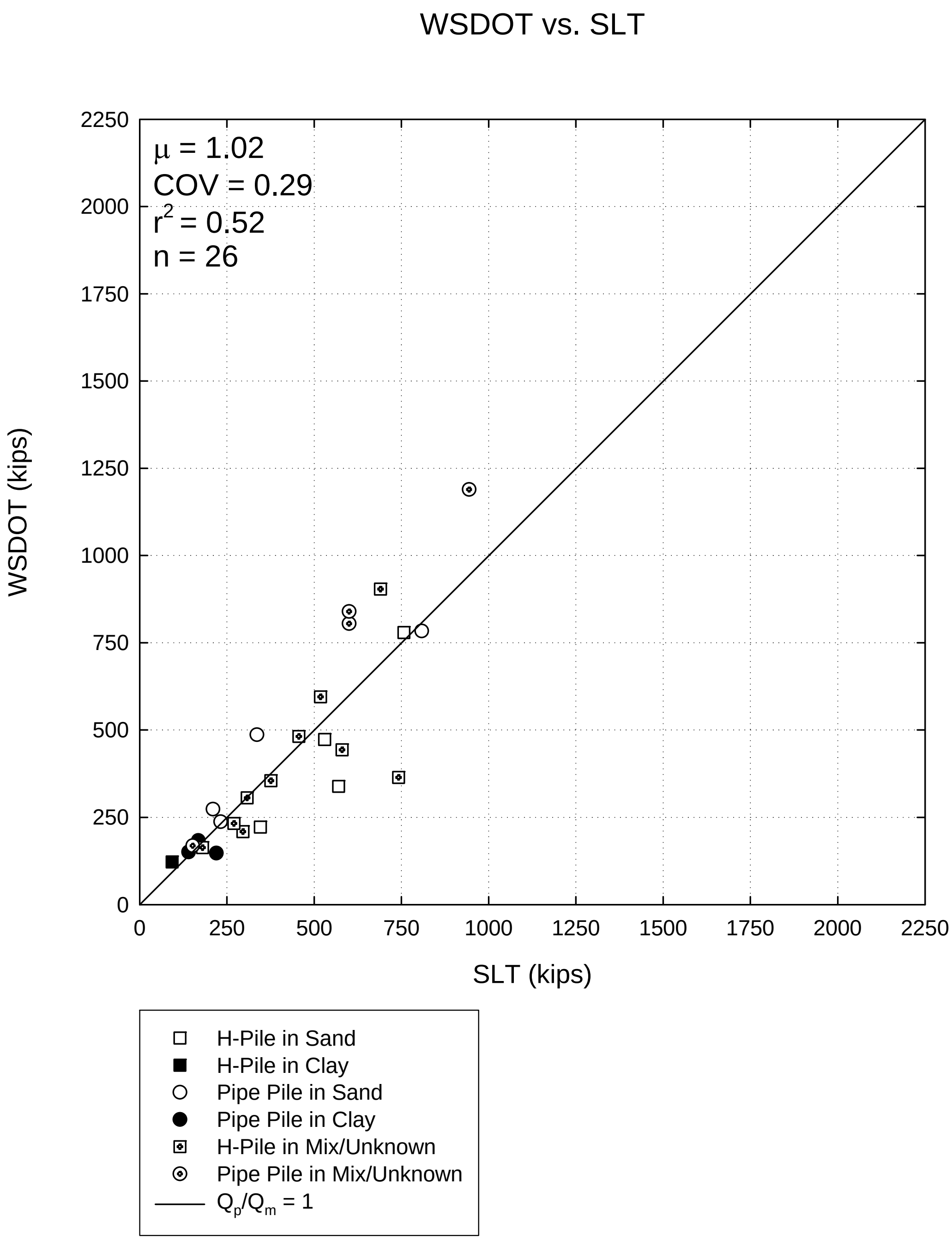

Figure C.7. WSDOT vs. SLT, Comprehensive Database.

ICP vs. SLT

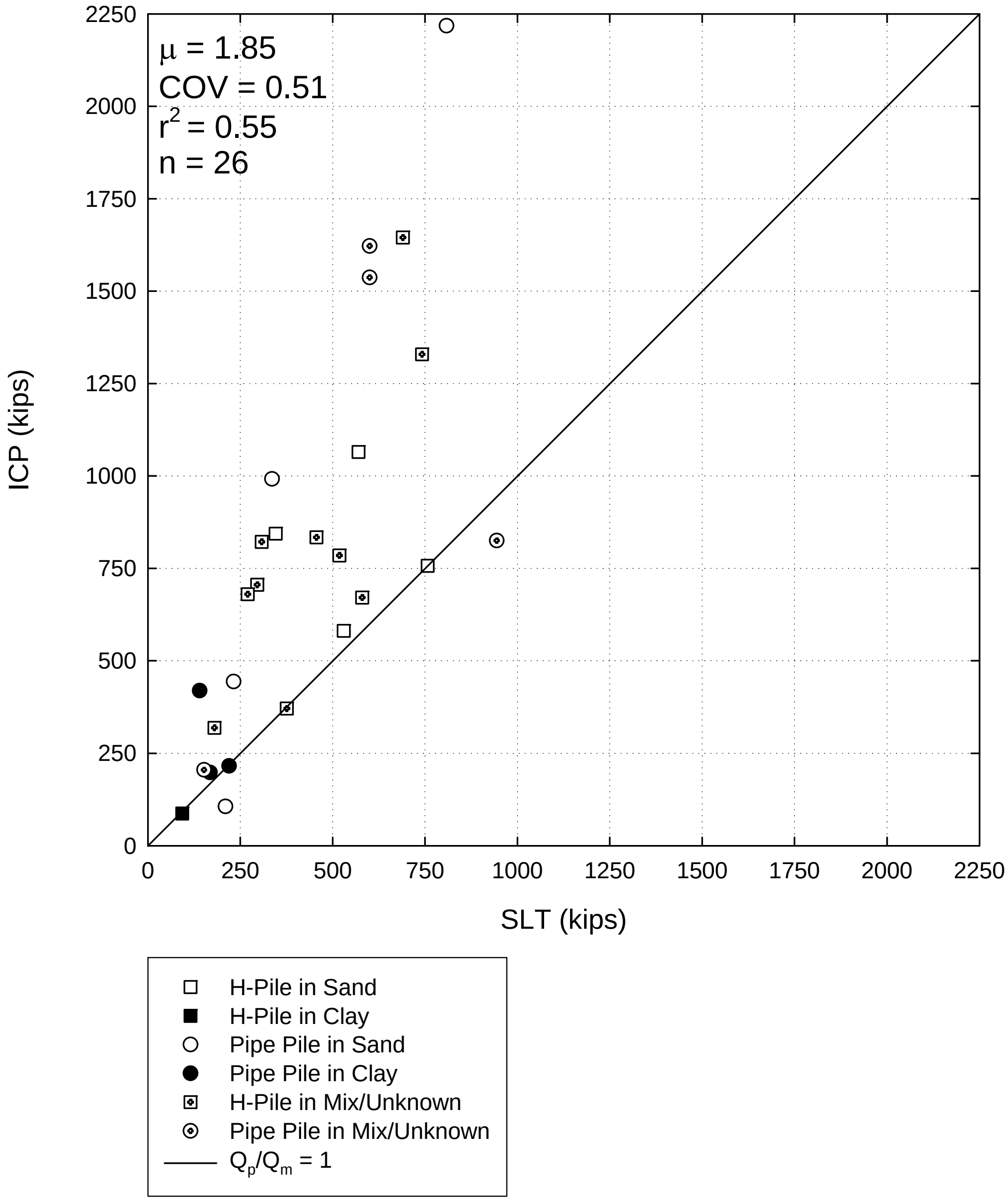

Figure C.8. ICP vs. SLT, Comprehensive Database.

IDOT Static vs. SLT

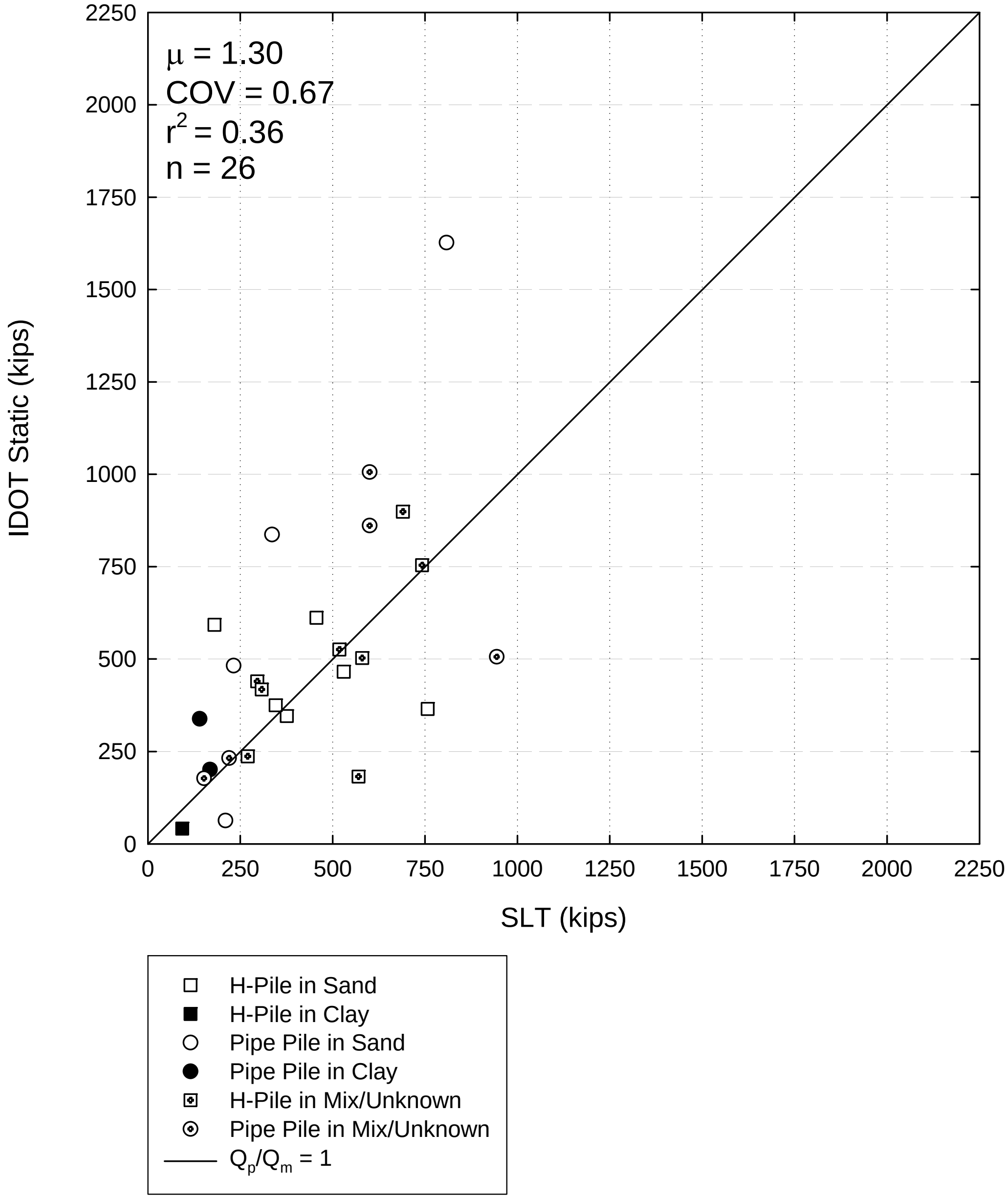

Figure C.9. IDOT Static vs. SLT, Comprehensive Database.

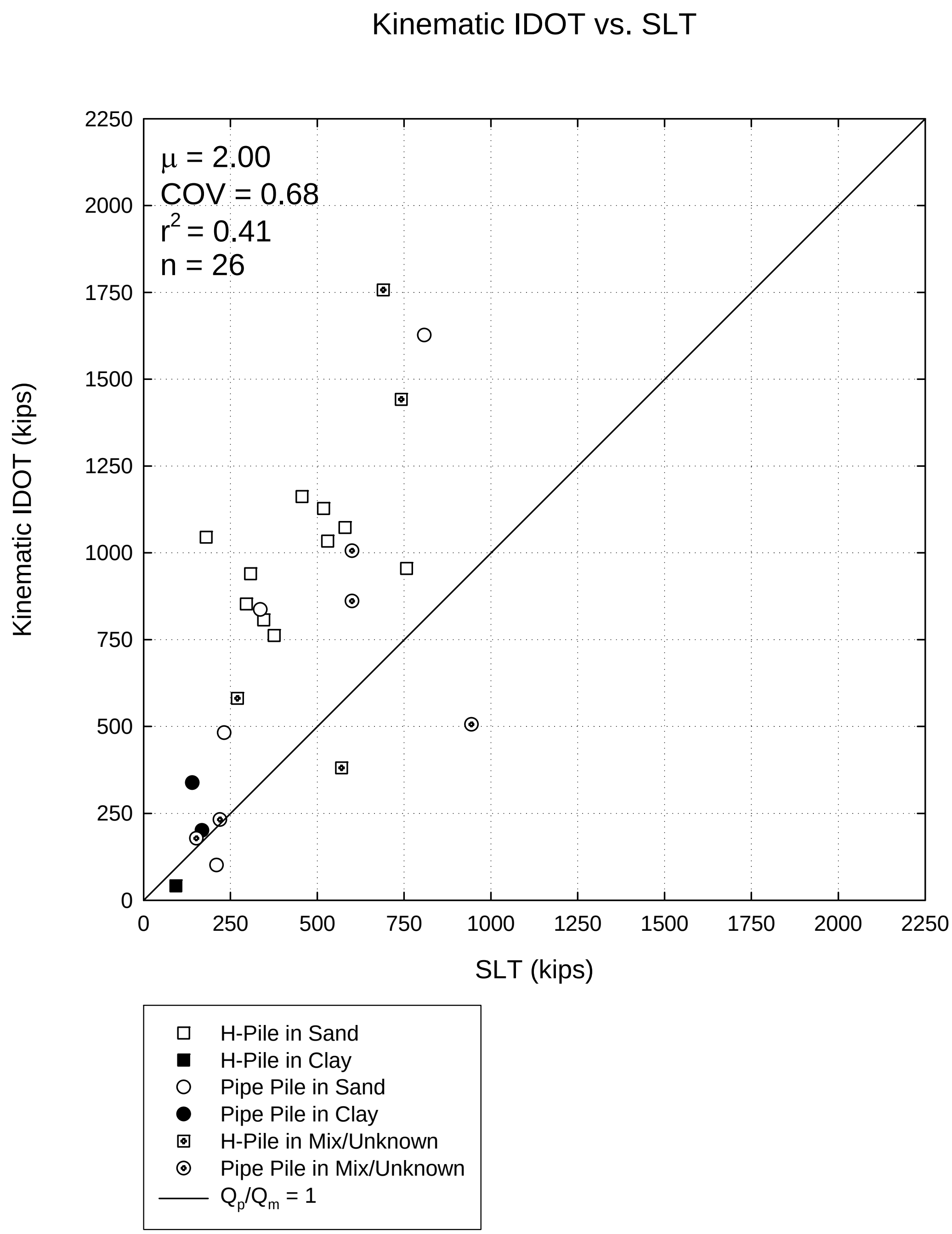

Figure C.10. K-IDOT vs. SLT, Comprehensive Database.

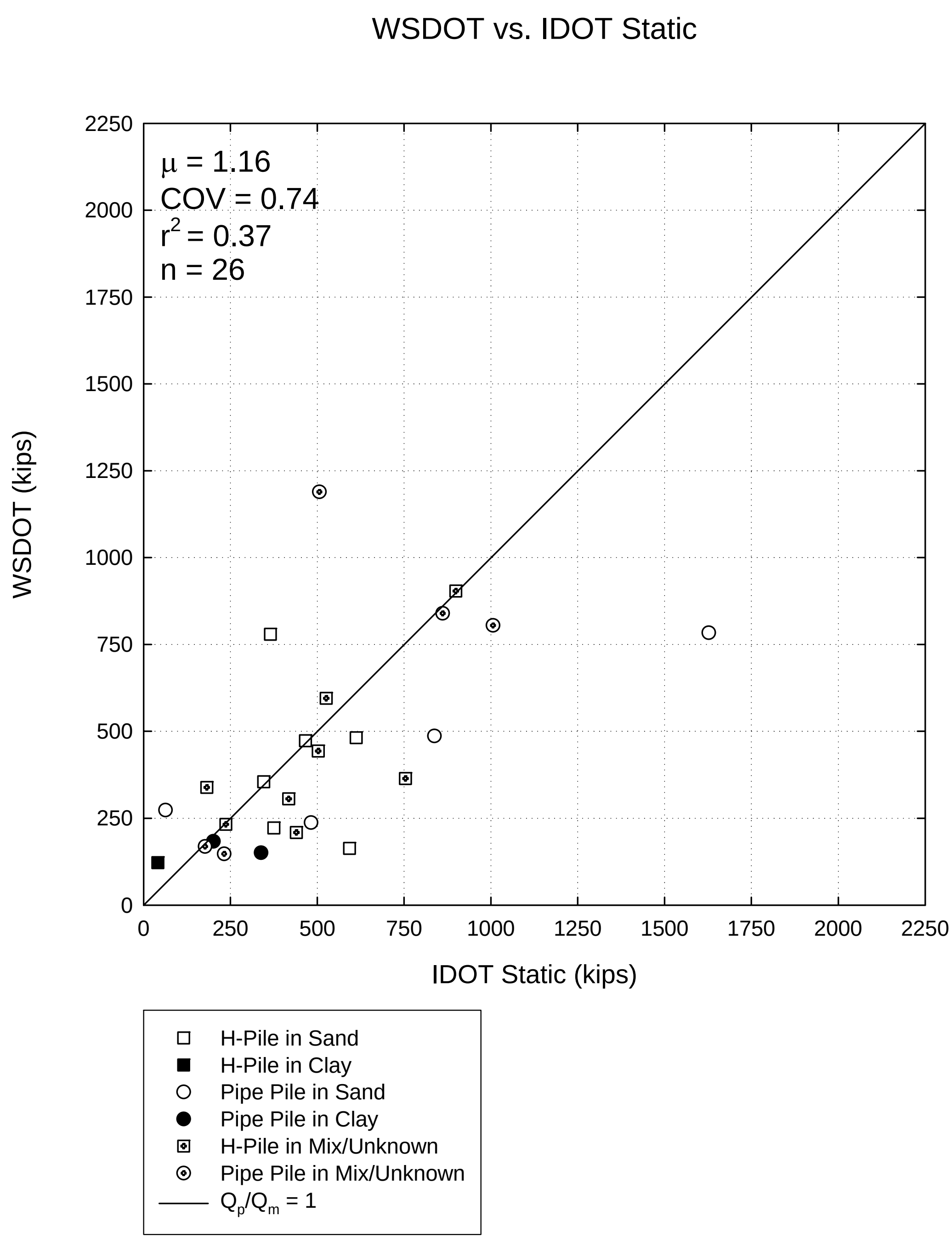

Figure C.11. WSDOT vs. IDOT Static, Comprehensive Database.

WSDOT vs. Kinematic IDOT

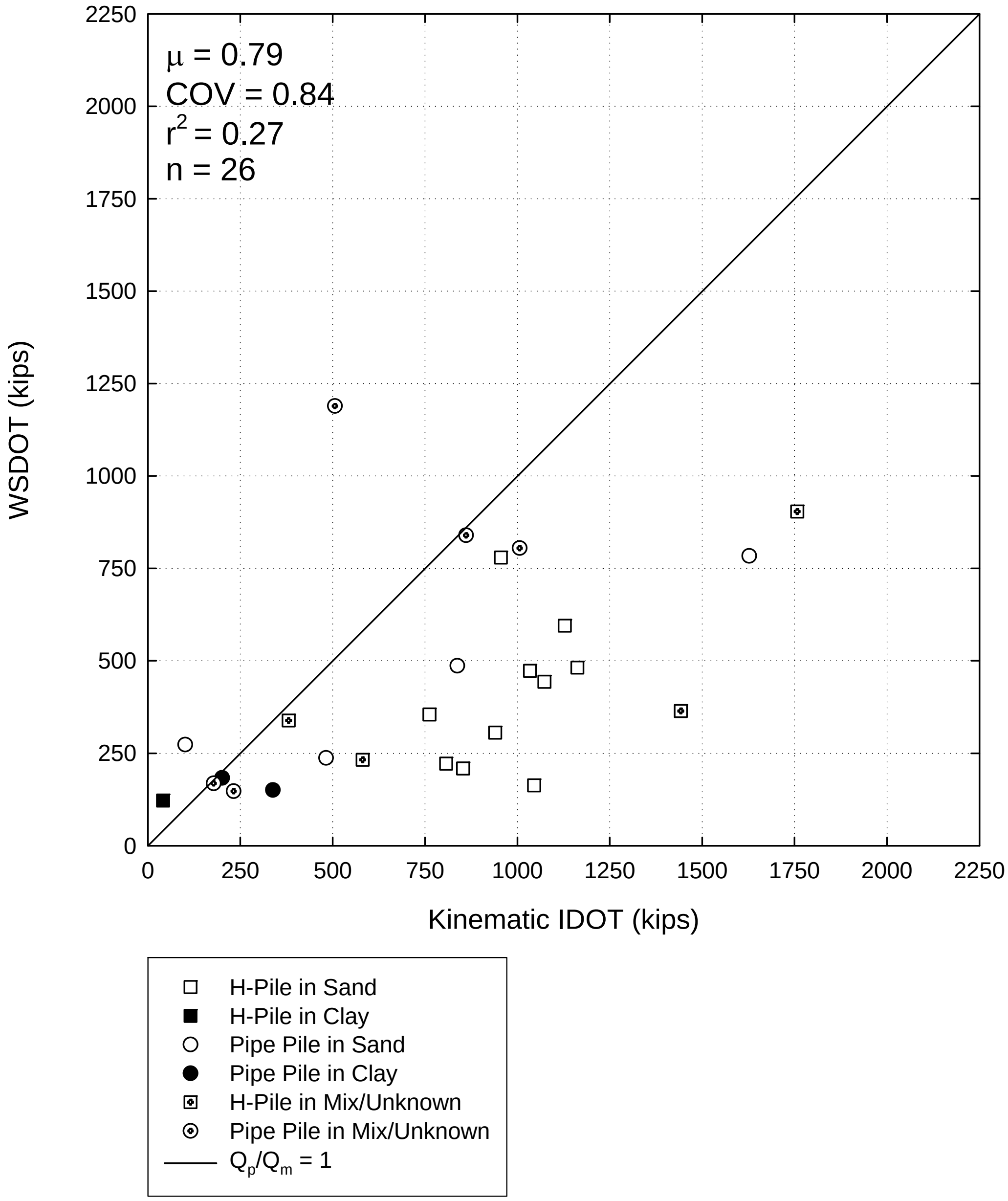

Figure C.12. WSDOT vs. K-IDOT, Comprehensive Database.

WSDOT vs. ICP

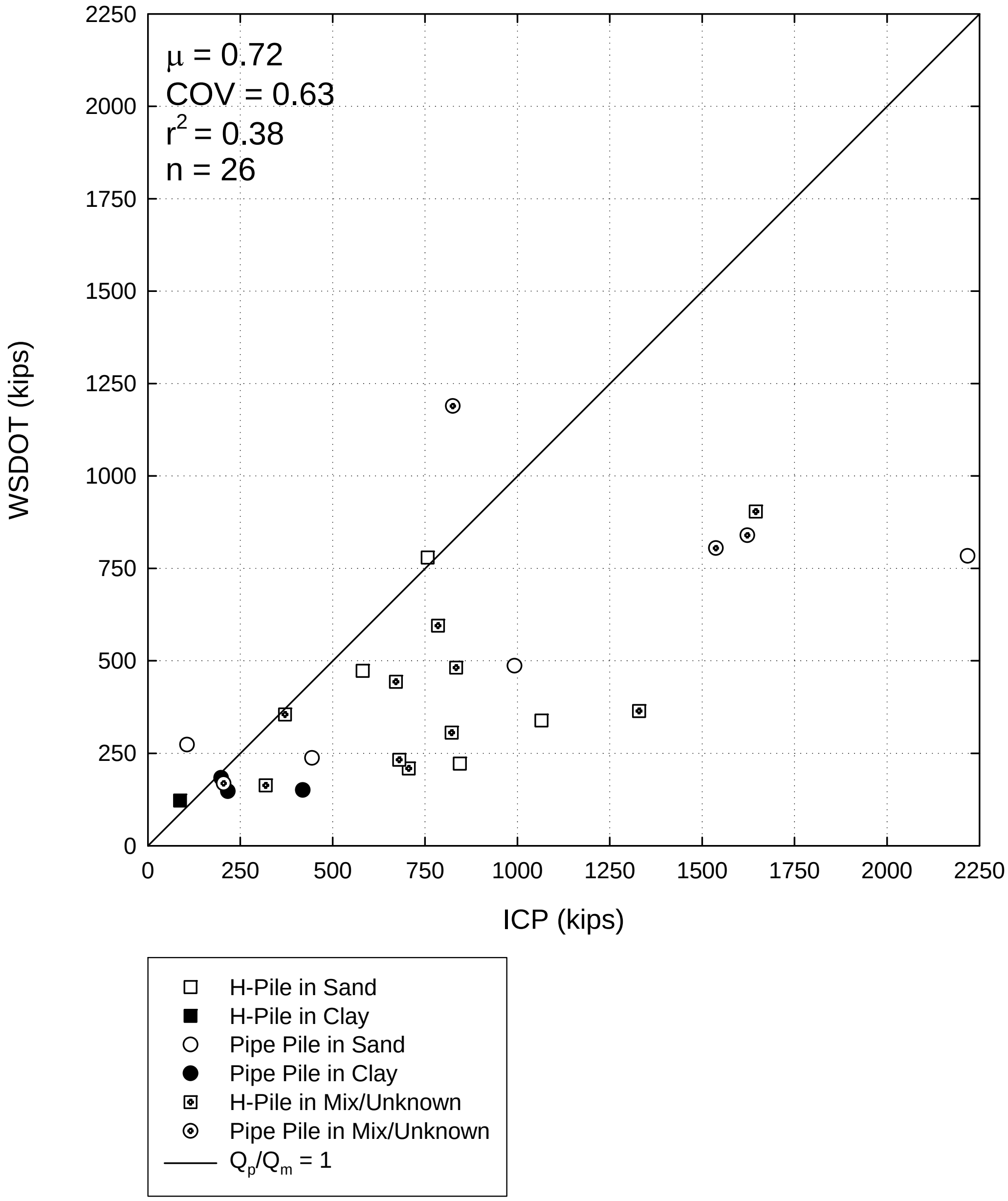

Figure C.13. WSDOT vs. ICP, Comprehensive Database.

FHWA-Gates vs. IDOT Static

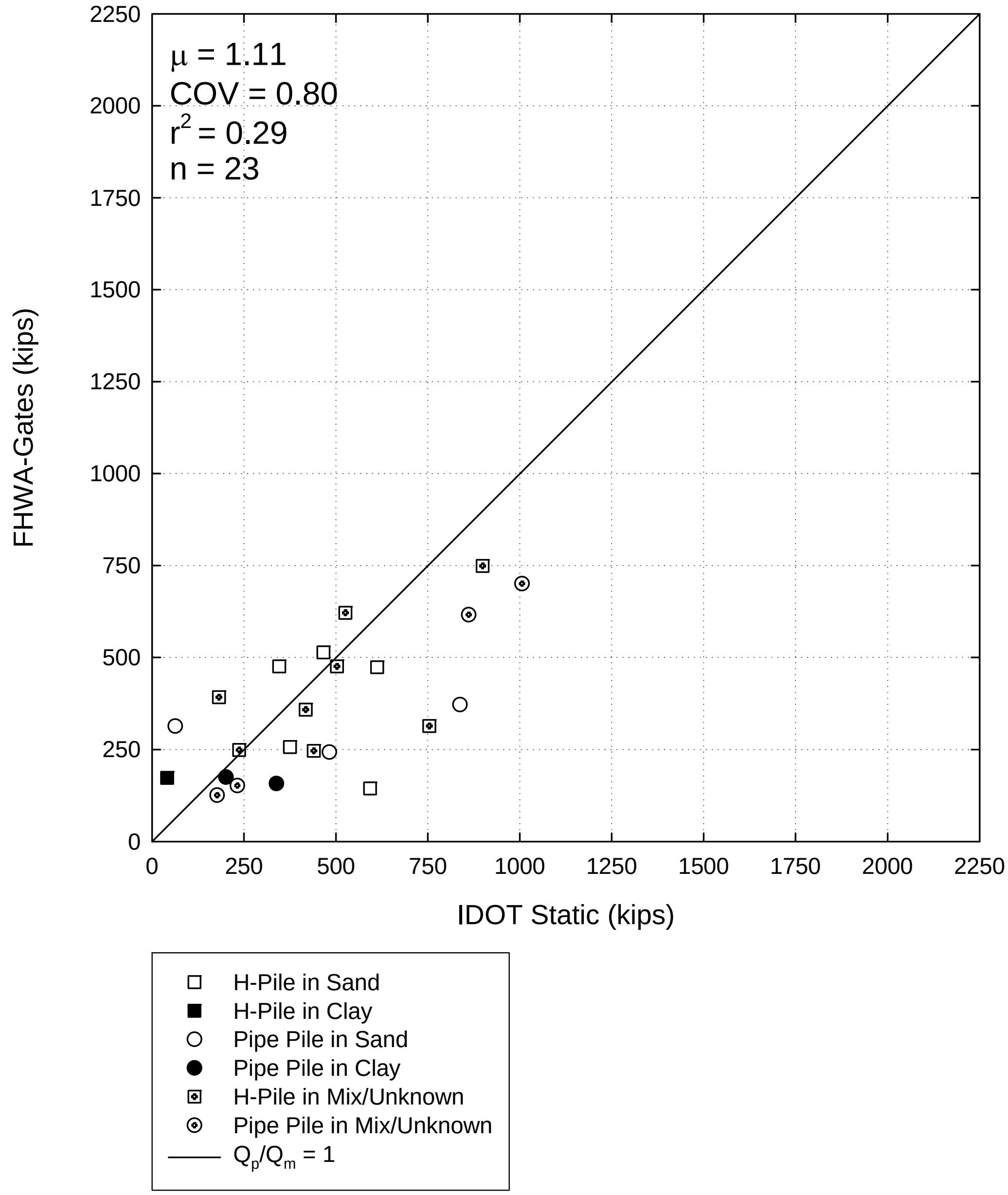

Figure C.14. FHWA-Gates vs. IDOT Static, Comprehensive Database.

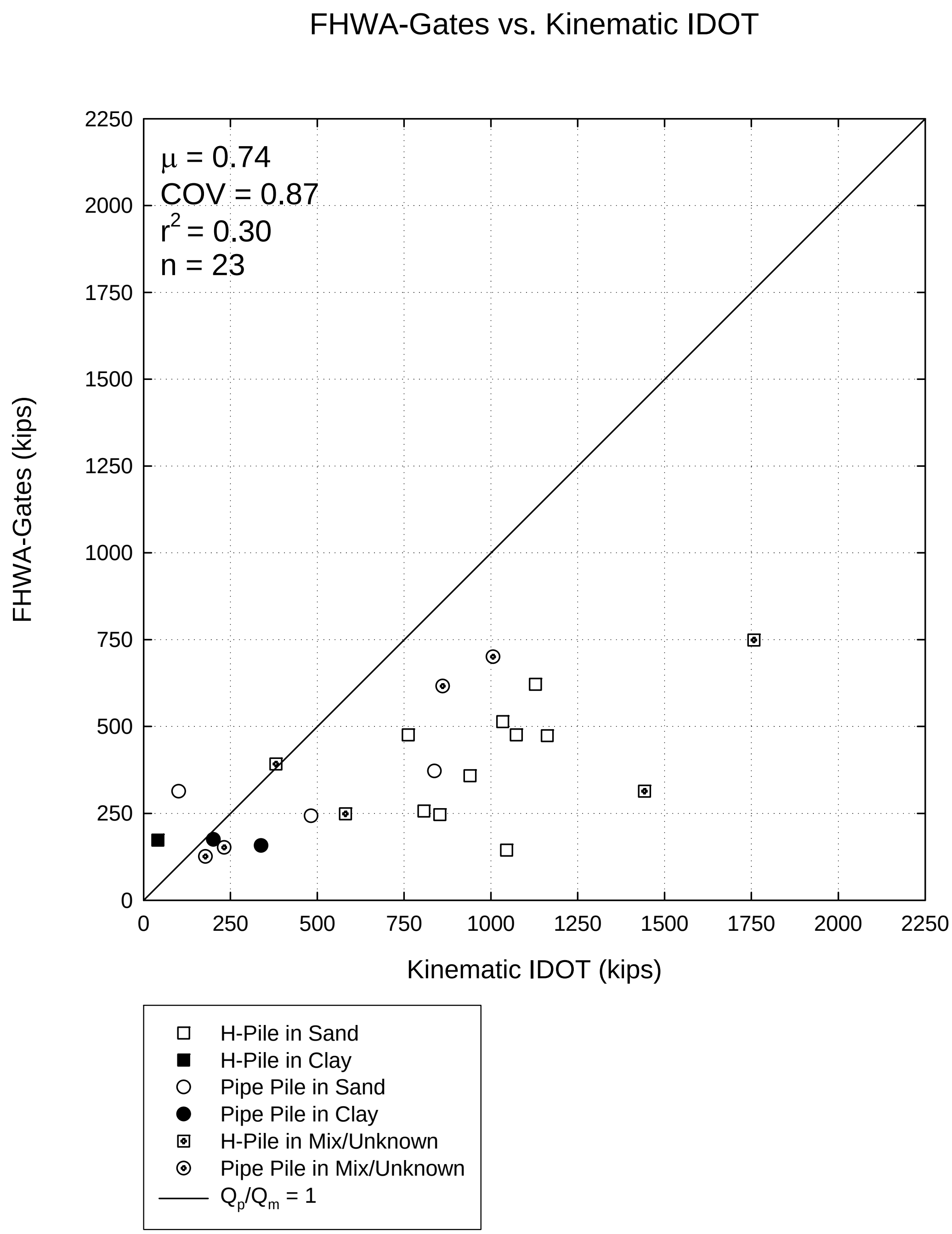

Figure C.15. FHWA-Gates vs. K-IDOT, Comprehensive Database.

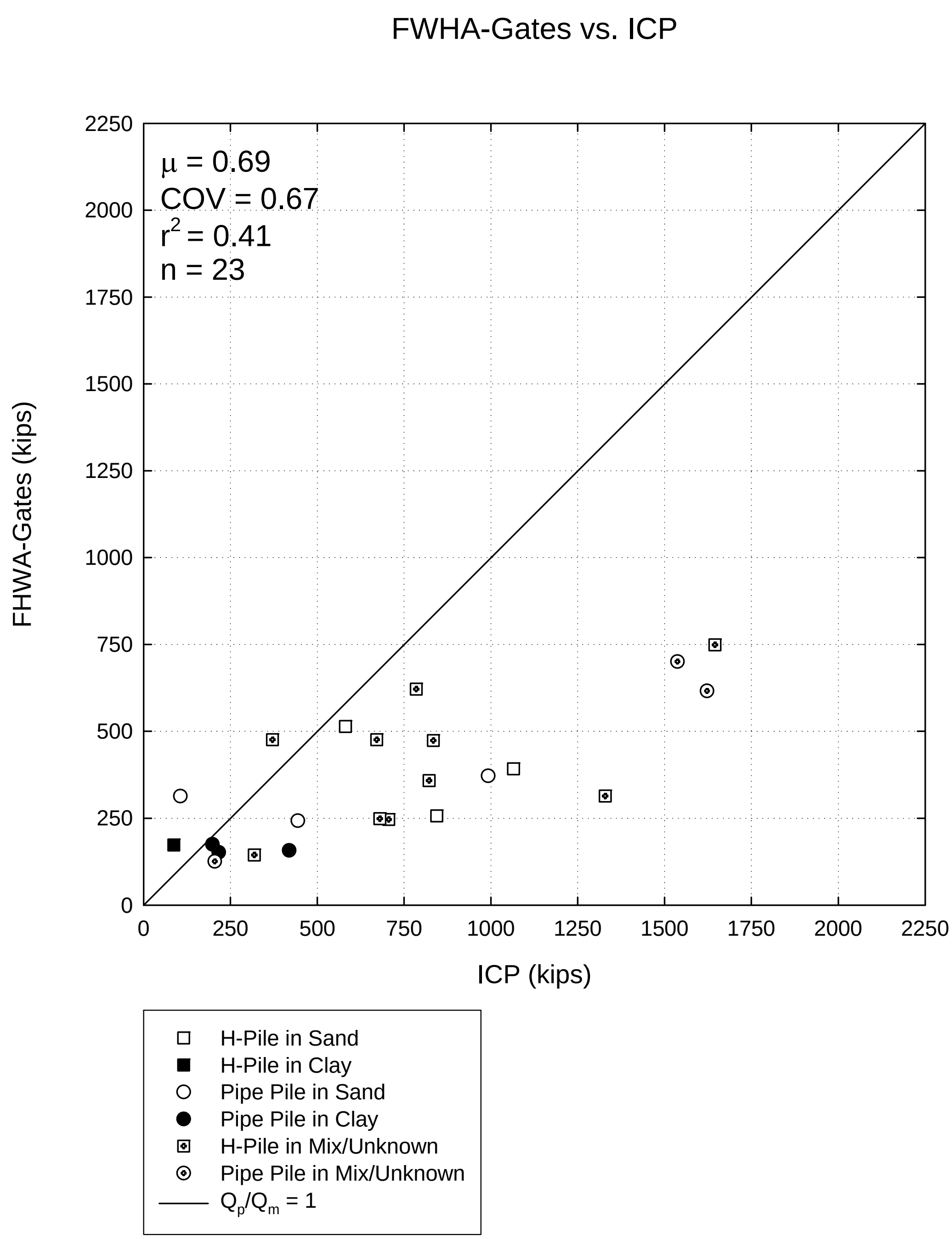

Figure C.16. FHWA-Gates vs. ICP, Comprehensive Database.

FHWA-UI vs. IDOT Static

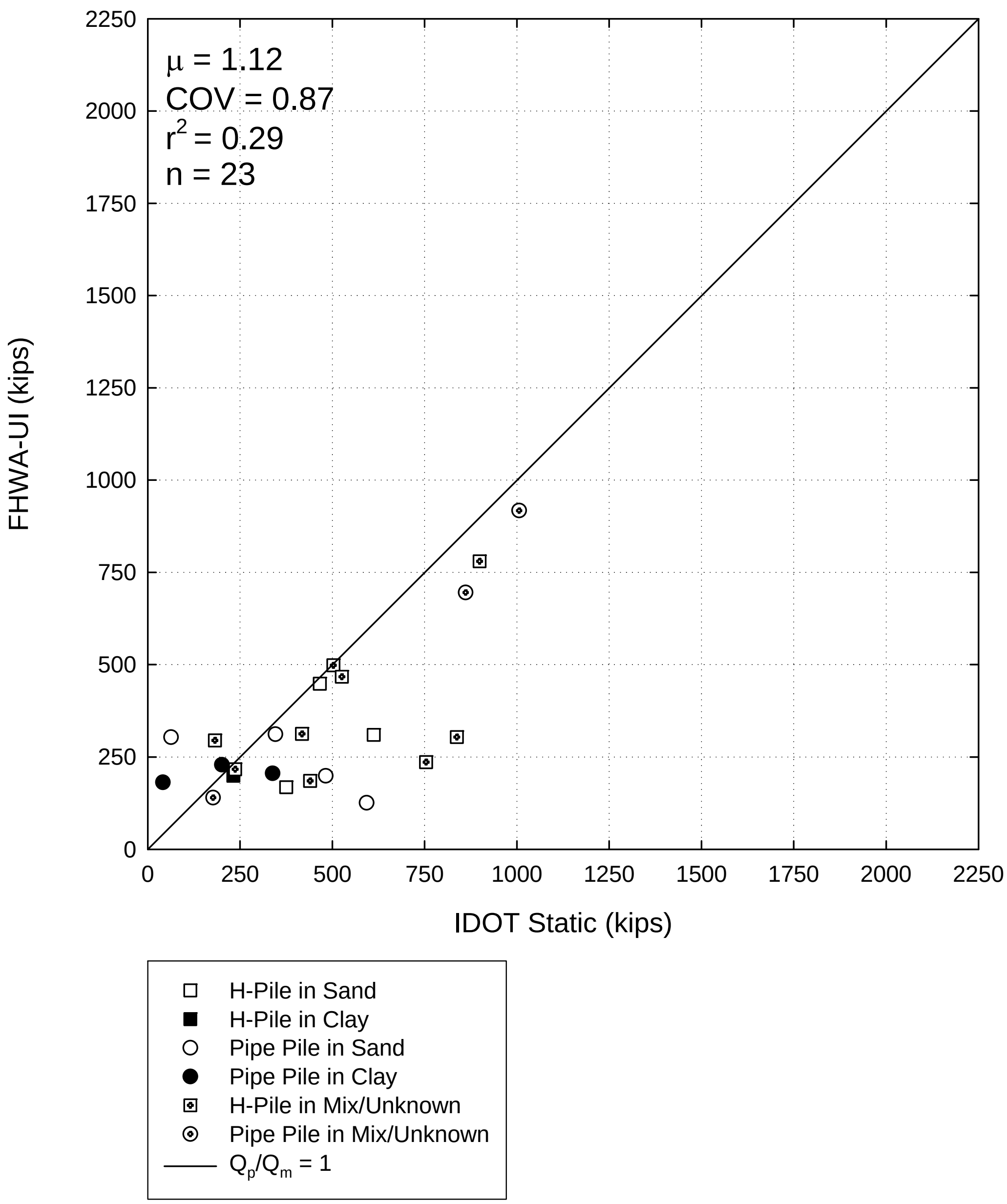

Figure C.17. FHWA-UI vs. IDOT Static, Comprehensive Database.

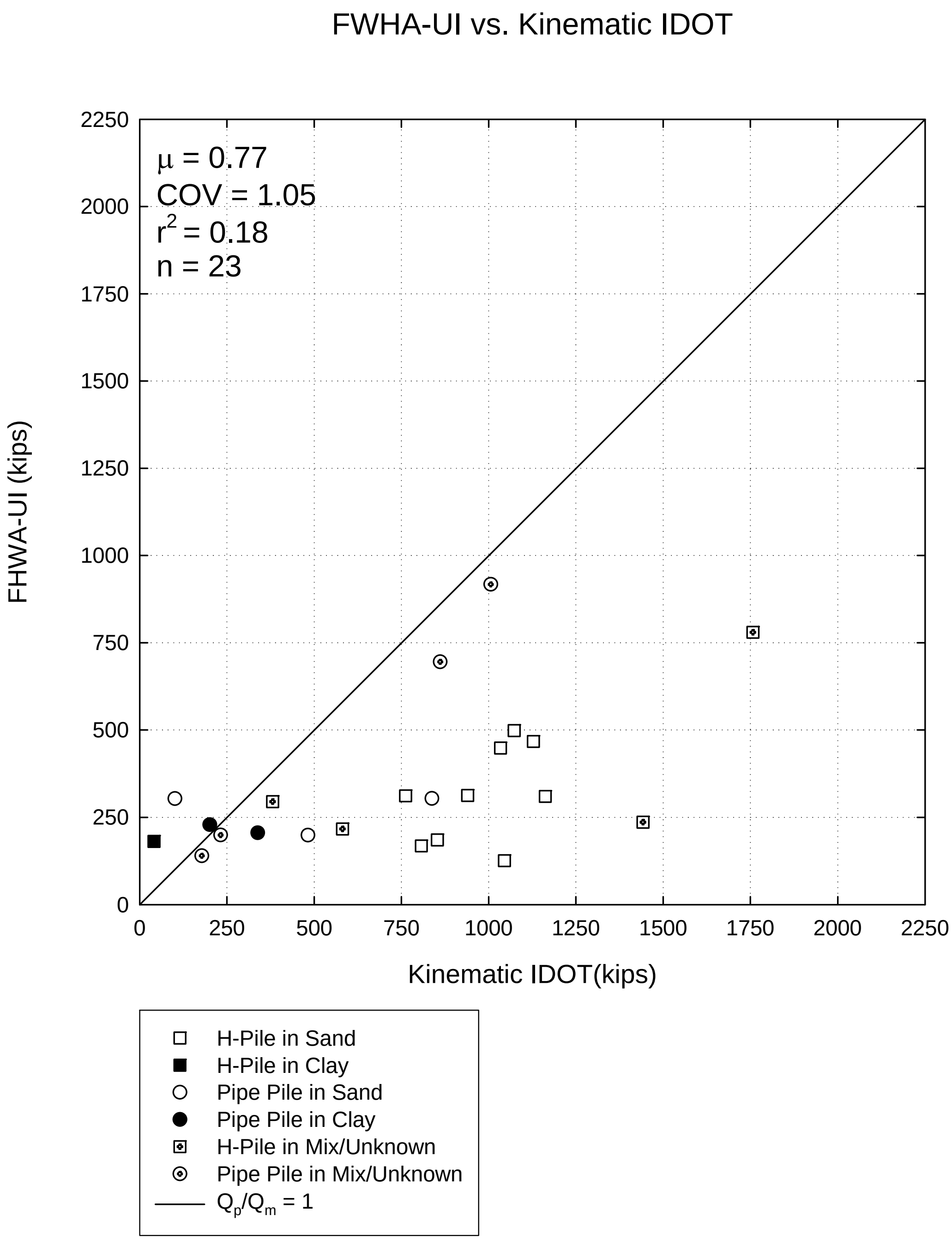

Figure C.18. FHWA-UI vs. K-IDOT, Comprehensive Database.

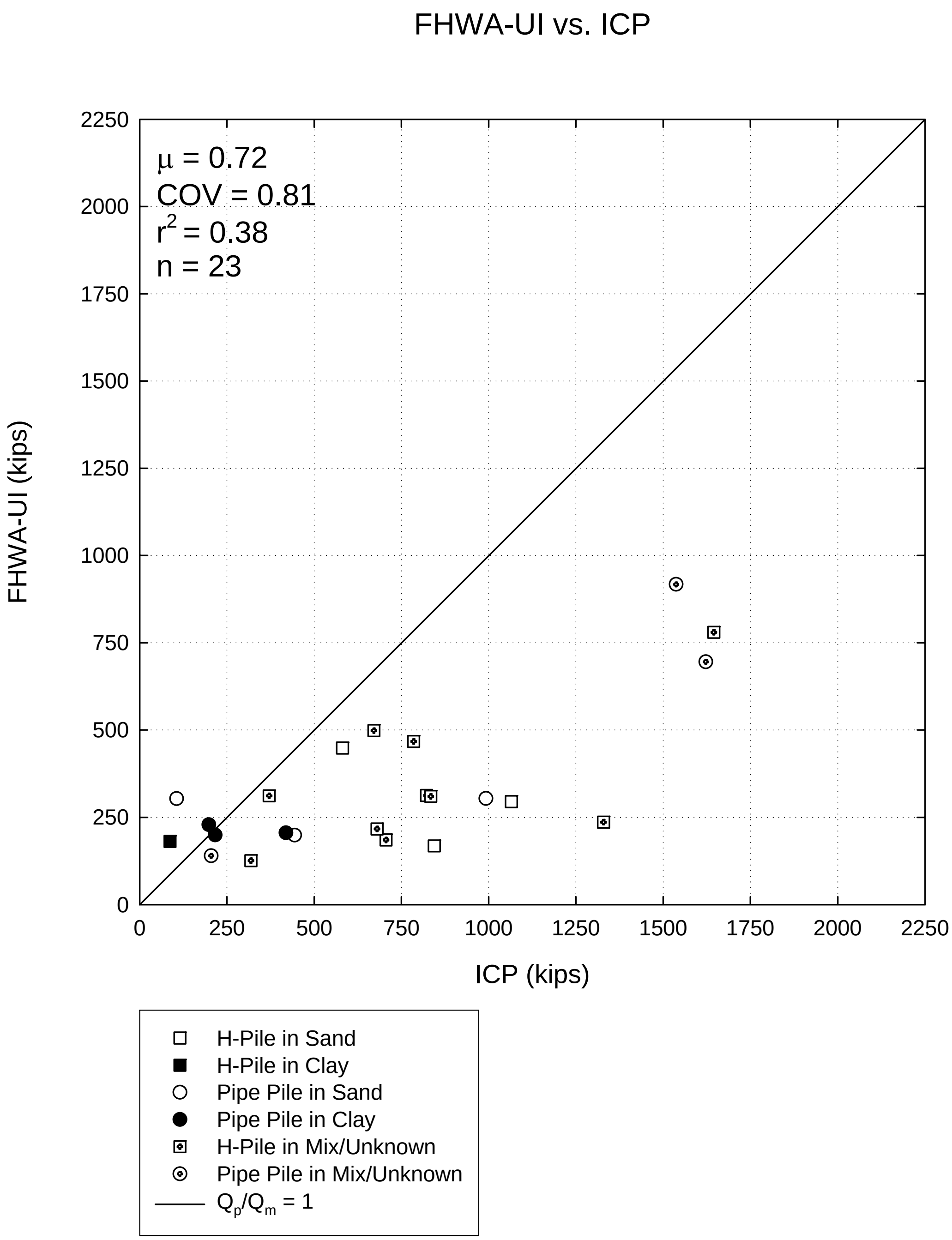

Figure C.19. FHWA-UI vs. ICP, Comprehensive Database.

APPENDIX D – ADDITIONAL INFORMATION REGARDING THE ILLINOIS DATABASE

D.1 INTRODUCTION

Statistics referred to but not presented in Chapter 5 of this report are presented in their entirety in this appendix. Tables are presented in the order in which the data they contain is referenced in Chapter 5. Headings in this appendix mirror those in Chapter 5 to facilitate referencing between the two. The study aimed to collect case studies of 100 piles driven in Illinois. The 92 case histories gathered are presented in Table D.1. Detailed information for each pile is presented in Tables D.2 – D.5.

D.2 STATISTICAL ANALYSIS

The statistics resulting from an analysis of the dynamic/static capacity data in the Illinois Database are discussed in Chapter 5. However, for the purposes of clarity and conciseness, only selected data is presented in the chapter. The following presents the complete results of the analyses.

D.3 AGREEMENT BETWEEN METHODS

D.3.1 H-Piles in Sand

The least scatter between static and dynamic methods for H-piles in sand was exhibited by:

- IDOT Static and FHWA Gates (COV 0.48)
- IDOT Static and WEAP (COV 0.51)
- IDOT Static and WSDOT (COV 0.52)
- IDOT Static and FHWA-UI (COV 0.52)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.6.

D.3.2 H-Piles in Clay

The least scatter between static and dynamic methods for H-piles in clay was exhibited by:

- IDOT Static and FHWA-UI (COV 0.37)
- IDOT Static and FHWA-Gates (COV 0.41)
- K-IDOT and FHWA-Gates (0.41)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.7.

D.3.3 Pipe Piles in Sand

The least scatter between static and dynamic methods for pipe piles in sand was exhibited by:

- IDOT Static and FHWA Gates (COV 0.37)

- Driven and WSDOT (COV 0.37)
- IDOT Static and WEAP (COV 0.38)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.8.

D.3.4 Pipe Piles in Clay

The least scatter between static and dynamic methods for pipe piles in clay was exhibited by:

- Driven and FHWA Gates (COV 0.25)
- Driven and EN-IDOT (COV 0.27)
- Driven and WSDOT (COV 0.27)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.9.

D.3.5 H-Piles

The least scatter between static and dynamic methods for all H-piles was exhibited by:

- IDOT Static and FHWA-Gates (COV 0.51)
- IDOT Static and WEAP (COV 0.53)
- IDOT Static and WSDOT (COV 0.55)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.10.

D.3.6 Pipe Piles

The least scatter between static and dynamic methods for all pipe piles was exhibited by:

- Driven and WSDOT (COV 0.32)
- IDOT Static and WEAP (COV 0.37)
- Driven and EN-IDOT (COV 0.38)
- Driven and FHWA-Gates (0.38)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.11.

D.3.7 Piles in Sand

The least scatter between static and dynamic methods for piles in sand was exhibited by:

- IDOT Static and FHWA Gates (COV 0.42)
- IDOT Static and WEAP (COV 0.46)
- IDOT Static and WSDOT (COV 0.48)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.12.

D.3.8 Piles in Clay

The least scatter between static and dynamic methods for piles in clay was exhibited by:

- K-IDOT and FHWA-Gates (0.44)
- IDOT Static and FHWA-UI (0.45)
- IDOT Static and FHWA-Gates (0.45)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.13.

D.3.9 All Piles

The least scatter between static and dynamic methods for all piles was exhibited by:

- IDOT Static and FHWA-Gates (COV 0.49)
- IDOT Static and WSDOT (COV 0.53)
- IDOT Static and WEAP (COV 0.56)

The mean, standard deviation, COV, correlation coefficient, and number of cases for each analysis method are presented in Table D.14.

D.4 RANKING OF METHODS

Combinations of dynamic capacity method (EN, FHWA-Gates, WSDOT, WEAP, and FHWA-UI) vs. static capacity method (IDOT Static, Driven, Olson, K-IDOT, and ICP) were ranked from "best" (number 1) to "worst" (number 19) for each of the 9 pile subcategories. The decision was made to include both the earlier analyses, which included some methods that are not considered promising, and the analyses based on the FHWA-UI, ICP, and K-IDOT data, hence the 19 different average capacity ratios. The rankings are based on the value of the COV. It is fairly simple to apply an empirical correction factor to any method so that the average capacity ratio for two methods becomes unity. It is much more difficult to reduce the COV between two methods, so the value of COV was taken as the best indication of agreement between methods. Table D.15 presents the rankings, along with the COV in parentheses.

Table D.1 – Summary of Pile Database

Test #	Length (ft)	Section	Soil Type	County	Hammer
A1	44.0	HP 10X42	Sand	Champaign	ICE 42-S
A2	20.0	HP 10X42	Sand	Christian	ICE 40-S
A3	83.6	HP 12X53	Sand	Cook	ICE I-19
A4	70.4	HP 10X57	Sand	Dupage	MKT 30 DE333020
A5	53.1	HP 10X57	Sand	Dupage	MKT 30 DE333020
A6	45.0	HP 10X42	Sand	Ford	MKT DE 40
A7	116.9	HP 14X73	Sand	Gallatin	Delmag D 19-32
A8	43.0	HP 10X42	Sand	Iroquois	LinkBelt LB 520
A9	27.0	HP 10X42	Sand	Kankakee	MKT DE 40
A10	75.9	HP 10X42	Sand	Logan	Delmag D 8-22
A11	119.2	HP 14X89	Sand	Logan	Delmag D 30-32
A12	62.8	HP 12X53	Sand	Cook	Delmag D 16-32
A13	40.0	HP 10X42	Sand	Champaign	ICE 42-S
A14	68.2	HP 10X57	Sand	Dupage	MKT 30 DE333020
A15	45.0	HP 12X53	Sand	Ford	MKT DE 40
A16	118.2	HP 14X73	Sand	Gallatin	Delmag D 19-32
A17	36.0	HP 10X42	Sand	Kankakee	MKT DE 40
A22	104.0	HP 10X42	Sand	White	Delmag D 19-32
A23	88.0	HP 10X42	Sand	White	Delmag D 19-32
A24	81.0	HP 12X63	Sand	White	Delmag D 19-32
A25	74.0	HP 12X63	Sand	White	Delmag D 19-32
B1	42.25	HP 12X53	Clay	Effingham	ICE 40-S
B2	33.00	HP 12X63	Clay	Champaign	ICE 42-S
B3	21.75	HP 10X42	Clay	Christian	ICE 40-S
B4	39.00	HP 10X42	Clay	Christian	Delmag D 16-32
B5	32.00	HP 12X53	Clay	Cook	Delmag D 12-32
B6	46.00	HP 12X53	Clay	Cook	Delmag D 12-32
B7	43.23	HP 12X53	Clay	Cook	ICE I-19
B8	83.42	HP 12X53	Clay	Cook	ICE I-19
B9	88.81	HP 12X53	Clay	Cook	ICE I-19
B10	36.11	HP 12X53	Clay	Hancock	Delmag D 19-32
B11	36.70	HP 12X53	Clay	Hancock	Delmag D 19-32
B12	43.67	HP 12X53	Clay	Kankakee	ICE 42-S
B13	20.22	HP 14X73	Clay	McDonough	Delmag D 19-42
B14	49.04	HP 12X53	Clay	Madison	Delmag D 19-42
B15	62.01	HP 10X42	Clay	Tazewell	ICE 40-S
B16	36.00	HP 12X63	Clay	Champaign	ICE 42-S
B17	42.00	HP 10X42	Clay	Christian	Delmag D 16-32
B18	35.66	HP 12X53	Clay	Hancock	Delmag D 19-32
B19	29.42	HP 12X53	Clay	Hancock	Delmag D 19-32
B20	30.50	HP 12X53	Clay	Kankakee	ICE 42-S
B21	58.74	HP 14X89	Clay	Tazewell	ICE 40-S

B22	47.00	HP 12X53	Clay	Cook	Delmag D 12-32
B23	66.63	HP 12X53	Clay	Cook	ICE I-19
B24	53.12	HP 12X53	Clay	Cook	ICE I-19
B25	49.68	HP 12X53	Clay	Cook	ICE I-19

Table D.1 (cont'd) – Summary of Pile Database

C1	73.30	14"X0.25"	Sand	Tazewell	Delmag D 30-32
C2	37.23	14"X0.25"	Sand	Hancock	Delmag D 19-32
C3	65.23	12"X0.179"	Sand	Henderson	Open-Ended Diesel
C4	62.99	12"X0.179"	Sand	Henderson	Open-Ended Diesel
C5	60.88	12"X0.25"	Sand	Henry	Delmag D 12-42
C6	35.66	14"X0.25"	Sand	Livingston	MKT DE 30
C7	86.16	12"X0.179"	Sand	Mason & Menard	MKT DA 35C
C8	36.19	14"X0.25"	Sand	Mercer	Delmag D 12
C9	51.35	14"X0.25"	Sand	Tazewell	Delmag D 19-32
C10	40.70	14"X0.25"	Sand	Tazewell	Delmag D 30-32
C11	55.44	12"X0.179"	Sand	Henderson	Open-Ended Diesel
C12	64.96	12"X0.179"	Sand	Henderson	Open-Ended Diesel
C13	26.62	14"X0.25"	Sand	Livingston	MKT DE 30
C14	43.00	12"X0.179"	Sand	Mason & Menard	MKT DA 35C
C15	61.59	12"X0.179"	Sand	Mason & Menard	MKT DA 35C
C16	35.11	14"X0.25"	Sand	Mercer	Delmag D 12
C17	71.35	14"X0.25"	Sand	Tazewell	Delmag D 30-32
C18	107.26	14"X0.25"	Sand	Tazewell	Delmag D 30-32
C19	56.18	14"X0.25"	Sand	Tazewell	Delmag D 30-32
C20	43.52	14"X0.25"	Sand	Henderson	ICE 40-S
C21	43.52	14"X0.25"	Sand	Henderson	ICE 40-S
D1	40.98	12"X0.179"	Clay	Cook & Will	Delmag D 12-32
D2	32.00	12"X0.179"	Clay	Ford	LinkBelt LB 520
D3	85.20	14"X0.25"	Clay	Morgan	Delmag D 30-32
D4	66.17	12"X0.25"	Clay	Montgomery	Delmag D 16-32
D5	63.00	12"X0.179"	Clay	Ford	ICE 42-S
D6	38.62	14"X0.25"	Clay	Ford	ICE 42-S
D7	51.38	12"X0.179"	Clay	Ford	ICE 42-S
D8	43.97	14"X0.25"	Clay	Grundy	Delmag D 19-42
D9	76.50	14"X0.25"	Clay	Hancock	ICE 40-S
D10	58.04	14"X0.25"	Clay	Hancock	Delmag D 19-32
D11	47.00	14"X0.25"	Clay	Grundy	Delmag D 19-42
D12	73.28	14"X0.25"	Clay	Livingston	ICE 42-S
D13	45.08	12"X0.25"	Clay	Madison	ICE 40-S
D14	37.18	14"X0.25"	Clay	Ford	ICE 42-S
D15	47.70	14"X0.25"	Clay	Livingston	ICE 42-S
D16	42.00	12"X0.179"	Clay	McLean	Delmag D 19-32
D17	45.28	12"X0.25"	Clay	Madison	ICE 40-S
D18	51.12	12"X0.179"	Clay	McLean	Delmag D 19-32
D19	49.89	12"X0.179"	Clay	Ford	ICE 42-S
D20	34.00	14"X0.25"	Clay	Grundy	Delmag D 19-42
D21	31.07	12"X0.25"	Clay	Madison	ICE 40-S

D22	38.80	14"X0.25"	Clay	Lake	ICE 42-S
D23	39.47	12"X0.25"	Clay	Madison	ICE 40-S
D24	39.50	12"X0.25"	Clay	Madison	ICE 40-S
D25	51.00	12"X0.25"	Clay	Montgomery	Delmag D 16-32

Table D.2 - H-Piles in Sand Database

Test No.	County	Contract No.	Structure No.	Pile No.	Pile Size	Cutoff	Tip	Ground Surface (Boring)	Ground Surface (Pile)	Length (ft)	Buried Length (ft)	Hammer Model	N (bpf)	W (lbs)	H (ft)	F_{eff}
A1	Champaign	70344	010-0281	Pier 1	HP 10X42	717.34	673.34	713.40	698.01	44.00	24.67	ICE 42-S	36	4088	7	0.47
A2	Christian	72938	011-2505	E. Abt.	HP 10X42	601.47	581.47	607.90	599.47	20.00	18.00	ICE 40-S	36	4000	9	0.47
A3	Cook	62107	016-2797	S. Abt.	HP 12X53	643.87	560.32	646.46	639.83	83.55	79.51	ICE I-19	61	4015	6.5	0.47
A4	Dupage	82634	022-0176	E. Abt.	HP 10X57	731.72	662.40	724.60	724.60	70.37	62.20	MKT 30 DE333020	35	3300	6.5	0.47
A5	Dupage	82634	022-0178	E. Abt.	HP 10X57	731.25	678.10	727.40	727.40	53.15	49.30	MKT 30 DE333020	38	3300	8	0.47
A6	Ford		027-0085	Pile 6	HP 10X42	736.32	691.30	725.80	734.00	45.02	42.70	MKT DE 40	63	4000	6	0.47
A7	Gallatin	99232	030-3116	Pier 1	HP 14X73	358.23	241.30	362.30	358.23	116.93	116.93	Delmag D 19-32	65	4000	6.5	0.47
A8	Iroquois		038-0025	N. Abt.	HP 10X42	649.97	606.97	654.60	647.59	43.00	40.62	LinkBelt LB 520	56	5070	3.6	0.35
A9	Kankakee		046-0113	E. Abt.	HP 10X42	261.50	234.50	280.70	259.50	27.00	25.00	MKT DE 40	48	4000	5.5	0.47
A10	Logan	72A04	054-0507	E. Abt.	HP 10X42	523.93	447.98	529.50	521.98	75.95	74.00	Delmag D 8-22	66	1762	6.5	0.47
A11	Logan	72A04	054-0507	Pier 1	HP 14X89	524.14	404.91	517.60	511.41	119.23	106.50	Delmag D 30-32	45	6615	6	0.47
A12	Cook	62103	016-2803	W. Abt.	HP 12X53	616.97	554.13	616.77	615.00	62.84	60.87	Delmag D 16-32	122	3527	7.5	0.47
A13	Champaign	70344	010-0281	S. Abt.	HP 10X42	717.51	677.51	722.50	715.51	40.00	38.00	ICE 42-S	59	4088	6	0.47
A14	Dupage	82634	022-0178	W. Abt.	HP 10X57	730.89	668.64	726.00	726.00	68.24	57.36	MKT 30 DE333020	28	3300	7.5	0.47
A15	Ford		027-0085	Pile 8	HP 12X53	736.73	691.70	725.80	729.00	45.03	37.30	MKT DE 40	95	4000	6	0.47
A16	Gallatin	99232	030-3116	Pier 6	HP 14X73	358.23	240.00	361.90	358.23	118.23	118.23	Delmag D 19-32	54	4000	7.5	0.47
A17	Kankakee		046-0113	W. Abt.	HP 10X42	261.50	225.50	280.70	259.50	36.00	34.00	MKT DE 40	29	4000	5.5	0.47
A22	White	99268	097-3186	Abt. 1	HP 10X42	381.67	277.67	379.20	379.67	104.00	102.00	Delmag D 19-32	49	4000	6.5	0.47
A23	White	99268	097-3186	Abt. 2	HP 10X42	381.67	293.67	379.20	381.67	88.00	88.00	Delmag D 19-32	44	4000	6.5	0.47
A24	White	99268	097-3186	Pier 1	HP 12X63	357.02	276.02	379.20	355.02	81.00	79.00	Delmag D 19-32	81	4000	7	0.47
A25	White	99268	097-3186	Pier 2	HP 12X63	357.02	283.02	379.10	355.02	74.00	72.00	Delmag D 19-32	42	4000	6.5	0.47

Table D.2 (cont'd) - H-Piles in Sand Database

Test No.	ENGINEERING NEWS (kips)	FHWA GATES (kips)	WS-DOT (kips)	DRIVEN (kips)	IDOT STATIC (kips)	OLSON (kips)	WEAP (kips)
A1	132.1	337.3	301.9	40.8	489.0	76.1	135.0
A2	166.2	390.5	379.8	38.1	166.0	121.3	195.3
A3	175.9	382.3	318.0	442.3	498.0	354.3	233.6
A4	96.9	275.5	224.4	232.1	370.0	325.6	155.2
A5	127.0	326.7	283.0	181.7	948.0	210.5	216.1
A6	165.2	366.4	294.9	133.7	232.0	170.5	241.6
A7	182.7	389.2	322.0	673.1	421.0	708.5	287.5
A8	116.1	294.6	162.0	158.5	440.0	238.7	162.0
A9	125.7	315.8	251.7	57.8	374.0	66.7	192.0
A10	81.3	225.9	142.4	260.4	292.0	314.0	157.3
A11	216.5	448.8	446.2	749.6	546.0	895.7	322.7
A12	266.7	471.3	379.2	372.1	428.0	247.2	335.2
A13	161.7	363.6	296.4	134.4	303.0	161.1	145.0
A14	93.6	276.6	241.8	252.4	466.0	250.6	166.6
A15	212.1	414.7	325.5	130.1	204.0	138.7	280.6
A16	186.2	401.1	354.2	787.5	462.0	620.3	303.2
A17	85.6	259.0	217.4	93.9	210.0	80.5	153.0
A22	150.8	354.6	299.2	444.8	240.0	383.4	240.4
A23	139.5	341.4	290.5	361.2	231.0	320.3	235.0
A24	225.7	435.7	365.8	285.3	203.0	367.8	320.9
A25	134.8	335.7	286.7	291.5	310.0	234.4	231.1

Table D.3 - H-Piles in Clay Database

Test No.	County	Contract No.	Structure No.	Pile No.	Pile Size	Cutoff	Tip	Ground Surface (Boring)	Ground Surface (Pile)	Length (ft)	Buried Length (ft)	Hammer Model	N (bpf)	W (lbs)	H (ft)	F_{eff}
B1	Effingham	94785	025-0102	S. Abt.	HP 12X53	618.00	575.75	620.33	616.00	42.25	40.25	ICE 40-S	160	4000	6.5	0.47
B2	Champaign	70355	010-0280	N. Abt.	HP 12X63	638.73	605.73	645.60	636.73	33.00	31.00	ICE 42-S	105	4088	7.5	0.47
B3	Christian	72938	011-2505	W. Abt.	HP 10X42	601.47	579.72	608.80	599.47	21.75	19.75	ICE 40-S	84	4000	10	0.47
B4	Christian	72784	011-2507	N. Abt.	HP 10X42	604.50	565.50	613.40	602.50	39.00	37.00	Delmag D 16-32	48	3520	8.5	0.47
B5	Cook	62829	016-0530	E. Abt.	HP 12X53	639.75	607.75	639.94	638.75	32.00	31.00	Delmag D 12-32	63	2820	8.17	0.47
B6	Cook	62829	016-2786	W. Abt.	HP 12X53	653.69	607.69	640.05	651.69	46.00	44.00	Delmag D 12-32	88	2820	8.17	0.47
B7	Cook	62107	016-2795	Center Pier	HP 12X53	596.54	553.31	604.85	596.31	43.23	43.00	ICE I-19	63	4015	8	0.47
B8	Cook	62107	016-2797	N. Abt.	HP 12X53	642.75	559.33	616.70	616.70	83.42	57.37	ICE I-19	63	4015	8	0.47
B9	Cook	62107	016-2798	N. Abt.	HP 12X53	648.68	559.87	646.36	644.74	88.81	84.87	ICE I-19	89	4015	7.5	0.47
B10	Hancock	72680	034-0506	E. Abt.	HP 12X53	599.97	563.86	598.00	598.00	36.11	34.14	Delmag D 19-32	64	4190	7	0.47
B11	Hancock	72680	034-0507	E. Abt. EBL	HP 12X53	600.67	563.97	592.50	599.00	36.70	35.03	Delmag D 19-32	58	4190	7	0.47
B12	Kankakee	66268	046-0133	Pier 2	HP 12X53	641.11	597.44	638.95	631.82	43.67	34.38	ICE 42-S	47	4000	10	0.47
B13	McDonough	68205	055-9903	E. Abt.	HP 14X73	665.05	644.83	689.50	666.92	20.22	20.22	Delmag D 19-42	49	4010	9	0.47
B14	Madison	76528	060-0304	W. Bent	HP 12X53	568.79	519.75	562.66	567.59	49.04	47.84	Delmag D 19-42	30	4189	9	0.47
B15	Tazewell	89303	090-3216	S. Abt.	HP 10X42	118.71	56.70	121.50	116.70	62.01	60.00	ICE 40-S	53	4000	6.5	0.47
B16	Champaign	70355	010-0280	Pier 3	HP 12X63	639.30	603.30	631.60	631.80	36.00	28.50	ICE 42-S	83	4088	7.5	0.47
B17	Christian	72784	011-2507	S. Abt.	HP 10X42	604.50	562.50	613.30	602.50	42.00	40.00	Delmag D 16-32	48	3520	8.5	0.47
B18	Hancock	72680	034-0506	W. Abt. WBL	HP 12X53	598.93	563.27	597.70	596.60	35.66	33.33	Delmag D 19-32	66	4190	7	0.47
B19	Hancock	72680	034-0507	W. Abt. EBL	HP 12X53	599.46	570.04	595.50	598.00	29.42	27.96	Delmag D 19-32	48	4190	7	0.47
B20	Kankakee	66268	046-0133	W. Abt.	HP 12X53	641.39	610.89	636.22	639.49	30.50	28.60	ICE 42-S	33	4000	9.5	0.47
B21	Tazewell	89303	090-3216	Pier 2	HP 14X89	114.14	55.40	118.00	94.40	58.74	39.00	ICE 40-S	55	4000	8	0.47
B22	Cook	62829	016-2786	E. Abt.	HP 12X53	653.82	606.82	640.40	651.82	47.00	45.00	Delmag D 12-32	90	2820	8.17	0.47
B23	Cook	62107	016-2795	N. Abt. A	HP 12X53	624.20	557.57	602.72	618.61	66.63	61.04	ICE I-19	53	4015	7.5	0.47
B24	Cook	62107	016-2797	Pier 1A	HP 12X53	609.91	556.79	647.38	609.91	53.12	53.12	ICE I-19	84	4015	8	0.47
B25	Cook	62107	016-2798	Pier 1	HP 12X53	609.91	560.23	647.38	608.60	49.68	48.37	ICE I-19	54	4015	7	0.47

Table D.3 (cont'd) - H-Piles in Clay Database

Test No.	ENGINEERING NEWS (kips)	FHWA GATES (kips)	WS-DOT (kips)	DRIVEN (kips)	IDOT STATIC (kips)	OLSON (kips)	WEAP (kips)
B1	297.1	499.6	394.6	172.2	236.0	134.4	243.7
B2	286.2	495.1	425.3	97.6	124.0	222.6	280.5
B3	329.4	545.8	527.2	47.9	126.0	111.9	354.6
B4	171.0	385.0	342.4	125.9	259.0	197.2	268.8
B5	158.6	356.9	283.1	140.9	226.0	133.8	261.6
B6	194.9	395.5	307.0	146.8	202.0	182.2	293.3
B7	221.2	439.5	394.6	167.0	245.0	139.2	282.3
B8	221.2	439.5	394.6	266.1	337.0	234.0	275.3
B9	256.5	467.9	402.2	433.8	508.0	427.3	299.7
B10	204.0	417.6	361.8	103.2	152.0	162.4	294.4
B11	191.1	404.8	352.8	111.2	211.0	211.8	284.0
B12	225.1	457.5	455.1	139.4	341.0	202.1	228.4
B13	209.3	435.6	415.3	85.6	198.0	157.7	309.4
B14	150.8	375.0	376.4	215.3	234.0	217.8	246.0
B15	159.3	364.2	305.5	203.1	244.0	132.6	176.0
B16	250.7	463.8	402.9	202.2	210.0	404.9	238.2
B17	171.0	385.0	342.4	124.6	230.0	203.4	269.7
B18	208.1	421.6	364.6	102.8	198.0	126.0	298.1
B19	167.6	380.1	335.6	72.9	124.0	43.6	256.2
B20	163.9	391.0	390.7	88.8	220.0	119.7	193.0
B21	201.1	420.0	379.7	203.6	235.0	165.0	229.4
B22	197.5	398.1	308.6	159.3	206.0	161.0	260.9
B23	184.5	399.6	353.8	258.9	329.0	222.0	243.7
B24	264.5	478.7	423.3	219.8	339.0	232.7	301.4
B25	174.4	385.0	331.9	191.7	274.0	203.5	228.2

Table D.4 - Shell Piles in Sand Database

Test No.	County	Contract No.	Structure No.	Pile No.	Pile Size	Cutoff	Tip	Ground Surface (Boring)	Ground Surface (Pile)	Length (ft)	Buried Length (ft)	Hammer Model	N (bpf)	W (lbs)	H (ft)	F_{eff}
C1	Tazewell	88804	090-0172	N. Abt.	14"X0.25"	454.89	381.59	450.37	453.25	73.30	71.66	Delmag D 30-32	26	6615	7	0.47
C2	Hancock	72680	034-0508	Pier 2	14"X0.25"	534.44	497.21	537.80	542.80	37.23	37.23	Delmag D 19-32	28	4190	7	0.47
C3	Henderson	88516	036-0049	Pier 1	12"X0.179"	521.43	456.20	522.17	510.17	65.23	53.97	Open-Ended Diesel	51	3300	5	0.47
C4	Henderson	88516	036-0050	E. Abt.	12"X0.179"	520.31	457.32	517.75	518.40	62.99	61.08	Open-Ended Diesel	43	3300	5.5	0.47
C5	Henry	64379	037-0035	W. Abt.	12"X0.25"	638.08	577.20	633.11	637.00	60.88	59.80	Delmag D 12-42	23	2830	6	0.47
C6	Livingston		053-0169	N. Abt.	14"X0.25"	775.66	740.00	782.40	773.66	35.66	33.66	MKT DE 30	69	2800	6.5	0.47
C7	Mason & Menard	72083	065-0001	Pier 1	12"X0.179"	500.16	414.00	489.40	490.00	86.16	76.00	MKT DA 35C	36	2800	7	0.35
C8	Mercer		066-0014	N. Abt.	14"X0.25"	539.19	503.00	543.10	536.95	36.19	33.95	Delmag D 12	31	2750	5	0.47
C9	Tazewell	68071	090-0171	S. Abt.	14"X0.25"	474.44	423.09	481.99	476.09	51.35	51.35	Delmag D 19-32	60	4190	6.5	0.47
C10	Tazewell	88804	090-0174	N. Abt.	14"X0.25"	461.23	420.53	464.09	460.23	40.70	39.70	Delmag D 30-32	17	6615	7.5	0.47
C11	Henderson	88516	036-0049	Pier 2	12"X0.179"	521.43	465.99	522.24	509.94	55.44	43.95	Open-Ended Diesel	62	3300	5	0.47
C12	Henderson	88516	036-0050	Pier 1	12"X0.179"	521.43	456.47	517.00	514.80	64.96	58.33	Open-Ended Diesel	40	3300	5	0.47
C13	Livingston		053-0169	S. Abt.	14"X0.25"	775.62	749.00	782.40	773.62	26.62	24.62	MKT DE 30	62	2800	6	0.47
C14	Mason & Menard	72083	065-0001	Pier 4	12"X0.179"	473.00	430.00	487.50	469.20	43.00	39.20	MKT DA 35C	21	2800	5	0.35
C15	Mason & Menard	72083	065-0001	Pier 7	12"X0.179"	500.89	439.30	492.80	492.30	61.59	53.00	MKT DA 35C	46	2800	7.5	0.35
C16	Mercer		066-0014	Pier 2	14"X0.25"	538.01	502.90	542.40	532.90	35.11	30.00	Delmag D 12	26	2750	5	0.47
C17	Tazewell	88804	090-0172	Pier 1	14"X0.25"	454.87	383.52	458.55	440.83	71.35	57.31	Delmag D 30-32	22	6615	4	0.47
C18	Tazewell	88804	090-0172	S. Abt.	14"X0.25"	454.91	347.65	458.65	446.75	107.26	99.10	Delmag D 30-32	17	6615	7.5	0.47
C19	Tazewell	88804	090-0174	Pier 2	14"X0.25"	461.83	405.65	460.96	450.50	56.18	44.85	Delmag D 30-32	19	6615	8	0.47
C20	Henderson		036-0045	E. Abt.	14"X0.25"	529.21	485.69	533.20	533.20	43.52	43.52	ICE 40-S	33	4088	7	0.47
C21	Henderson		036-0045	W. Abt.	14"X0.25"	529.21	485.69	532.50	532.50	43.52	43.52	ICE 40-S	33	4088	7	0.47

Table D.4 (cont'd) - Shell Piles in Sand Database

Test No.	ENGINEERING NEWS (kips)	FHWA GATES (kips)	WS-DOT (kips)	DRIVEN (kips)	IDOT STATIC (kips)	OLSON (kips)
C1	164.9	403.0	441.8	238.0	367.0	425.6
C2	111.0	310.0	286.6	119.2	165.0	106.5
C3	98.4	266.0	191.9	77.7	211.0	175.5
C4	95.8	266.4	201.5	102.8	173.0	225.6
C5	54.6	192.5	155.5	165.9	220.0	146.1
C6	132.9	315.4	228.7	142.5	367.0	155.8
C7	90.5	261.9	154.0	236.2	421.0	408.5
C8	56.5	189.8	138.7	86.3	163.0	74.2
C9	181.6	390.7	330.5	219.4	395.0	270.5
C10	123.1	348.8	408.0	208.9	321.0	360.9
C11	112.4	285.1	201.9	60.7	180.0	184.5
C12	82.5	242.3	179.5	144.0	416.0	346.1
C13	114.5	288.6	205.6	113.9	507.0	113.3
C14	41.7	157.4	92.6	34.8	170.0	51.8
C15	116.4	301.6	176.9	129.8	301.0	335.5
C16	49.0	174.1	131.2	96.8	188.0	94.1
C17	82.0	259.6	238.7	239.9	501.0	368.3
C18	123.1	348.8	408.0	388.0	277.0	445.1
C19	144.7	382.9	453.4	243.1	577.0	345.8
C20	123.4	326.1	294.2	149.8	181.0	296.8
C21	123.4	326.1	294.2	122.0	239.0	344.8

Table D.5 - Shell Piles in Clay Database

Test No.	County	Contract No.	Structure No.	Pile No.	Pile Size	Cutoff	Tip	Ground Surface (Boring)	Ground Surface (Pile)	Length (ft)	Buried Length (ft)	Hammer Model	N (bpf)	W (lbs)	H (ft)	F_{eff}
D1	Cook & Will	82462	099-0115	NE Wingwall	12"X0.179"	734.17	693.19	713.00	733.19	40.98	40.00	Delmag D 12-32	46	2820	7.83	0.47
D2	Ford		027-0071	N. Abt.	12"X0.179"	654.66	622.66	658.30	653.66	32.00	31.00	LinkBelt LB 520	45	5070	3	0.35
D3	Morgan	72530	069-0507	Pier 1	14"X0.25"	593.29	508.09	564.92	557.09	85.20	49.00	Delmag D 30-32	24	6615	9.5	0.47
D4	Montgomery	92535	027-0090	E. Abt.	12"X0.25"	703.52	637.35	707.10	702.54	66.17	65.19	Delmag D 16-32	54	3520	7	0.47
D5	Ford	66070	027-0091	N. Abt.	12"X0.179"	796.20	733.20	802.39	795.20	63.00	62.00	ICE 42-S	38	4000	7	0.47
D6	Ford	66363	027-0094	E. Abt.	14"X0.25"	743.79	705.17	747.43	742.17	38.62	37.00	ICE 42-S	38	4000	8	0.47
D7	Ford	87291	027-3434	Pier 2	12"X0.179"	101.46	50.08	104.60	90.08	51.38	40.00	ICE 42-S	25	4088	7.5	0.47
D8	Grundy	66044	032-0100	E. Abt.	14"X0.25"	613.29	569.32	617.59	611.32	43.97	42.00	Delmag D 19-42	38	4190	8	0.47
D9	Hancock	72068	034-0503	S. Abt.	14"X0.25"	683.54	607.04	665.21	683.54	76.50	76.50	ICE 40-S	84	4000	6	0.47
D10	Hancock	72680	034-0508	Pier 4	14"X0.25"	552.80	494.76	541.40	528.76	58.04	34.00	Delmag D 19-32	53	4190	7	0.47
D11	Grundy	66044	032-0100	W. Abt.	14"X0.25"	612.46	565.46	617.26	610.46	47.00	45.00	Delmag D 19-42	40	4190	8.5	0.47
D12	Livingston	66287	053-0178	Pier	14"X0.25"	673.61	600.33	676.96	669.33	73.28	69.00	ICE 42-S	28	4088	8.5	0.47
D13	Madison	96742	060-0290	N. Abt. SB	12"X0.25"	495.73	450.66	497.31	494.75	45.08	44.09	ICE 40-S	24	4000	7.5	0.47
D14	Ford	66363	027-0094	W. Abt.	14"X0.25"	743.83	706.65	745.13	741.65	37.18	35.00	ICE 42-S	30	4000	8	0.47
D15	Livingston	66287	053-0178	Pile 3	14"X0.25"	673.64	625.94	676.96	673.19	47.70	47.25	ICE 42-S	24	4088	8.5	0.47
D16	McLean	66093	057-0231	E. Abt.	12"X0.179"	817.91	775.91	836.10	816.93	42.00	41.02	Delmag D 19-32	48	4190	6	0.47
D17	Madison	96742	060-0289	N. Abt. NB	12"X0.25"	499.67	454.40	497.31	498.69	45.28	44.29	ICE 40-S	34	4000	7	0.47
D18	McLean	66093	057-0231	Pier 1	12"X0.179"	809.38	758.26	830.50	808.40	51.12	50.14	Delmag D 19-32	41	4190	6	0.47
D19	Ford	87291	027-3434	W. Abt.	12"X0.179"	101.46	51.57	104.60	100.57	49.89	49.00	ICE 42-S	17	4088	7.5	0.47
D20	Grundy	66044	032-0100	Pier 1	14"X0.25"	592.19	558.19	617.10	590.40	34.00	32.21	Delmag D 19-42	36	4190	8	0.47
D21	Madison	96742	060-0289	Pier NB	12"X0.25"	489.50	458.43	489.73	488.85	31.07	30.42	ICE 40-S	24	4000	8	0.47
D22	Lake	60997	049-0188	S. Abt.	14"X0.25"	845.01	806.21	868.12	843.00	38.80	36.79	ICE 42-S	54	4088	7	0.47
D23	Madison	96742	060-0289	NB A	12"X0.25"	489.50	450.03	492.43	488.85	39.47	38.82	ICE 40-S	28	4000	8.5	0.47
D24	Madison	96742	060-0290	Pier SB	12"X0.25"	486.88	447.38	489.61	485.89	39.50	38.51	ICE 40-S	36	4000	7.5	0.47
D25	Montgomery	92535	068-0061	Pier 1	12"X0.25"	679.46	628.46	682.92	678.48	51.00	50.02	Delmag D 16-32	50	3520	7	0.47

Table D.5 (cont'd) - Shell Piles in Clay Database

Test No.	ENGINEERING NEWS (kips)	FHWA GATES (kips)	WS-DOT (kips)	DRIVEN (kips)	IDOT STATIC (kips)	OLSON (kips)	WEAP (kips)
D1	122.4	311.8	249.8	115.9	246.0	178.9	190.0
D2	83.0	239.7	127.3	123.0	244.0	164.9	122.5
D3	209.5	470.8	584.0	259.9	433.0	256.2	312.3
D4	152.9	354.1	291.0	356.7	853.0	655.2	207.7
D5	134.7	339.4	300.1	239.3	329.0	157.8	133.0
D6	153.9	369.8	343.0	150.6	184.0	143.1	152.6
D7	105.7	304.1	288.8	181.9	320.0	193.1	116.5
D8	161.2	380.8	359.3	157.8	286.0	172.7	222.6
D9	197.6	400.2	316.3	257.1	285.0	232.8	151.0
D10	179.7	393.0	344.6	202.9	977.0	313.3	234.3
D11	178.1	402.9	387.4	209.1	361.0	221.4	243.5
D12	131.5	346.3	339.5	323.7	317.0	188.8	146.5
D13	100.0	294.4	278.8	191.3	212.0	128.4	112.9
D14	128.0	337.6	319.5	157.0	277.0	225.1	133.8
D15	115.8	324.4	322.9	224.7	235.0	137.5	130.9
D16	143.7	344.5	287.7	174.6	151.0	81.4	192.2
D17	123.6	325.3	290.4	166.6	215.0	131.3	123.2
D18	128.0	325.5	275.4	219.6	245.0	142.1	180.4
D19	76.1	252.8	252.1	190.0	304.0	178.1	97.8
D20	154.7	373.3	353.7	156.2	338.0	209.1	215.5
D21	106.7	307.3	297.4	113.8	119.0	71.3	117.3
D22	177.6	389.4	337.9	190.3	230.0	150.1	152.9
D23	128.6	341.4	332.2	202.4	240.0	137.2	158.0
D24	138.5	347.7	316.5	150.1	173.0	102.3	138.4
D25	144.9	345.0	285.1	179.8	229.0	139.1	204.8

Table D.6. H-Piles in Sand

vs. EN	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	1.0	2.4	2.0	-	1.5	1.9	2.0	2.7	-	-
Std. Dev.	0.0	0.3	0.3	-	0.3	1.2	1.2	1.5	-	-
COV	0.0	0.1	0.2	-	0.2	0.6	0.6	0.6	-	-
r^2	1.0	0.96	0.71	-	0.74	0.18	0.14	0.00	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.0	0.8	-	0.6	0.8	0.8	1.1	2.18	1.81
Std. Dev.	0.1	0.0	0.1	-	0.1	0.5	0.5	0.6	1.30	1.44
COV	0.1	0.0	0.1	-	0.2	0.7	0.6	0.5	0.59	0.80
r^2	1.0	1.0	0.85	-	0.71	0.19	0.16	0.00		
n	21	21	21	-	21	21	21	21	21	21
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.2	1.0	-	0.8	1.0	1.0	1.4	2.70	2.26
Std. Dev.	0.1	0.2	0.0	-	0.2	0.6	0.6	0.7	1.67	1.90
COV	0.2	0.1	0.0	-	0.2	0.6	0.6	0.5	0.62	0.84
r^2	0.7	0.85	1.0	-	0.56	0.21	0.19	0.00		
n	21	21	21	-	21	21	21	21	21	21
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	1.58	3.19	2.66
Std. Dev.	-	-	-	0.0	-	-	-	0.86	2.1	2.23
COV	-	-	-	0.0	-	-	-	0.55	0.66	0.84
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	21	-	-	-	21	21	21
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.7	1.6	1.4	-	1.0	1.2	1.3	1.8	-	-
Std. Dev.	0.1	0.3	0.3	-	0.0	0.7	0.7	1.0	-	-
COV	0.2	0.2	0.2	-	0.0	0.6	0.5	0.5	-	-
r^2	0.74	0.71	0.56	-	1.0	0.44	0.36	0.00	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.0	2.4	2.0	-	1.4	1.0	1.2	2.4	-	-
Std. Dev.	1.1	2.6	2.4	-	1.2	0.0	0.5	2.7	-	-
COV	1.1	1.1	1.2	-	0.9	0.0	0.4	1.1	-	-
r^2	0.18	0.19	0.21	-	0.44	1.0	0.88	0.05	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	1.8	1.5	-	1.1	0.9	1.0	1.9	-	-
Std. Dev.	0.5	1.2	1.1	-	0.7	0.3	0.0	1.6	-	-
COV	0.7	0.7	0.7	-	0.6	0.3	0.0	0.9	-	-
r^2	0.14	0.16	0.19	-	0.36	0.88	1.0	0.05	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.1	0.9	0.82	0.7	0.8	0.9	1.0	-	-
Std. Dev.	0.3	0.5	0.5	0.45	0.4	0.6	0.5	0.0	-	-
COV	0.6	0.5	0.5	0.55	0.5	0.7	0.6	0.0	-	-
r^2	0.0	0.00	0.00	0.00	0.00	0.05	0.05	1.0	-	-
n	21	21	21	21	21	21	21	21	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	0.62	0.51	0.45	-	-	-	-	1.00	-
Std. Dev.	-	0.37	0.32	0.30	-	-	-	-	0.00	-
COV	-	0.59	0.62	0.66	-	-	-	-	0.00	-
r^2	-	0.01	0.00	0.01	-	-	-	-	1.00	-
n	-	21	21	21	-	-	-	-	21	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	0.90	0.75	0.64	-	-	-	-	-	1.00
Std. Dev.	-	0.72	0.63	0.54	-	-	-	-	-	0.00
COV	-	0.80	0.84	0.84	-	-	-	-	-	0.00

r^2	-	0.02	0.05	0.02	-	-	-	-	-	1.00
n	-	21	21	21	-	-	-	-	-	21

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.7. H-Piles in Clay

vs. EN	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.0	2.1	1.8	-	1.3	0.8	0.9	1.2	-	-
Std. Dev.	0.0	0.2	0.3	-	0.2	0.4	0.4	0.4	-	-
COV	0.0	0.1	0.1	-	0.2	0.5	0.4	0.3	-	-
r^2	1.0	0.97	0.59	-	0.27	0.00	0.06	0.00	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.0	0.9	-	0.6	0.4	0.4	0.6	1.03	0.91
Std. Dev.	0.1	0.0	0.1	-	0.1	0.2	0.2	0.2	0.42	0.56
COV	0.1	0.0	0.1	-	0.1	0.5	0.4	0.3	0.41	0.62
r^2	1.0	1.0	0.75	-	0.26	0.00	0.06	0.00		
n	25	25	25	-	25	25	25	25	25	25
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.6	1.1	1.0	-	0.7	0.4	0.5	0.70	1.18	1.05
Std. Dev.	0.1	0.1	0.0	-	0.1	0.2	0.2	0.20	0.50	0.67
COV	0.1	0.1	0.0	-	0.2	0.5	0.4	0.30	0.43	0.65
r^2	0.6	0.75	1.0	-	0.16	0.01	0.03	0.00		
n	25	25	25	-	25	25	25	25	25	25
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	0.66	1.19	1.05
Std. Dev.	-	-	-	0.0	-	-	-	0.25	0.51	0.66
COV	-	-	-	0.0	-	-	-	0.37	0.43	0.63
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	25	-	-	-	25	25	25
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	1.6	1.4	-	1.0	0.6	0.7	0.9	-	-
Std. Dev.	0.2	0.2	0.2	-	0.0	0.3	0.3	0.3	-	-
COV	0.2	0.1	0.2	-	0.0	0.5	0.4	0.4	-	-
r^2	0.27	0.26	0.16	-	1.0	0.02	0.00	0.01	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.6	3.3	2.9	-	2.1	1.0	1.3	1.6	-	-
Std. Dev.	1.2	2.1	2.0	-	1.4	0.0	0.5	0.5	-	-
COV	0.8	0.6	0.7	-	0.7	0.0	0.4	0.3	-	-
r^2	0.00	0.00	0.01	-	0.02	1.0	0.51	0.75	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.3	2.7	2.4	-	1.7	0.9	1.0	1.4	-	-
Std. Dev.	0.7	1.5	1.4	-	1.0	0.3	0.0	0.5	-	-
COV	0.6	0.6	0.6	-	0.6	0.4	0.0	0.6	-	-
r^2	0.06	0.06	0.03	-	0.00	0.51	1.0	0.38	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.0	2.0	1.7	1.72	1.2	0.7	0.8	1.0	-	-
Std. Dev.	0.5	0.8	0.8	0.64	0.5	0.2	0.4	0.0	-	-
COV	0.5	0.4	0.4	0.37	0.4	0.3	0.4	0.0	-	-
r^2	0.0	0.00	0.00	0.00	0.01	0.75	0.38	1.0	-	-
n	25	25	25	25	25	25	25	25	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.13	1.00	0.99	-	-	-	-	1.00	-
Std. Dev.	-	0.46	0.43	0.43	-	-	-	-	0.00	-
COV	-	0.41	0.43	0.43	-	-	-	-	0.00	-
r^2	-	0.02	0.00	0.02	-	-	-	-	1.00	-
n	-	25	25	25	-	-	-	-	25	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.53	1.36	1.33	-	-	-	-	-	1.00

Std. Dev.	-	0.95	0.87	0.84	-	-	-	-	-	0.00
COV	-	0.62	0.65	0.63	-	-	-	-	-	0.00
r^2	-	0.00	0.00	0.00	-	-	-	-	-	1.00
n	-	25	25	25	-	-	-	-	-	25

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.8. Pipe Piles in Sand

vs. EN	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	1.0	2.8	2.4	-	1.7	1.6	2.4	3.1	-	-
Std. Dev.	0.0	0.4	0.5	-	0.3	0.8	1.1	1.3	-	-
COV	0.0	0.1	0.2	-	0.2	0.5	0.5	0.4	-	-
r^2	1.0	0.94	0.62	-	0.67	0.21	0.27	0.17	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.0	0.8	-	0.6	0.5	0.9	1.1	1.06	1.2
Std. Dev.	0.0	0.0	0.2	-	0.1	0.2	0.4	0.4	0.42	0.71
COV	0.1	0.0	0.2	-	0.1	0.4	0.4	0.4	0.39	0.59
r^2	0.94	1.0	0.80	-	0.74	0.33	0.40	0.18		
n	21	21	21	-	21	21	21	21	21	21
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.3	1.0	-	0.7	0.7	1.0	1.4	1.36	1.48
Std. Dev.	0.1	0.3	0.0	-	0.1	0.3	0.5	0.6	0.68	0.92
COV	0.2	0.2	0.0	-	0.2	0.4	0.5	0.5	0.5	0.62
r^2	0.62	0.80	1.0	-	0.77	0.48	0.39	0.14		
n	21	21	21	-	21	21	21	21	21	21
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	1.25	1.25	1.39
Std. Dev.	-	-	-	0.0	-	-	-	0.52	0.52	0.84
COV	-	-	-	0.0	-	-	-	0.42	0.42	0.61
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	21	-	-	-	21	21	21
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.6	1.8	1.5	-	1.0	0.9	1.5	1.9	-	-
Std. Dev.	0.2	0.3	0.4	-	0.0	0.4	0.8	0.8	-	-
COV	0.2	0.2	0.3	-	0.0	0.4	0.5	0.4	-	-
r^2	0.67	0.74	0.77	-	1.0	0.41	0.25	0.18	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	2.2	1.8	-	1.3	1.0	1.7	2.2	-	-
Std. Dev.	0.4	1.0	0.6	-	0.6	0.0	0.7	1.0	-	-
COV	0.5	0.5	0.4	-	0.5	0.0	0.4	0.5	-	-
r^2	0.21	0.33	0.48	-	0.41	1.0	0.60	0.27	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.5	1.2	-	0.9	0.7	1.0	1.5	-	-
Std. Dev.	0.3	0.7	0.5	-	0.4	0.3	0.0	1.0	-	-
COV	0.5	0.5	0.5	-	0.5	0.4	0.0	0.6	-	-
r^2	0.27	0.40	0.39	-	0.25	0.60	1.0	0.23	-	-
n	21	21	21	-	21	21	21	21	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.1	0.9	0.94	0.6	0.5	0.9	1.0	-	-
Std. Dev.	0.2	0.4	0.4	0.39	0.2	0.3	0.4	0.0	-	-
COV	0.4	0.4	0.5	0.42	0.4	0.5	0.5	0.0	-	-
r^2	0.2	0.18	0.14	0.18	0.18	0.27	0.23	1.0	-	-
n	21	21	21	21	21	21	21	21	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.09	0.91	0.94	-	-	-	-	1.0	-
Std. Dev.	-	0.43	0.45	0.39	-	-	-	-	0.0	-
COV	-	0.39	0.50	0.42	-	-	-	-	0.0	-
r^2	-	0.18	0.14	0.18	-	-	-	-	1.0	-

n	-	21	21	21	-	-	-	-	21	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.13	0.93	0.99	-	-	-	-	-	1.0
Std. Dev.	-	0.67	0.58	0.60	-	-	-	-	-	0.0
COV	-	0.59	0.62	0.61	-	-	-	-	-	0.0
r^2	-	0.10	0.11	0.10	-	-	-	-	-	1.0
n	-	21	21	21	-	-	-	-	-	21

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.9. Pipe Piles in Clay

vs. EN	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	1.0	2.5	2.3	-	1.2	1.5	1.4	2.3	-	-
Std. Dev.	0.0	0.3	0.4	-	0.2	0.5	0.7	1.2	-	-
COV	0.0	0.1	0.2	-	0.2	0.3	0.5	0.5	-	-
r^2	1.0	0.94	0.54	-	0.58	0.12	0.10	0.14	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.0	0.9	-	0.5	0.6	0.5	0.9	0.89	0.92
Std. Dev.	0.0	0.0	0.1	-	0.1	0.2	0.3	0.5	0.40	0.32
COV	0.1	0.0	0.1	-	0.2	0.3	0.6	0.6	0.45	0.35
r^2	0.94	1.0	0.76	-	0.60	0.13	0.07	0.10		
n	25	25	25	-	25	25	25	25	25	25
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.1	1.0	-	0.5	0.6	0.6	1.0	1.01	1.04
Std. Dev.	0.1	0.2	0.0	-	0.2	0.2	0.4	0.6	0.50	0.45
COV	0.2	0.2	0.0	-	0.3	0.3	0.6	0.6	0.50	0.43
r^2	0.54	0.76	1.0	-	0.46	0.11	0.02	0.04		
n	25	25	25	-	25	25	25	25	25	25
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	0.84	0.84	0.85
Std. Dev.	-	-	-	0.0	-	-	-	0.44	0.44	0.34
COV	-	-	-	0.0	-	-	-	0.52	0.52	0.41
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	25	-	-	-	25	25	25
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.9	2.2	2.0	-	1.0	1.2	1.1	1.9	-	-
Std. Dev.	0.2	0.4	0.5	-	0.0	0.4	0.5	0.9	-	-
COV	0.2	0.2	0.2	-	0.0	0.4	0.5	0.5	-	-
r^2	0.58	0.60	0.46	-	1.0	0.06	0.15	0.22	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.7	1.9	1.7	-	0.9	1.0	1.0	1.6	-	-
Std. Dev.	0.2	0.5	0.5	-	0.3	0.0	0.4	0.8	-	-
COV	0.3	0.2	0.3	-	0.3	0.0	0.4	0.5	-	-
r^2	0.12	0.13	0.11	-	0.06	1.0	0.41	0.27	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.9	2.2	2.0	-	1.0	1.2	1.0	1.7	-	-
Std. Dev.	0.3	0.8	0.8	-	0.4	0.4	0.0	0.4	-	-
COV	0.4	0.4	0.4	-	0.4	0.3	0.0	0.2	-	-
r^2	0.10	0.07	0.02	-	0.15	0.41	1.0	0.69	-	-
n	25	25	25	-	25	25	25	25	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.3	1.2	1.52	0.6	0.7	0.6	1.0	-	-
Std. Dev.	0.2	0.5	0.5	0.79	0.2	0.2	0.1	0.0	-	-
COV	0.4	0.4	0.4	0.52	0.4	0.3	0.2	0.0	-	-
r^2	0.1	0.10	0.04	0.10	0.22	0.27	0.69	1.0	-	-
n	25	25	25	25	25	25	25	25	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**

Avg.	-	1.35	1.23	1.52	-	-	-	-	1.0	-
Std. Dev.	-	0.61	0.61	0.79	-	-	-	-	0.0	-
COV	-	0.45	0.50	0.52	-	-	-	-	0.0	-
r^2	-	0.10	0.04	0.10	-	-	-	-	1.0	-
n	-	25	25	25.0	-	-	-	-	25	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.23	1.13	1.37	-	-	-	-	-	1.0
Std. Dev.	-	0.43	0.48	0.56	-	-	-	-	-	0.0
COV	-	0.35	0.43	0.41	-	-	-	-	-	0.0
r^2	-	0.11	0.02	0.10	-	-	-	-	-	1.0
n	-	25	25	25.0	-	-	-	-	-	25

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.10 H-Piles

vs. EN	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	1.0	2.2	1.9	-	1.4	1.3	-	1.9	-	-
Std. Dev.	0.0	0.3	0.3	-	0.3	1.0	-	1.3	-	-
COV	0.0	0.1	0.2	-	0.2	0.8	-	0.7	-	-
r^2	1.0	1.00	0.7	-	0.60	0.00	-	0.1	-	-
n	46	46	46	-	46	46	-	46	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.0	0.9	-	0.6	0.6	-	0.80	1.53	1.29
Std. Dev.	0.1	0.0	0.1	-	0.1	0.4	-	0.50	0.97	1.01
COV	0.1	0.0	0.1	-	0.1	0.8	-	0.60	0.63	0.78
r^2	0.96	1.0	0.86	-	0.58	0.00	-	0.06		
n	46	46	46	-	46	46	-	46	46	46
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.2	1.0	-	0.7	0.7	-	1.0	1.84	1.56
Std. Dev.	0.1	0.1	0.0	-	0.1	0.5	-	0.6	1.26	1.31
COV	0.2	0.1	0.0	-	0.2	0.8	-	0.6	0.68	0.84
r^2	0.74	0.86	1.0	-	0.47	0.00	-	0.04		
n	46	46	46	-	46	46	-	46	46	46
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	1.07	2.06	1.74
Std. Dev.	-	-	-	0.0	-	-	-	0.69	1.55	1.57
COV	-	-	-	0.0	-	-	-	0.65	0.75	0.90
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	46	-	-	-	46	46	46
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	1.6	1.4	-	1.0	0.9	-	1.3	-	-
Std. Dev.	0.2	0.3	0.3	-	0.0	0.6	-	0.8	-	-
COV	0.2	0.2	0.2	-	0.0	0.7	-	0.6	-	-
r^2	0.56	0.58	0.47	-	1.0	0.08	-	0.03	-	-
n	46	46	46	-	46	46	-	46	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.4	2.9	2.5	-	1.7	1.0	-	2.0	-	-
Std. Dev.	1.2	2.3	2.2	-	1.3	0.0	-	1.9	-	-
COV	0.9	0.8	0.9	-	0.8	0.0	-	1.0	-	-
r^2	0.00	0.00	0.00	-	0.08	1.0	-	0.20	-	-
n	46	46	46	-	46	46	-	46	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	-	-	-	1.0	-	-	-
Std. Dev.	-	-	-	-	-	-	0.0	-	-	-
COV	-	-	-	-	-	-	0.0	-	-	-
r^2	-	-	-	-	-	-	1.0	-	-	-
n	-	-	-	-	-	-	46	-	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	1.6	1.4	1.33	1.0	0.7	-	1.0	-	-
Std. Dev.	0.5	0.8	0.8	0.86	0.5	0.4	-	0.0	-	-
COV	0.6	0.5	0.5	0.65	0.5	0.5	-	0.0	-	-
r^2	0.1	0.06	0.05	0.15	0.03	0.20	-	1.0	-	-

n	46	46	46	46	46	46	-	25	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	0.91	0.80	0.76	-	-	-	-	1.0	-
Std. Dev.	-	0.58	0.55	0.57	-	-	-	-	0.0	-
COV	-	0.63	0.68	0.75	-	-	-	-	0.0	-
r^2	-	0.07	0.05	0.16	-	-	-	-	1.0	-
n	-	46	46	46	-	-	-	-	25	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.24	1.09	1.04	-	-	-	-	-	1.0
Std. Dev.	-	0.97	0.91	0.93	-	-	-	-	-	0.0
COV	-	0.78	0.84	0.90	-	-	-	-	-	0.0
r^2	-	0.01	0.01	0.07	-	-	-	-	-	1.0
n	-	46	46	46	-	-	-	-	-	25

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.11. Pipe Piles

vs. EN	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.0	2.7	2.3	-	1.4	1.5	1.4	2.6	-	-
Std. Dev.	0.0	0.4	0.5	-	0.4	0.6	0.7	1.3	-	-
COV	0.0	0.1	0.2	-	0.3	0.4	0.5	0.5	-	-
r^2	1.0	0.90	0.60	-	0.50	0.20	0.10	0.10	-	-
n	46	46	46	-	46	46	46	46	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.0	0.9	-	0.5	0.6	-	1.0	0.97	1.03
Std. Dev.	0.1	0.0	0.2	-	0.1	0.2	-	0.5	0.43	0.49
COV	0.1	0.0	0.2	-	0.2	0.4	-	0.5	0.44	0.47
r^2	0.94	1.0	0.81	-	0.53	0.30	-	0.10		
n	46	46	46	-	46	46	-	46	46	46
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.2	1.0	-	0.6	0.6	-	1.2	1.16	1.23
Std. Dev.	0.1	0.2	0.0	-	0.2	0.2	-	0.6	0.61	0.65
COV	0.2	0.2	0.0	-	0.3	0.4	-	0.6	0.52	0.53
r^2	0.63	0.81	1.0	-	0.53	0.35	-	0.06		
n	46	46	25	-	46	46	-	46	46	46
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	1.03	1.03	1.08
Std. Dev.	-	-	-	0.0	-	-	-	0.55	0.55	0.59
COV	-	-	-	0.0	-	-	-	0.53	0.53	0.55
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	25	-	-	-	46	46	46
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	2.0	1.7	-	1.0	1.1	-	1.9	-	-
Std. Dev.	0.2	0.4	0.5	-	0.0	0.4	-	0.8	-	-
COV	0.3	0.2	0.3	-	0.0	0.4	-	0.4	-	-
r^2	0.50	0.53	0.53	-	1.0	0.19	-	0.20	-	-
n	46	46	46	-	46	46	-	46	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	2.0	1.7	-	1.1	1.0	-	1.9	-	-
Std. Dev.	0.3	0.8	0.6	-	0.5	0.0	-	0.9	-	-
COV	0.4	0.4	0.3	-	0.5	0.0	-	0.5	-	-
r^2	0.22	0.30	0.35	-	0.19	1.0	-	0.23	-	-
n	46	46	46	-	46	46	-	46	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	-	-	-	1.0	-	-	-
Std. Dev.	-	-	-	-	-	-	0.0	-	-	-
COV	-	-	-	-	-	-	0.0	-	-	-
r^2	-	-	-	-	-	-	1.0	-	-	-
n	-	-	-	-	-	-	46	-	-	-

vs. IDOT Static	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	0.5	1.2	1.1	1.25	0.6	0.6	-	1.0	-	-
Std. Dev.	0.2	0.5	0.5	0.67	0.2	0.3	-	0.0	-	-
COV	0.4	0.4	0.4	0.53	0.4	0.4	-	0.0	-	-
r^2	0.1	0.10	0.06	0.05	0.20	0.23	-	1.0	-	-
n	46	46	46	46	46	46	-	25	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.23	1.09	1.25	-	-	-	-	1.0	-
Std. Dev.	-	0.54	0.57	0.67	-	-	-	-	0.0	-
COV	-	0.44	0.52	0.53	-	-	-	-	0.0	-
r^2	-	0.10	0.06	0.05	-	-	-	-	1.0	-
n	-	46	46	46	-	-	-	-	25	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.19	1.05	1.20	-	-	-	-	-	1.0
Std. Dev.	-	0.56	0.56	0.65	-	-	-	-	-	0.0
COV	-	0.47	0.53	0.55	-	-	-	-	-	0.0
r^2	-	0.06	0.05	0.01	-	-	-	-	-	1.0
n	-	46	46	46	-	-	-	-	-	25

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.12. Piles in Sand

vs. EN	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	1.0	2.6	2.2	-	1.6	1.7	-	2.9	-	-
Std. Dev.	0.0	0.4	0.5	-	0.3	1.0	-	1.4	-	-
COV	0.0	0.2	0.2	-	0.2	0.6	-	0.5	-	-
r^2	1.0	0.90	0.60	-	0.80	0.30	-	0.00	-	-
n	50	50	50	-	50	50	-	50	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.0	0.8	-	0.6	0.7	-	1.1	1.60	1.48
Std. Dev.	0.1	0.0	0.1	-	0.1	0.4	-	0.5	1.00	1.06
COV	0.2	0.0	0.2	-	0.2	0.6	-	0.4	0.62	0.71
r^2	0.93	1.0	0.78	-	0.76	0.27	-	0.07		
n	50	50	50	-	50	50	-	50	50	50
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.2	1.0	-	0.7	0.8	-	1.4	2.01	1.85
Std. Dev.	0.1	0.2	0.0	-	0.2	0.5	-	0.7	1.35	1.39
COV	0.2	0.2	0.0	-	0.2	0.6	-	0.5	0.67	0.75
r^2	0.59	0.78	1.0	-	0.63	0.24	-	0.06		
n	50	50	50	-	50	50	-	50	50	50
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	1.41	2.18	1.97
Std. Dev.	-	-	-	0.0	-	-	-	0.69	1.61	1.54
COV	-	-	-	0.0	-	-	-	0.49	0.74	0.78
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	50	-	-	-	50	50	50
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.7	1.7	1.4	-	1.0	1.1	-	1.8	-	-
Std. Dev.	0.1	0.3	0.4	-	0.0	0.6	-	0.9	-	-
COV	0.2	0.2	0.3	-	0.0	0.5	-	0.5	-	-
r^2	0.77	0.76	0.63	-	1.0	0.47	-	0.07	-	-
n	50	50	50	-	50	50	-	50	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.9	2.3	1.9	-	1.3	1.0	-	2.3	-	-
Std. Dev.	0.8	1.9	1.8	-	0.9	0.0	-	2.0	-	-
COV	0.9	0.8	0.9	-	0.7	0.0	-	0.9	-	-
r^2	0.27	0.27	0.24	-	0.47	1.0	-	0.11	-	-
n	50	50	50	-	50	50	-	50	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	-	-	-	1.0	-	-	-
Std. Dev.	-	-	-	-	-	-	0.0	-	-	-
COV	-	-	-	-	-	-	0.0	-	-	-
r^2	-	-	-	-	-	-	1.0	-	-	-
n	-	-	-	-	-	-	50	-	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.1	0.9	1.62	0.7	0.7	-	1.0	-	-
Std. Dev.	0.2	0.5	0.4	0.73	0.3	0.4	-	0.0	-	-
COV	0.5	0.4	0.5	0.45	0.5	0.7	-	0.0	-	-
r^2	0.0	0.07	0.06	0.06	0.07	0.11	-	1.0	-	-
n	50	50	50	50	50	50	-	50	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	0.86	0.72	0.71	-	-	-	-	1.0	-
Std. Dev.	-	0.53	0.49	0.52	-	-	-	-	0.0	-
COV	-	0.62	0.67	0.74	-	-	-	-	0.0	-
r^2	-	0.08	0.05	0.00	-	-	-	-	1.0	-
n	-	50	50	50	-	-	-	-	25	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.01	0.85	0.82	-	-	-	-	-	1.0
Std. Dev.	-	0.72	0.64	0.64	-	-	-	-	-	0.0
COV	-	0.71	0.75	0.78	-	-	-	-	-	0.0
r^2	-	0.11	0.02	0.0	-	-	-	-	-	1.0
n	-	50	50	50	-	-	-	-	-	25

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.13. Piles in Clay

vs. EN	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	1.0	2.3	2.1	-	1.3	1.1	-	1.7	-	-
Std. Dev.	0.0	0.4	0.4	-	0.2	0.5	-	1.0	-	-
COV	0.0	0.2	0.2	-	0.2	0.5	-	0.6	-	-
r^2	1.0	1.00	0.60	-	0.60	0.00	-	0.00	-	-
n	50	50	50	-	50	50	-	50	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.0	0.9	-	0.6	0.5	-	0.7	0.96	0.91
Std. Dev.	0.1	0.0	0.1	-	0.1	0.2	-	0.4	0.42	0.45
COV	0.2	0.0	0.1	-	0.2	0.4	-	0.6	0.44	0.50
r^2	0.96	1.0	0.75	-	0.66	0.00	-	0.00		
n	50	50	50	-	50	50	-	50	50	50
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.1	1.0	-	0.6	0.5	-	0.8	1.09	1.04
Std. Dev.	0.1	0.1	0.0	-	0.2	0.2	-	0.5	0.50	0.55
COV	0.2	0.1	0.0	-	0.3	0.4	-	0.6	0.46	0.53
r^2	0.58	0.75	1.0	-	0.45	0.00	-	0.00		
n	50	50	50	-	50	50	-	50	50	50
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	0.74	1.01	0.94
Std. Dev.	-	-	-	0.0	-	-	-	0.33	0.53	0.49
COV	-	-	-	0.0	-	-	-	0.45	0.52	0.52
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	50	-	-	-	50	50	50
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	1.9	1.7	-	1.0	0.9	-	1.4	-	-
Std. Dev.	0.2	0.4	0.5	-	0.0	0.5	-	0.8	-	-
COV	0.2	0.2	0.3	-	0.0	0.5	-	0.6	-	-
r^2	0.63	0.66	0.45	-	1.0	0.02	-	0.00	-	-
n	50	50	50	-	50	50	-	50	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.2	2.6	2.3	-	1.5	1.0	-	1.6	-	-
Std. Dev.	1.0	1.6	1.6	-	1.2	0.0	-	0.6	-	-
COV	0.8	0.6	0.7	-	0.8	0.0	-	0.4	-	-
r^2	0.00	0.00	0.00	-	0.02	1.0	-	0.34	-	-
n	50	50	50	-	50	50	-	50	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	-	-	-	1.0	-	-	-
Std. Dev.	-	-	-	-	-	-	0.0	-	-	-
COV	-	-	-	-	-	-	0.0	-	-	-
r^2	-	-	-	-	-	-	1.0	-	-	-
n	-	-	-	-	-	-	50	-	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	1.7	1.5	1.62	0.9	0.7	-	1.0	-	-
Std. Dev.	0.4	0.7	0.7	0.73	0.5	0.2	-	0.0	-	-
COV	0.6	0.4	0.5	0.45	0.6	0.3	-	0.0	-	-
r^2	0.0	0.00	0.00	0.06	0.00	0.34	-	1.0	-	-
n	50	50	50	50	50	50	-	50	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.24	1.11	1.26	-	-	-	-	1.0	-
Std. Dev.	-	0.55	0.51	0.66	-	-	-	-	0.0	-
COV	-	0.44	0.46	0.52	-	-	-	-	0.0	-
r^2	-	0.14	0.07	0.05	-	-	-	-	1.0	-
n	-	50	50	50	-	-	-	-	50	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**

Avg.	-	1.36	1.24	1.35	-	-	-	-	-	1.0
Std. Dev.	-	0.68	0.66	0.70	-	-	-	-	-	0.0
COV	-	0.50	0.53	0.52	-	-	-	-	-	0.0
r^2	-	0.05	0.01	0.02	-	-	-	-	-	1.0
n	-	50	50	50	-	-	-	-	-	50

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.14. All Piles

vs. EN	EN-IDOT	FHWA-Gates	WSDOT	FHWA-UI	WEAP	Driven	Olson	IDOT Static	K-IDOT	ICP
Avg.	1.0	2.4	2.1	-	1.4	1.4	-	2.2	-	-
Std. Dev.	0.0	0.4	0.5	-	0.3	0.8	-	1.3	-	-
COV	0.0	0.2	0.2	-	0.2	0.6	-	0.6	-	-
r^2	1.0	0.90	0.60	-	0.70	0.00	-	0.00	-	-
n	92	92	92	-	92	92	-	92	-	-
vs. FHWA-Gates	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.4	1.0	0.9	-	0.6	0.6	-	0.9	1.24	1.16
Std. Dev.	0.1	0.0	0.1	-	0.1	0.3	-	0.5	0.72	0.73
COV	0.2	0.0	0.1	-	0.2	0.6	-	0.5	0.58	0.63
r^2	0.94	1.0	0.91	-	0.66	0.05	-	0.0		
n	92	92	92	-	92	92	-	92	92	92
vs. WSDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.5	1.2	1.0	-	0.7	0.7	-	1.1	1.49	1.39
Std. Dev.	0.1	0.2	0.0	-	0.2	0.4	-	0.6	0.94	0.97
COV	0.2	0.2	0.0	-	0.2	0.6	-	0.6	0.63	0.70
r^2	0.63	0.81	1.0	-	0.51	0.06	-	0.00		
n	92	92	92	-	92	92	-	92	92	92
vs. FHWA-UI	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	1.0	-	-	-	1.05	1.52	1.38
Std. Dev.	-	-	-	0.0	-	-	-	0.61	1.12	1.04
COV	-	-	-	0.0	-	-	-	0.58	0.74	0.75
r^2	-	-	-	1.0	-	-	-			
n	-	-	-	92	-	-	-	92	92	92
vs. WEAP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.8	1.8	1.6	-	1.0	1.0	-	1.6	-	-
Std. Dev.	0.2	0.4	0.4	-	0.0	0.5	-	0.9	-	-
COV	0.2	0.2	0.3	-	0.0	0.5	-	0.5	-	-
r^2	0.66	0.66	0.51	-	1.0	0.12	-	0.01	-	-
n	92	92	92	-	92	92	-	92	-	-
vs. Driven	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	1.1	2.5	2.1	-	1.4	1.0	-	1.9	-	-
Std. Dev.	0.9	1.8	1.7	-	1.1	0.0	-	1.5	-	-
COV	0.9	0.7	0.8	-	0.8	0.0	-	0.8	-	-
r^2	0.04	0.05	0.06	-	0.12	1.0	-	0.16	-	-
n	92	92	92	-	92	92	-	92	-	-
vs. Olson	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	-	-	-	-	-	1.0	-	-	-
Std. Dev.	-	-	-	-	-	-	0.0	-	-	-
COV	-	-	-	-	-	-	0.0	-	-	-
r^2	-	-	-	-	-	-	1.0	-	-	-
n	-	-	-	-	-	-	92	-	-	-
vs. IDOT Static	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	0.6	1.4	1.2	1.28	0.8	0.7	-	1.0	-	-
Std. Dev.	0.4	0.7	0.6	0.74	0.5	0.3	-	0.0	-	-
COV	0.6	0.5	0.5	0.58	0.6	0.5	-	0.0	-	-
r^2	0.00	0.00	0.00	0.00	0.01	0.16	-	1.0	-	-
n	92	92	92	92	92	92	-	92	-	-
vs. K-IDOT	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.08	0.94	1.02	-	-	-	-	1.0	-
Std. Dev.	-	0.63	0.59	0.75	-	-	-	-	0.0	-
COV	-	0.57	0.63	0.74	-	-	-	-	0.0	-
r^2	-	0.03	0.01	0.03	-	-	-	-	1.0	-
n	-	92	92	92	-	-	-	-	92	-
vs. ICP	**EN-IDOT**	**FHWA-Gates**	**WSDOT**	**FHWA-UI**	**WEAP**	**Driven**	**Olson**	**IDOT Static**	**K-IDOT**	**ICP**
Avg.	-	1.21	1.07	1.13	-	-	-	-	-	1.0
Std. Dev.	-	0.76	0.75	0.85	-	-	-	-	-	0.0
COV	-	0.63	0.70	0.75	-	-	-	-	-	0.0
r^2	-	0.02	0.01	0.01	-	-	-	-	-	1.0
n	-	92	92	92	-	-	-	-	-	92

Note 1) A dash (-) indicates that the particular capacity ratio is not applicable to the study.
Note 2) The values presented are determined by Method (Column) vs. Method (Row)

Table D.15. Rankings of Dynamic/Static Agreement Presented as [Rank (COV)]

H-Piles in Sand					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	5 (0.56)	**1 (0.48)**	**3 (0.52)**	**2 (0.51)**	4 (0.52)
vs. Driven	17 (1.06)	18 (1.08)	19 (1.19)	16 (0.90)	-
vs. Olson	10 (0.68)	11 (0.69)	12 (0.72)	7 (0.62)	-
vs. K-IDOT	-	6 (0.59)	7 (0.62)	-	9 (0.66)
vs. ICP	-	13 (0.80)	14 (0.84)	-	14 (0.84)

H-Piles in Clay					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	8 (0.51)	**2 (0.41)**	4 (0.43)	4 (0.43)	**1 (0.37)**
vs. Driven	19 (0.75)	14 (0.63)	18 (0.68)	17 (0.66)	-
vs. Olson	9 (0.56)	9 (0.56)	11 (0.57)	12 (0.61)	-
vs. K-IDOT	-	**2 (0.41)**	4 (0.43)	-	4 (0.43)
vs. ICP	-	13 (0.62)	16 (0.65)	-	14 (0.63)

Pipe Piles in Sand					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	5 (0.41)	**1 (0.37)**	8 (0.45)	**3 (0.38)**	6 (0.42)
vs. Driven	12 (0.47)	9 (0.46)	**1 (0.37)**	9 (0.46)	-
vs. Olson	13 (0.49)	15 (0.51)	9 (0.46)	16 (0.53)	-
vs. K-IDOT	-	4 (0.39)	14 (0.50)	-	6 (0.42)
vs. ICP	-	17 (0.59)	19 (0.62)	-	18 (0.61)

Pipe Piles in Clay					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	8 (0.39)	6 (0.38)	11 (0.40)	6 (0.38)	18 (0.52)
vs. Driven	**2 (0.27)**	**1 (0.25)**	**2 (0.27)**	4 (0.35)	-
vs. Olson	8 (0.39)	8 (0.39)	12 (0.41)	12 (0.41)	-
vs. K-IDOT	-	16 (0.45)	17 (0.50)	-	18 (0.52)
vs. ICP	-	4 (0.35)	15 (0.43)	-	12 (0.41)

H-Piles					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	4 (0.63)	**1 (0.51)**	**3 (0.55)**	**2 (0.53)**	7 (0.65)
vs. Driven	17 (0.88)	15 (0.81)	17 (0.88)	13 (0.77)	-
vs. Olson	7 (0.65)	6 (0.64)	9 (0.66)	9 (0.66)	-
vs. K-IDOT	-	4 (0.63)	11 (0.68)	-	12 (0.75)
vs. ICP	-	14 (0.78)	16 (0.84)	-	19 (0.90)

Pipe Piles					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	6 (0.42)	5 (0.39)	7 (0.44)	**2 (0.37)**	15 (0.53)
vs. Driven	**3 (0.38)**	**3 (0.38)**	**1 (0.32)**	9 (0.45)	-
vs. Olson	12 (0.49)	10 (0.47)	13 (0.50)	19 (0.73)	-
vs. K-IDOT	-	7 (0.44)	14 (0.52)	-	15 (0.53)
vs. ICP	-	10 (0.47)	15 (0.53)	-	18 (0.55)

Piles in Sand					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	5 (0.52)	**1 (0.42)**	**3 (0.48)**	**2 (0.46)**	4 (0.49)
vs. Driven	18 (0.88)	17 (0.84)	19 (0.93)	13 (0.72)	-
vs. Olson	10 (0.66)	8 (0.63)	9 (0.64)	6 (0.59)	-
vs. K-IDOT	-	7 (0.62)	11 (0.67)	-	14 (0.74)
vs. ICP	-	12 (0.71)	15 (0.75)	-	16 (0.78)

Piles in Clay					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	14 (0.59)	**2 (0.45)**	4 (0.46)	12 (0.55)	**2 (0.45)**
vs. Driven	19 (0.83)	16 (0.63)	17 (0.68)	18 (0.77)	-
vs. Olson	13 (0.56)	7 (0.51)	8 (0.52)	15 (0.62)	-
vs. K-IDOT	-	**1 (0.44)**	4 (0.46)	-	8 (0.52)
vs. ICP	-	6 (0.50)	11 (0.53)	-	8 (0.52)

All Piles					
	EN-IDOT	**FHWA-Gates**	**WSDOT**	**WEAP**	**FHWA-UI**
vs. IDOT Static	10 (0.64)	**1 (0.49)**	**2 (0.53)**	**3 (0.56)**	5 (0.58)
vs. Driven	19 (0.86)	14 (0.72)	18 (0.78)	16 (0.75)	-
vs. Olson	12 (0.65)	6 (0.59)	7 (0.61)	10 (0.64)	-

vs. K-IDOT	-	4 (0.57)	8 (0.63)	-	15 (0.74)
vs. ICP	-	8 (0.63)	13 (0.70)	-	16 (0.75)

APPENDIX E – STATISTICS FOR CORRECTED CAPACITIES

E.1 INTRODUCTION

Statistics referred to but not presented in Chapter 6 of this report are reported in this appendix in their entirety. The statistics for the Dynamic/Corrected Static data for each subcategory were determined as part of the analysis.

E.2 STATISTICS BASED ON CORRECTED STATIC METHODS

As discussed in Chapter 6, the IDOT Static, K-IDOT, and ICP methods were corrected based on soil and pile type. Tables E.1 – E.9 present the complete average Dynamic/Corrected Static capacity ratio statistics for each of the nine sets of Dynamic/Corrected Static data considered in the Illinois Database. Tables E.10 – E.18 present the complete average Dynamic/Corrected static capacity ratio statistics for each of the nine sets of Dynamic/Corrected Static data considered in the Comprehensive Database.

Figures E.1 – E.9 graph the Dynamic/Corrected Static data for each Dynamic/Corrected Static combination considered for the Illinois Database. Figures E.10 – E.18 present the Dynamic/Corrected Static data for the Comprehensive Database.

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Analysis	**Database**	**Location**
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FHWA-Gates/Corrected ICP	Illinois Database	Table E.4, Figure E.4
FHWA-Gates/Corrected IDOT Static	Illinois Database	Table E.5, Figure E.5
FHWA-Gates/Corrected K-IDOT	Illinois Database	Table E.6, Figure E.6
FHWA-UI/Corrected ICP	Illinois Database	Table E.7, Figure E.7
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WSDOT/Corrected ICP	Comprehensive Database	Table E.10, Figure E.10
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FHWA-UI/Corrected ICP	Comprehensive Database	Table E.16, Figure E.16
FHWA-UI/Corrected IDOT Static	Comprehensive Database	Table E.17, Figure E.17
FHWA-UI/Corrected K-IDOT	Comprehensive Database	Table E.18, Figure E.18

Table E.1. WSDOT/Corrected ICP, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.07	1.18	1.12
	Std. Dev:	0.43	0.75	0.56
	COV:	0.39	0.63	0.50
	r^2:	0.02	0.12	0.10
	n:	25	21	46
H-Piles	**Average:**	1.16	1.27	1.20
	Std. Dev:	0.69	0.99	0.81
	COV:	0.59	0.78	0.67
	r^2:	0.00	0.04	0.03
	n:	25	21	46
All Piles	**Average:**	1.12	1.22	1.16
	Std. Dev:	0.56	0.85	0.67
	COV:	0.50	0.70	0.58
	r^2:	0.00	0.00	0.09
	n:	50	46	92

Table E.2. WSDOT/Corrected IDOT Static, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	Average:	1.08	1.11	1.09
	Std. Dev:	0.45	0.54	0.48
	COV:	0.42	0.49	0.44
	r^2:	0.10	0.17	0.17
	n:	25	21	46
H-Piles	Average:	1.52	0.96	1.27
	Std. Dev:	0.76	0.52	0.74
	COV:	0.50	0.55	0.58
	r^2:	0.00	0.00	0.01
	n:	25	21	46
All Piles	Average:	1.30	1.03	1.19
	Std. Dev:	0.63	0.54	0.62
	COV:	0.49	0.52	0.52
	r^2:	0.04	0.00	0.05
	n:	50	46	92

Table E.3. WSDOT/Corrected K-IDOT, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.08	1.11	1.09
	Std. Dev:	0.45	0.54	0.48
	COV:	0.42	0.49	0.44
	r^2:	0.10	0.17	0.17
	n:	25	21	46
H-Piles	**Average:**	1.31	0.91	1.13
	Std. Dev:	0.59	0.48	0.59
	COV:	0.45	0.52	0.52
	r^2:	0.00	0.00	0.00
	n:	25	21	46
All Piles	**Average:**	1.20	1.02	1.11
	Std. Dev:	0.52	0.52	0.54
	COV:	0.44	0.51	0.49
	r^2:	0.02	0.00	0.07
	n:	50	46	92

Table E.4. FHWA-Gates/Corrected ICP, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.05	1.17	1.10
	Std. Dev:	0.35	0.71	0.51
	COV:	0.33	0.61	0.46
	r^2:	0.12	0.10	0.11
	n:	25	21	46
H-Piles	**Average:**	1.15	1.23	1.18
	Std. Dev:	0.66	0.87	0.73
	COV:	0.57	0.71	0.62
	r^2:	0.00	0.07	0.05
	n:	25	21	46
All Piles	**Average:**	1.10	1.19	1.14
	Std. Dev:	0.59	0.77	0.62
	COV:	0.45	0.65	0.55
	r^2:	0.01	0.00	0.11
	n:	50	46	92

Table E.5. FHWA-Gates/Corrected IDOT Static, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.08	1.07	1.07
	Std. Dev:	0.44	0.42	0.42
	COV:	0.41	0.39	0.39
	r^2:	0.13	0.18	0.18
	n:	25	21	46
H-Piles	**Average:**	1.49	0.92	1.23
	Std. Dev:	0.62	0.43	0.64
	COV:	0.42	0.47	0.52
	r^2:	0.00	0.06	0.00
	n:	25	21	46
All Piles	**Average:**	1.28	1.00	1.16
	Std. Dev:	0.56	0.44	0.54
	COV:	0.44	0.44	0.46
	r^2:	0.02	0.00	0.01
	n:	50	46	92

Table E.6. FHWA-Gates/Corrected K-IDOT, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.08	1.07	1.07
	Std. Dev:	0.44	0.42	0.42
	COV:	0.41	0.39	0.39
	r^2:	0.13	0.18	0.18
	n:	25	21	46
H-Piles	**Average:**	1.35	0.95	1.16
	Std. Dev:	0.52	0.42	0.52
	COV:	0.38	0.44	0.45
	r^2:	0.00	0.01	0.01
	n:	25	21	46
All Piles	**Average:**	1.20	1.01	1.12
	Std. Dev:	0.49	0.42	0.48
	COV:	0.41	0.42	0.43
	r^2:	0.03	0.00	0.05
	n:	50	46	92

Table E.7. FHWA-UI/Corrected ICP, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.05	1.20	1.11
	Std. Dev:	0.32	0.79	0.52
	COV:	0.31	0.66	0.47
	r^2:	0.10	0.08	0.25
	n:	25	21	46
H-Piles	**Average:**	1.23	1.08	1.17
	Std. Dev:	0.70	0.79	0.75
	COV:	0.57	0.73	0.64
	r^2:	0.00	0.07	0.09
	n:	25	21	46
All Piles	**Average:**	1.14	1.13	1.13
	Std. Dev:	0.51	0.77	0.63
	COV:	0.45	0.68	0.56
	r^2:	0.00	0.00	0.15
	n:	50	46	92

Table E.8. FHWA-UI/Corrected IDOT Static, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.08	1.08	1.08
	Std. Dev:	0.40	0.45	0.41
	COV:	0.37	0.42	0.38
	r^2:	0.13	0.18	0.21
	n:	25	21	46
H-Piles	**Average:**	1.79	0.90	1.38
	Std. Dev:	1.06	0.47	0.94
	COV:	0.59	0.52	0.68
	r^2:	0.00	0.03	0.01
	n:	25	21	46
All Piles	**Average:**	1.42	0.99	1.22
	Std. Dev:	0.77	0.48	0.67
	COV:	0.55	0.49	0.55
	r^2:	0.00	0.00	0.08
	n:	50	46	92

Table E.9. FHWA-UI/Corrected K-IDOT, Illinois Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	1.08	1.08	1.08
	Std. Dev:	0.40	0.45	0.41
	COV:	0.37	0.42	0.38
	r^2:	0.16	0.17	0.39
	n:	25	21	46
H-Piles	**Average:**	1.45	0.75	1.12
	Std. Dev:	0.62	0.34	0.61
	COV:	0.43	0.46	0.57
	r^2:	0.00	0.01	0.03
	n:	25	21	46
All Piles	**Average:**	1.26	0.91	1.10
	Std. Dev:	0.52	0.44	0.53
	COV:	0.42	0.49	0.49
	r^2:	0.00	0.00	0.08
	n:	50	46	92

Table E.10. WSDOT/Corrected ICP, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.65	1.41	0.96
	Std. Dev:	0.33	1.54	0.66
	COV:	0.51	1.09	0.69
	r^2:	0.33	0.84	0.07
	n:	3	4	11
H-Piles	**Average:**	-	1.54	0.94
	Std. Dev:	-	1.34	0.58
	COV:	-	0.87	0.62
	r^2:	-	0.77	0.02
	n:	1	4	15
All Piles	**Average:**	0.77	1.42	0.94
	Std. Dev:	0.42	1.27	0.60
	COV:	0.55	0.89	0.64
	r^2:	0.71	0.76	0.00
	n:	4	8	26

Table E.11. WSDOT/Corrected IDOT Static, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.62	2.02	1.28
	Std. Dev:	0.31	2.91	1.07
	COV:	0.51	1.44	0.84
	r^2:	1	0.90	0.39
	n:	2	4	11
H-Piles	**Average:**	-	1.29	1.15
	Std. Dev:	-	1.04	0.73
	COV:	-	0.81	0.63
	r^2:	-	0.55	0.30
	n:	1	6	15
All Piles	**Average:**	1.22	1.47	1.20
	Std. Dev:	1.24	1.42	0.86
	COV:	1.01	0.96	0.71
	r^2:	0.25	0.31	0.37
	n:	3	10	26

Table E.12. WSDOT/Corrected K-IDOT, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.62	1.45	1.15
	Std. Dev:	0.32	1.45	0.80
	COV:	0.51	1.00	0.70
	r^2:	1	0.91	0.39
	n:	2	4	11
H-Piles	**Average:**	-	1.09	1.06
	Std. Dev:	-	0.58	0.55
	COV:	-	0.53	0.52
	r^2:	-	0.17	0.43
	n:	1	10	15
All Piles	**Average:**	1.17	1.16	1.09
	Std. Dev:	1.13	0.73	0.63
	COV:	0.96	0.63	0.58
	r^2:	0.25	0.35	0.27
	n:	3	14	26

Table E.13. FHWA-Gates/Corrected ICP, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.58	1.24	0.74
	Std. Dev:	0.28	1.87	0.57
	COV:	0.47	1.51	0.77
	r^2:	0.44	0.73	0.15
	n:	3	3	9
H-Piles	**Average:**	-	0.90	0.77
	Std. Dev:	-	0.50	0.45
	COV:	-	0.56	0.58
	r^2:	-	0.23	0.03
	n:	1	3	14
All Piles	**Average:**	0.81	1.11	0.78
	Std. Dev:	0.54	1.08	0.53
	COV:	0.67	0.97	0.67
	r^2:	0.11	0.46	0.00
	n:	4	6	23

Table E.14. FHWA-Gates/Corrected IDOT Static, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.55	2.69	0.97
	Std. Dev:	0.25	6.14	0.87
	COV:	0.45	2.28	0.90
	r^2:	1	0.79	0.36
	n:	2	3	9
H-Piles	**Average:**	-	1.96	0.95
	Std. Dev:	-	1.48	0.69
	COV:	-	0.75	0.73
	r^2:	-	0.13	0.23
	n:	1	5	14
All Piles	**Average:**	1.60	1.19	0.94
	Std. Dev:	2.35	1.37	0.72
	COV:	1.46	1.15	0.77
	r^2:	0.63	0.12	0.29
	n:	3	8	23

Table E.15. FHWA-Gates/Corrected K-IDOT, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.55	1.65	0.83
	Std. Dev:	0.25	2.46	0.57
	COV:	0.45	1.49	0.68
	r^2:	1	0.81	0.39
	n:	2	3	9
H-Piles	**Average:**	-	0.85	0.95
	Std. Dev:	-	0.37	0.57
	COV:	-	0.44	0.59
	r^2:	-	0.14	0.43
	n:	1	9	14
All Piles	**Average:**	1.54	0.97	0.90
	Std. Dev:	2.15	0.63	0.56
	COV:	1.40	0.65	0.62
	r^2:	0.63	0.27	0.30
	n:	3	12	23

Table E.16. FHWA-UI/Corrected ICP, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.66	1.43	0.83
	Std. Dev:	0.31	2.23	0.63
	COV:	0.47	1.56	0.76
	r^2:	0.48	0.21	0.32
	n:	3	3	9
H-Piles	**Average:**	-	1.03	0.81
	Std. Dev:	-	0.75	0.47
	COV:	-	0.73	0.58
	r^2:	-	0.08	0.03
	n:	1	3	14
All Piles	**Average:**	0.95	1.24	0.84
	Std. Dev:	0.66	1.26	0.56
	COV:	0.70	1.02	0.66
	r^2:	-	-	-
	n:	4	6	23

Table E.17. FHWA-UI/Corrected IDOT Static, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.62	3.51	1.20
	Std. Dev:	0.27	9.27	1.13
	COV:	0.43	2.64	0.95
	r^2:	1	0.60	0.27
	n:	2	3	9
H-Piles	**Average:**	-	1.01	1.17
	Std. Dev:	-	0.66	0.82
	COV:	-	0.66	0.70
	r^2:	-	0.37	0.28
	n:	1	5	14
All Piles	**Average:**	1.68	1.50	1.17
	Std. Dev:	2.28	1.73	0.91
	COV:	1.35	1.15	0.78
	r^2:			
	n:	3	8	23

Table E.18. FHWA-UI/Corrected K-IDOT, Comprehensive Database

		Clay	Sand	All Soil
Pipe Piles	**Average:**	0.62	2.13	1.01
	Std. Dev:	0.27	3.64	0.73
	COV:	0.43	1.71	0.73
	r^2:	1	0.62	0.27
	n:	2	3	9
H-Piles	**Average:**	-	0.83	0.96
	Std. Dev:	-	0.36	0.61
	COV:	-	0.44	0.63
	r^2:	-	0.23	0.37
	n:	1	9	14
All Piles	**Average:**	1.77	1.01	0.96
	Std. Dev:	2.51	0.70	0.62
	COV:	1.42	0.70	0.65
	r^2:			
	n:	3	12	23

WSDOT vs. Corrected ICP

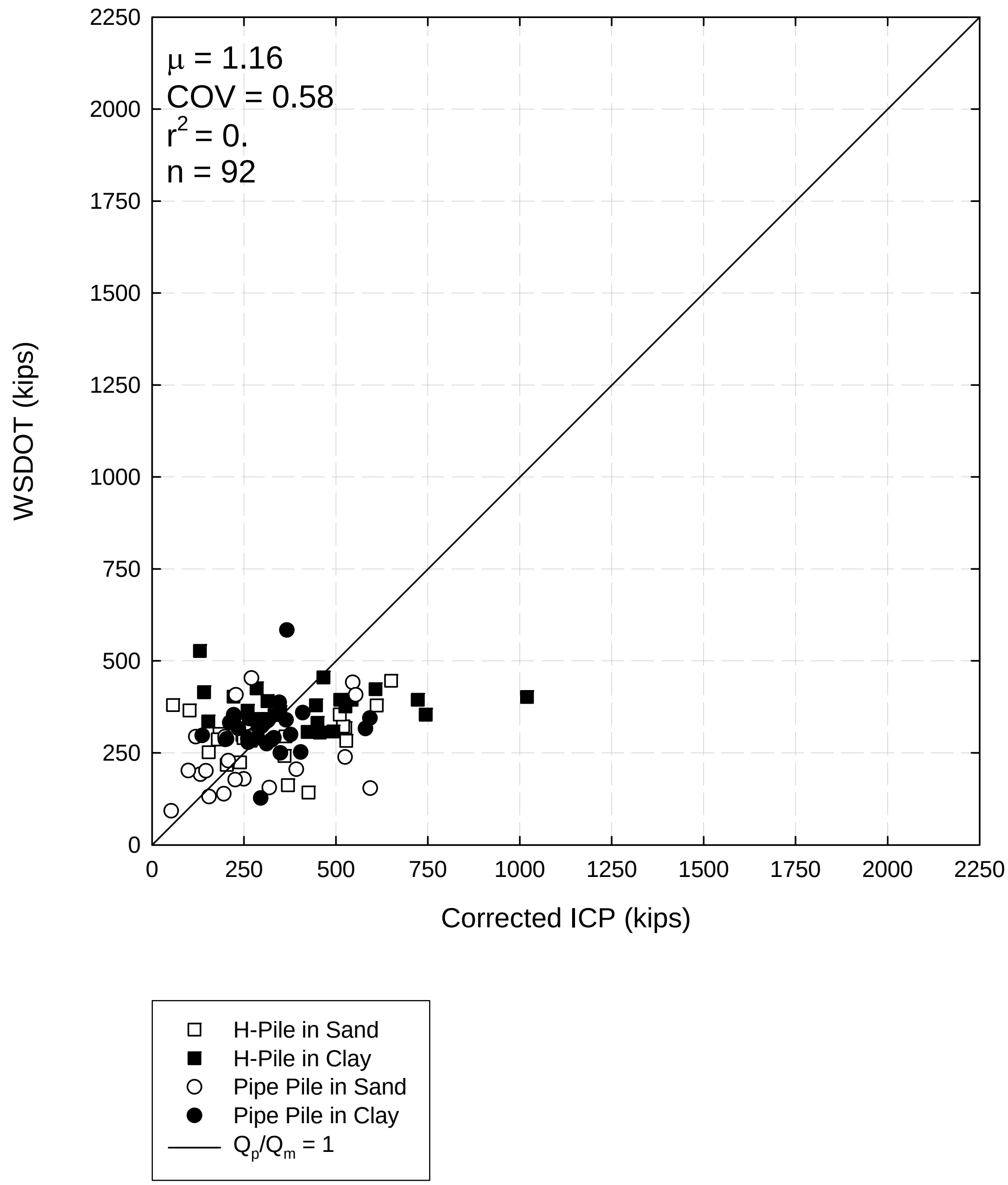

Figure E.1. WSDOT vs. Corrected ICP, Illinois Database.

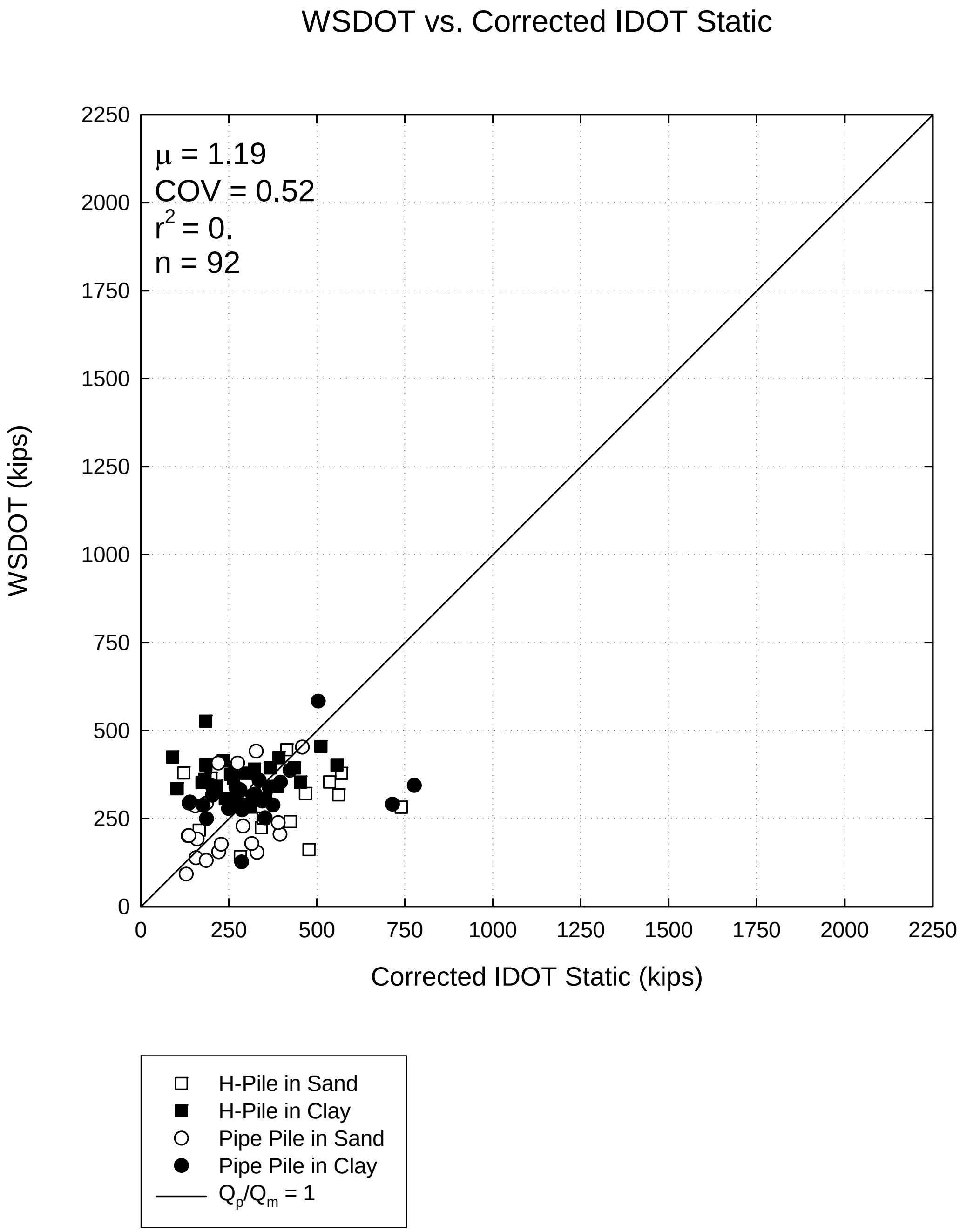

Figure E.2. WSDOT vs. Corrected IDOT Static, Illinois Database.

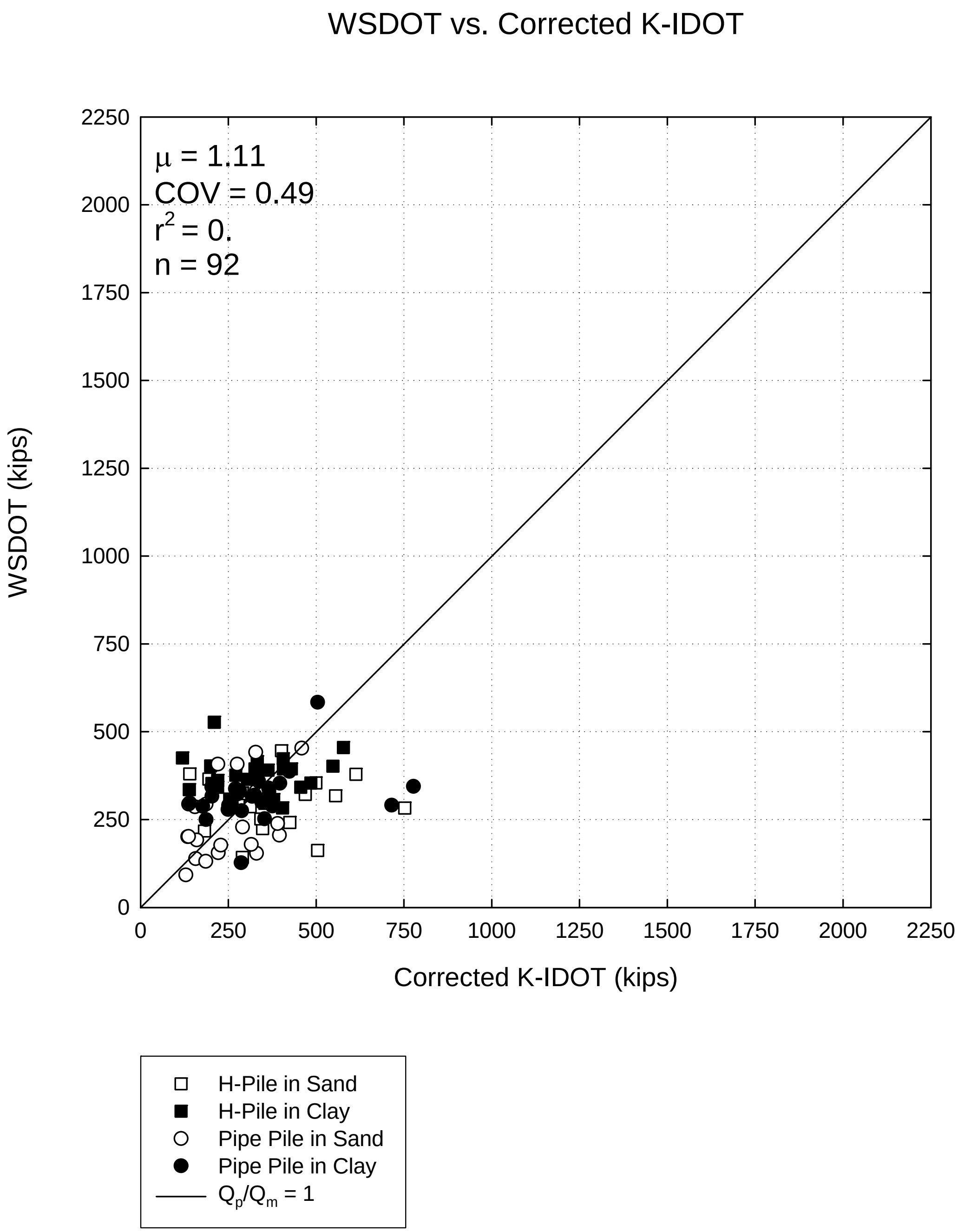

Figure E.3. WSDOT vs. Corrected K-IDOT, Illinois Database.

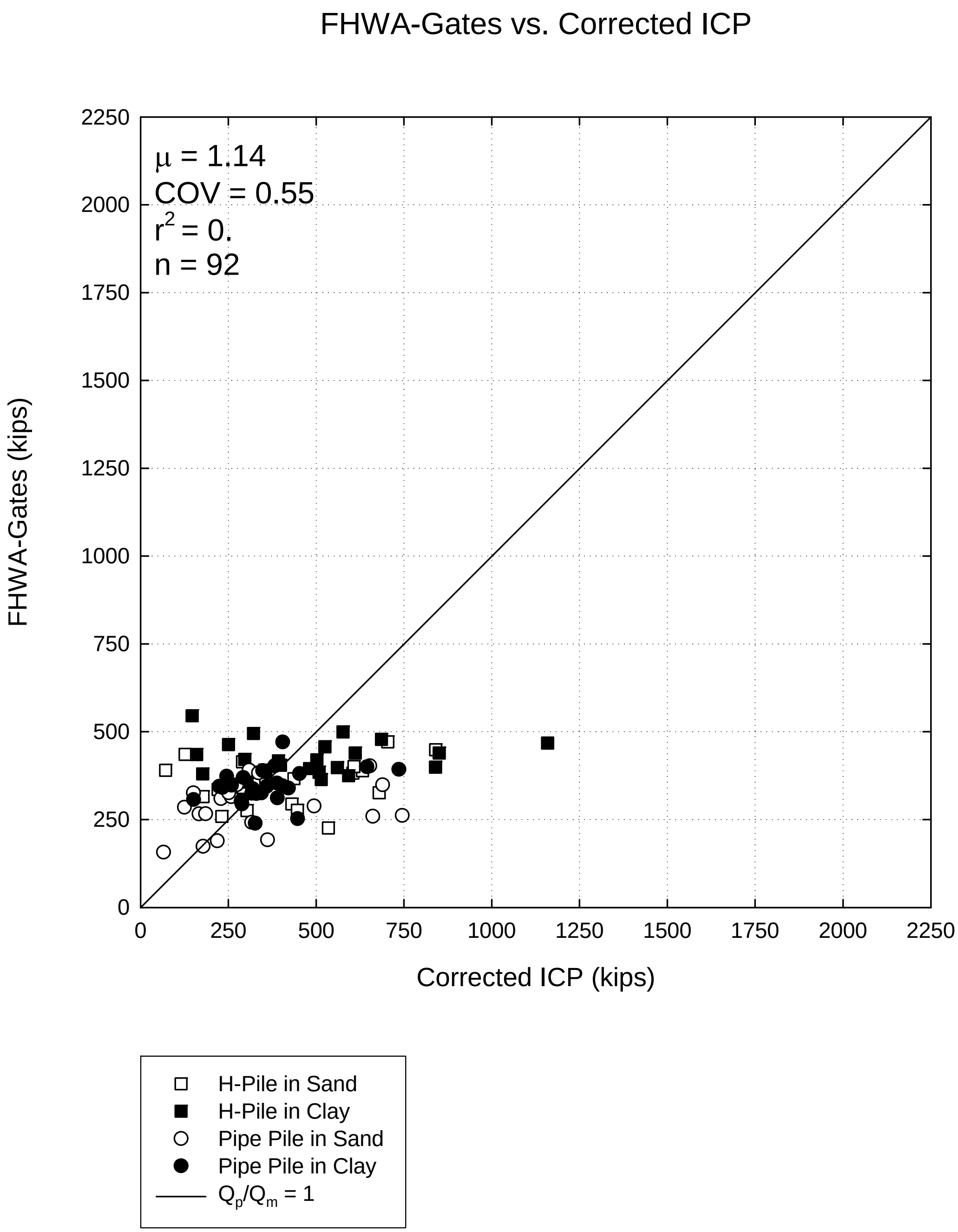

Figure E.4. FHWA-Gates vs. Corrected ICP, Illinois Database.

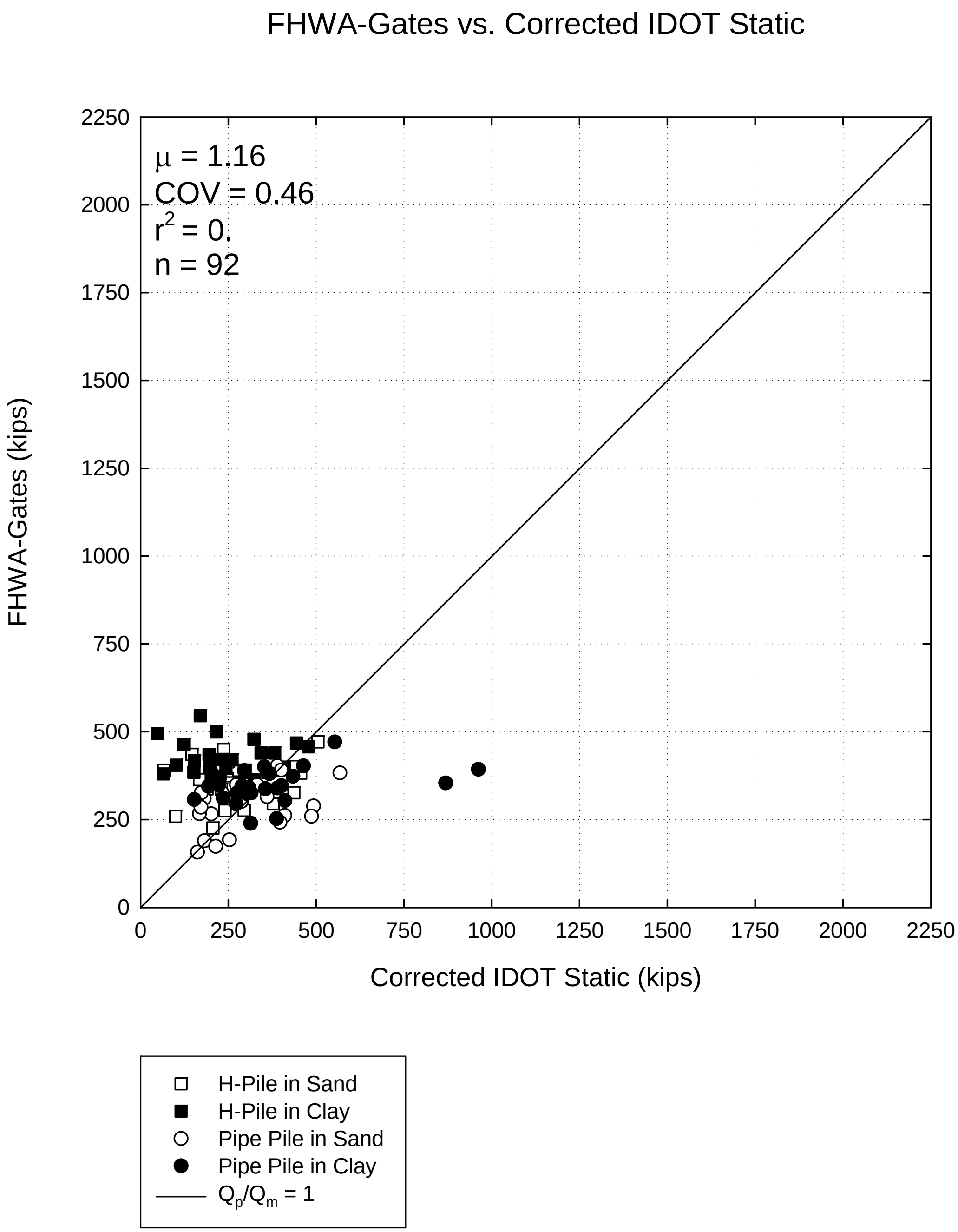

Figure E.5. FHWA-Gates vs. Corrected IDOT Static, Illinois Database.

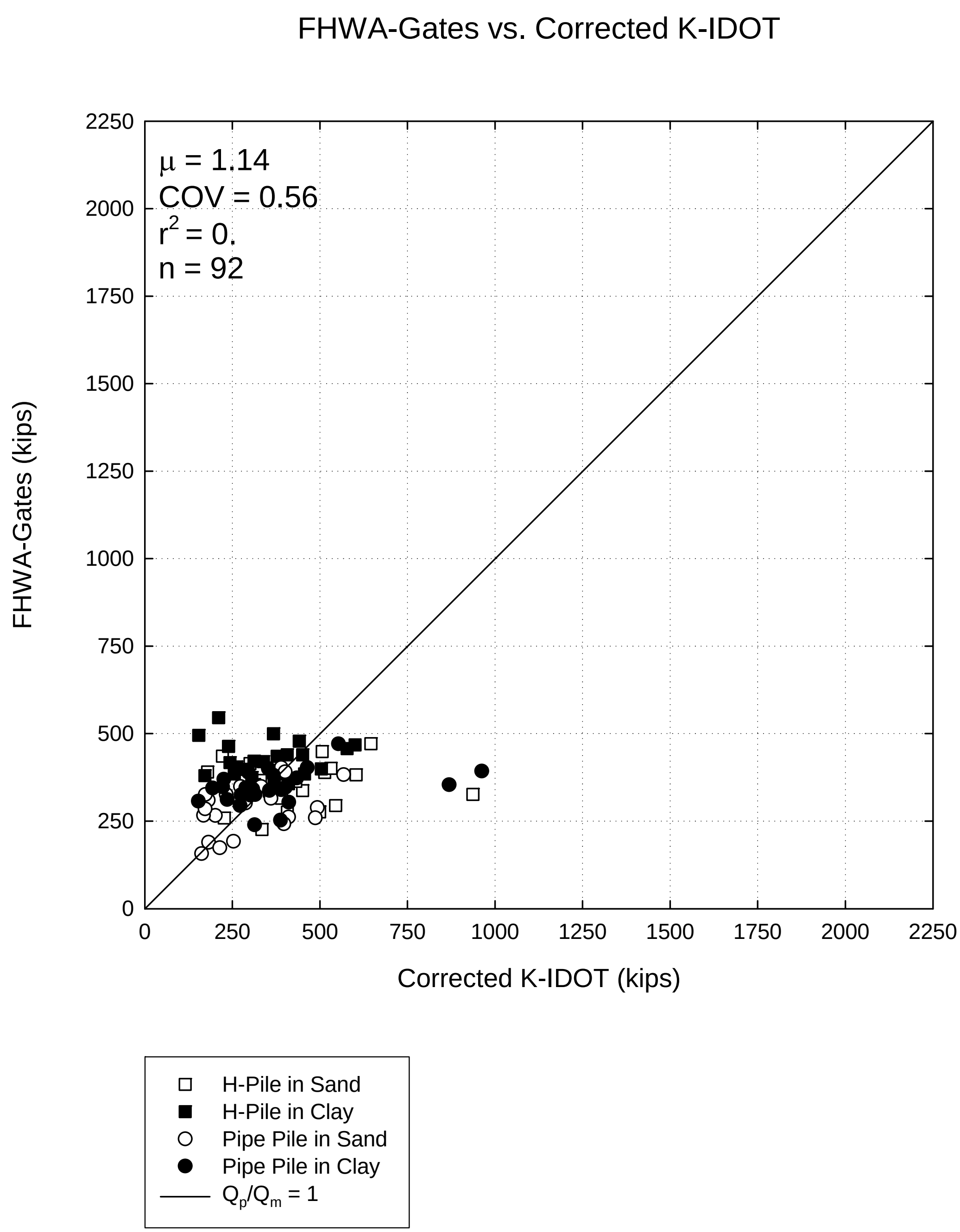

Figure E.6. FHWA-Gates vs. Corrected K-IDOT, Illinois Database.

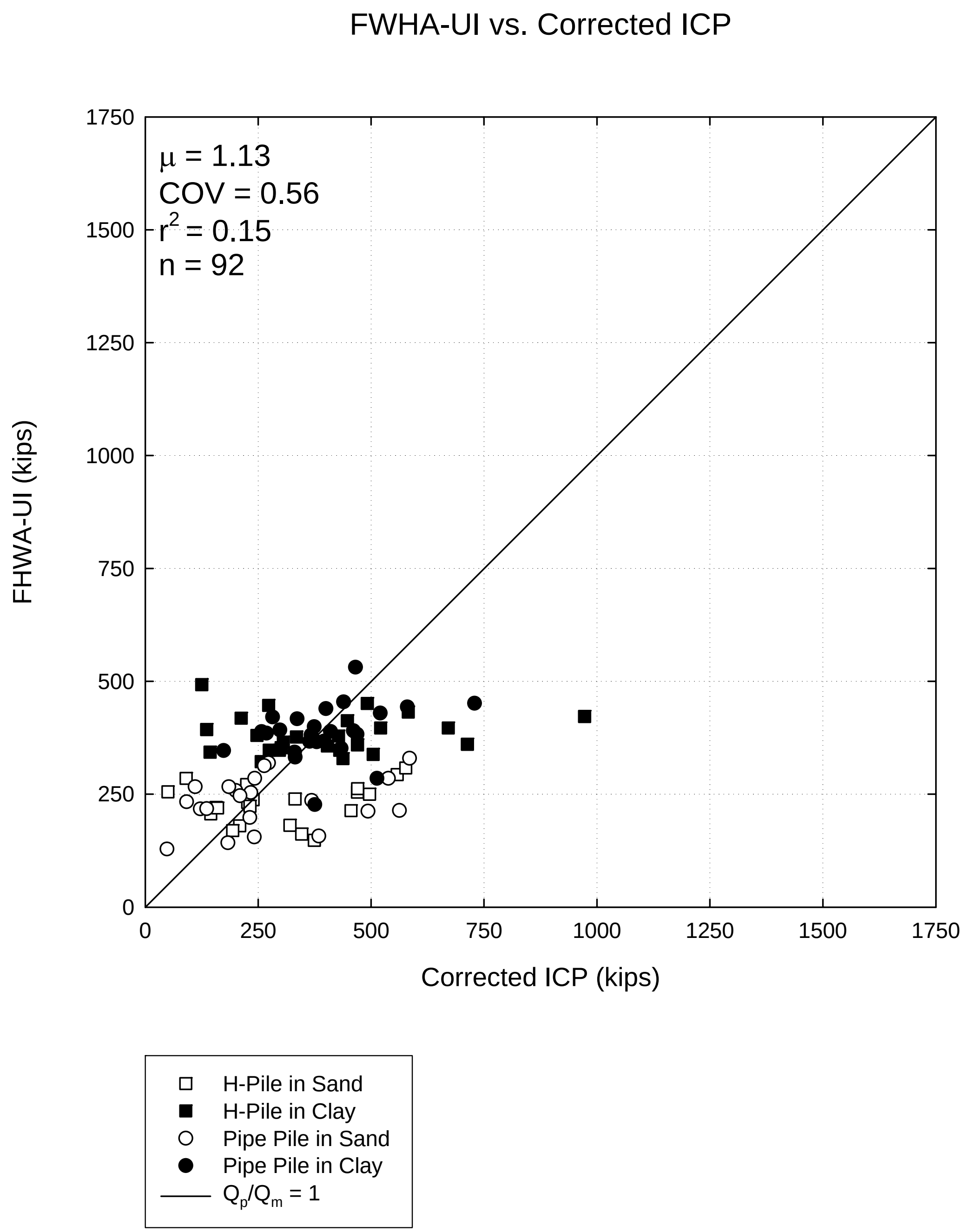

Figure E.7. FWHA-UI vs. Corrected ICP, Illinois Database.

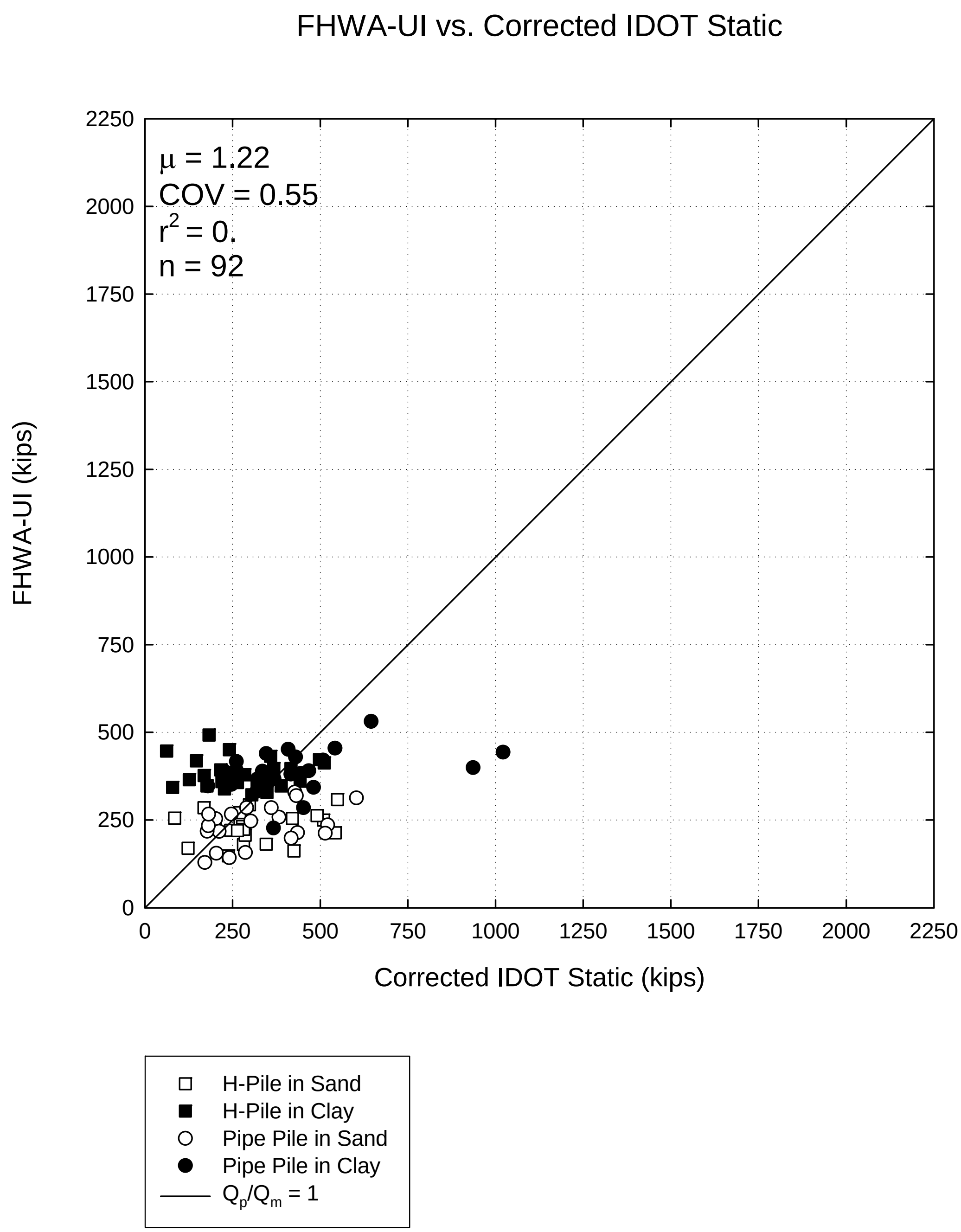

Figure E.8. FHWA-UI vs. Corrected IDOT Static, Illinois Database.

FHWA-UI vs. Corrected K-IDOT

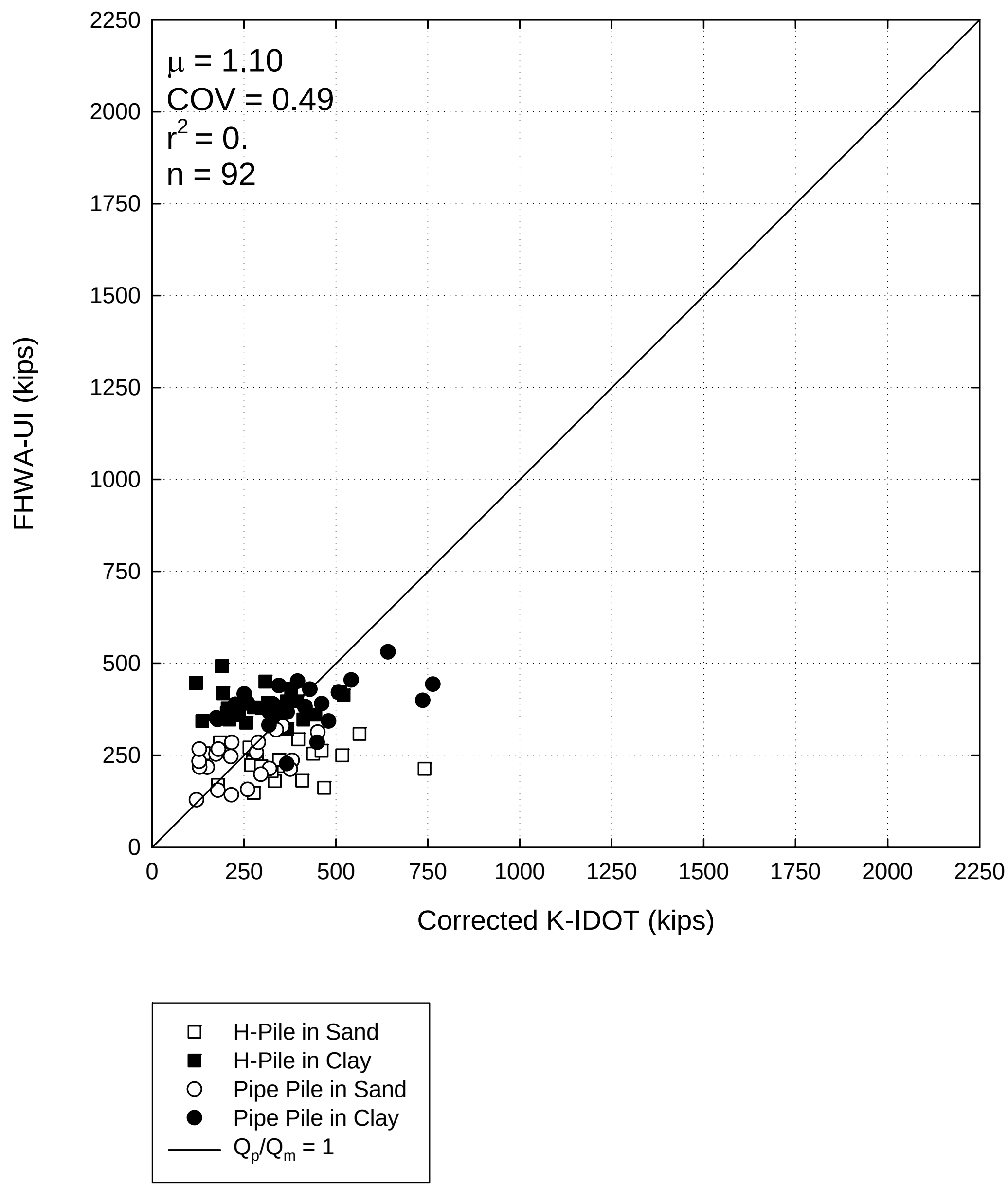

Figure E.9. FHWA-UI vs. Corrected K-IDOT, Illinois Database.

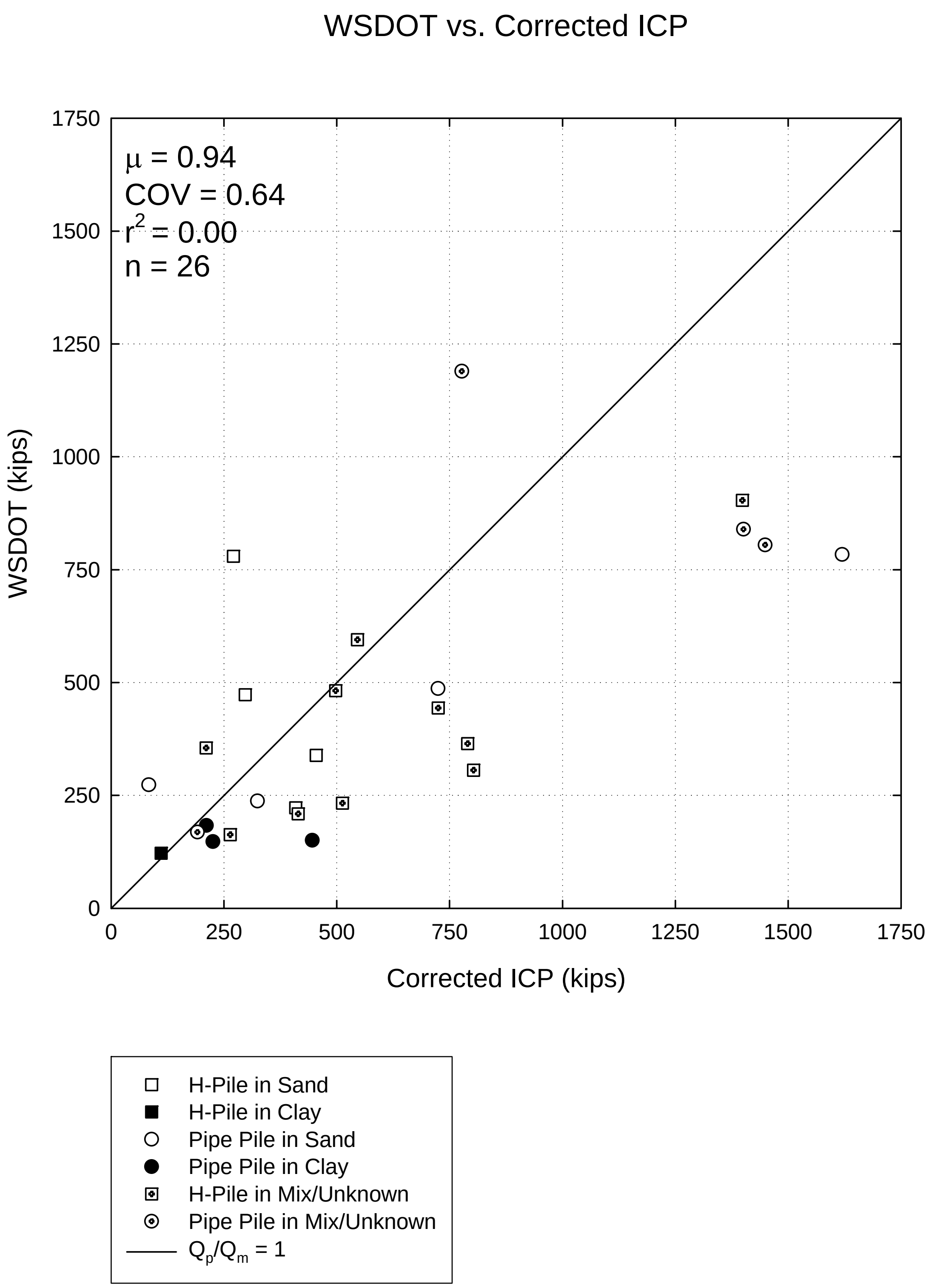

Figure E.10. WSDOT vs. Corrected ICP, Comprehensive Database.

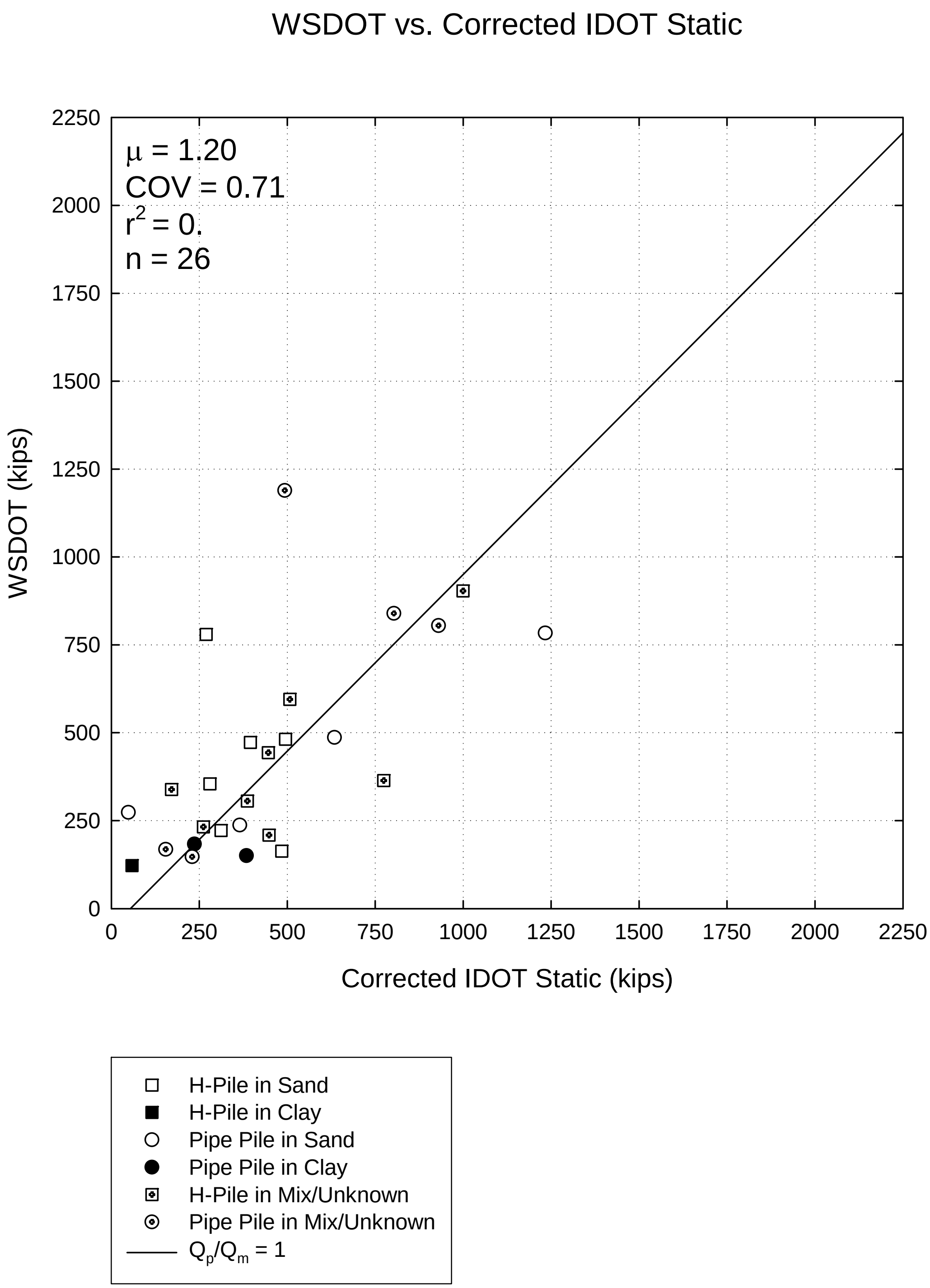

Figure E.11. WSDOT vs. Corrected IDOT Static, Comprehensive Database.

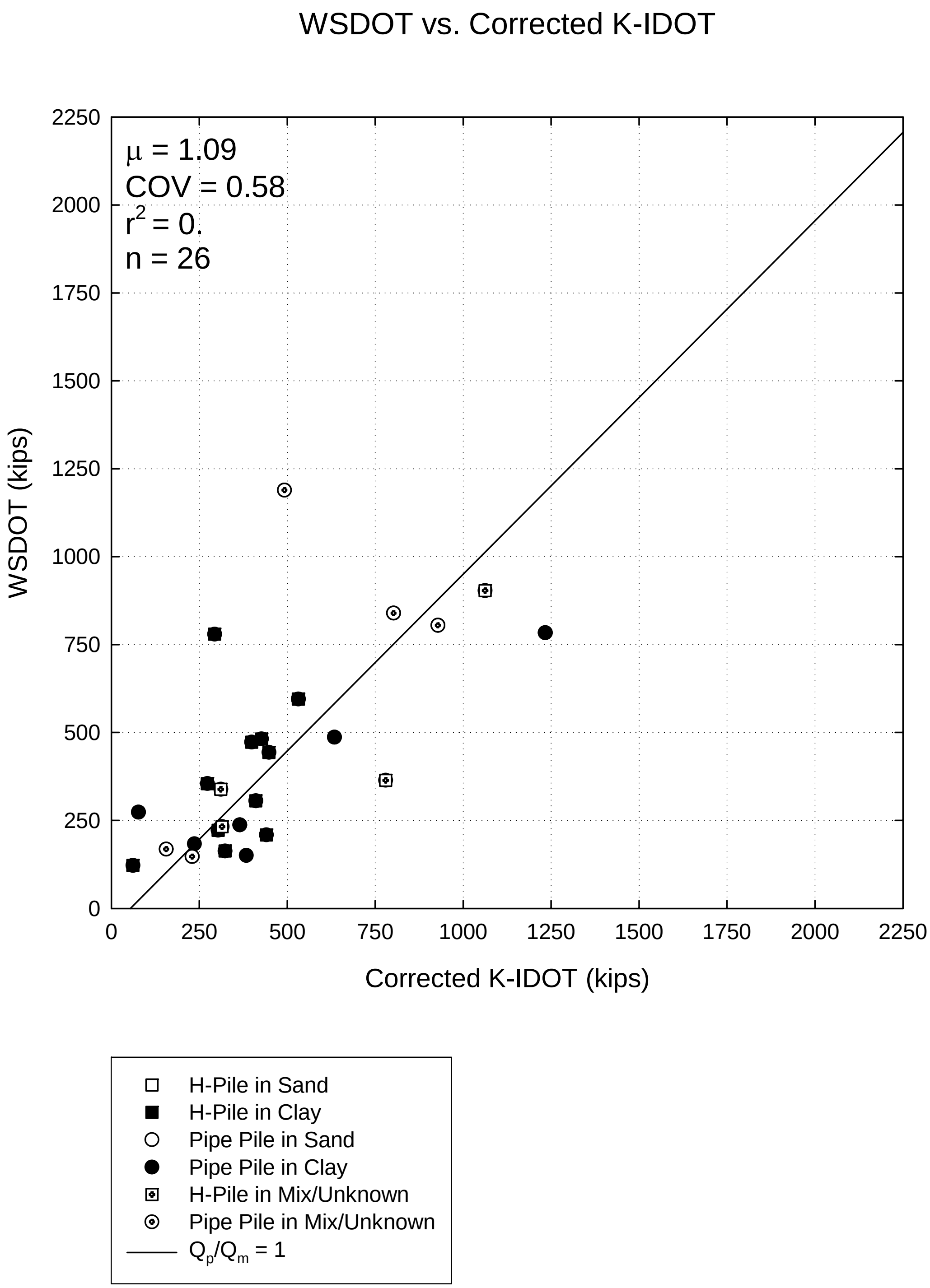

Figure E.12. WSDOT vs. Corrected K-IDOT, Comprehensive Database.

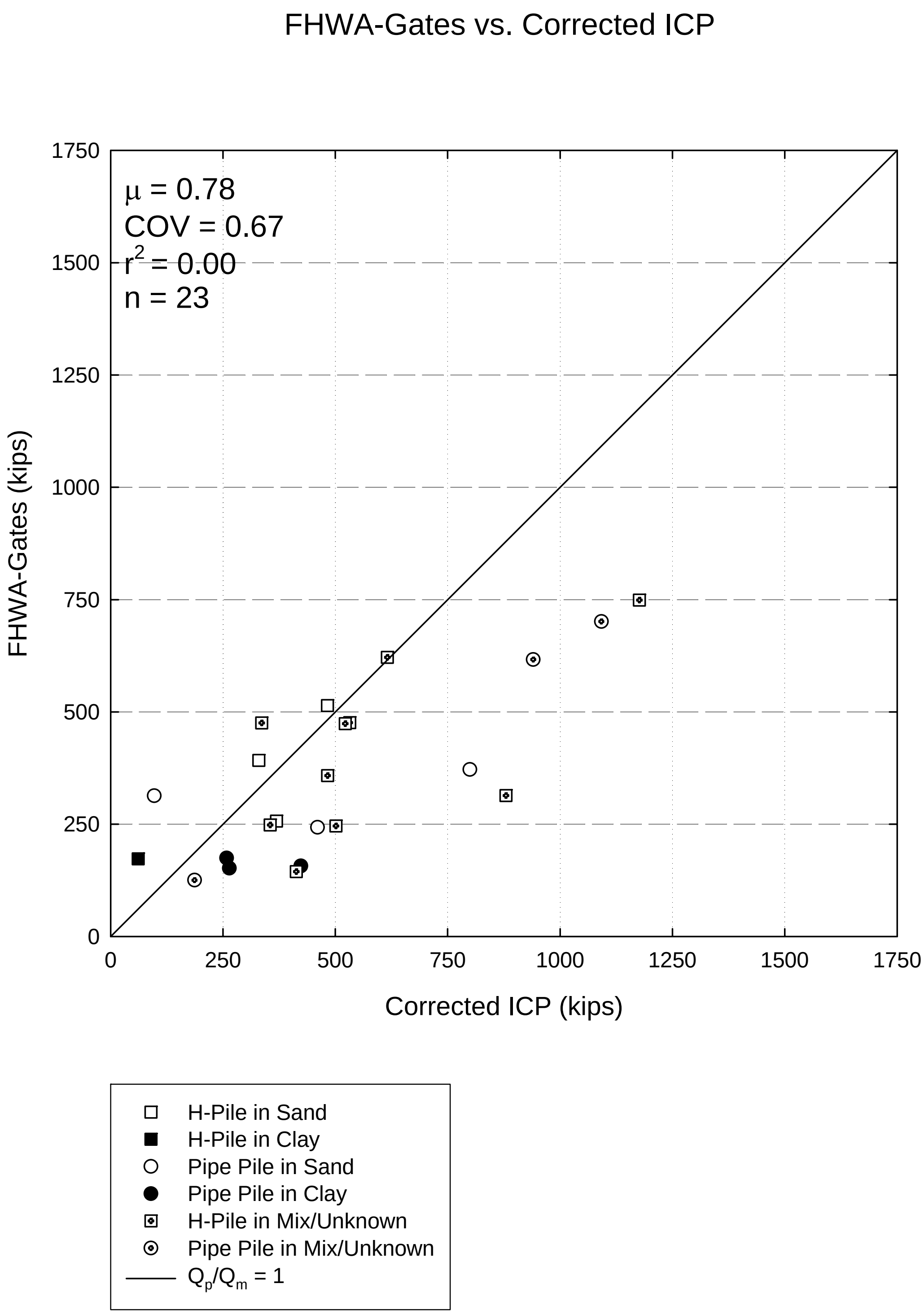

Figure E.13. FHWA-Gates vs. Corrected ICP, Comprehensive Database.

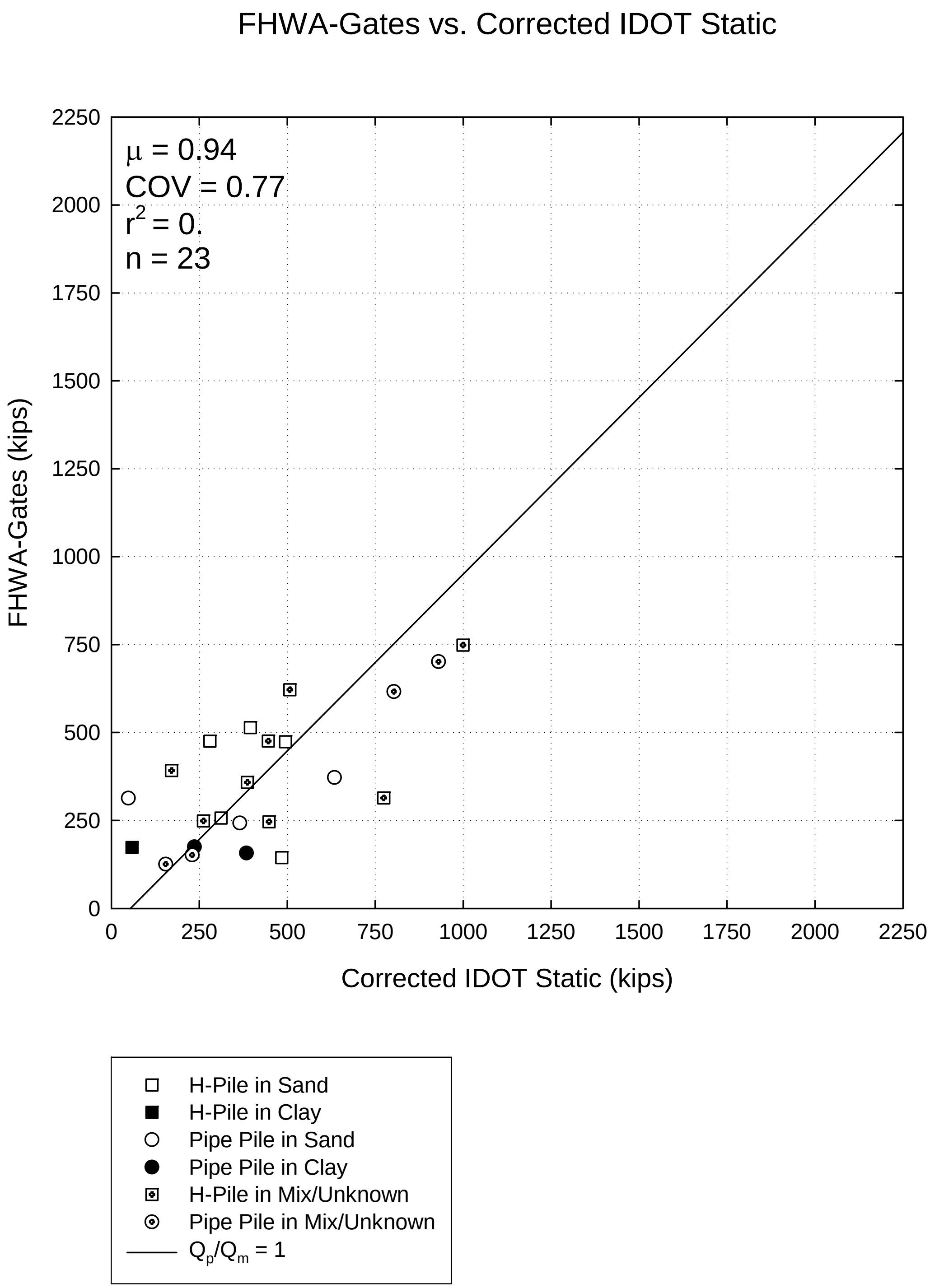

Figure E.14. FHWA-Gates vs. Corrected IDOT Static, Comprehensive Database.

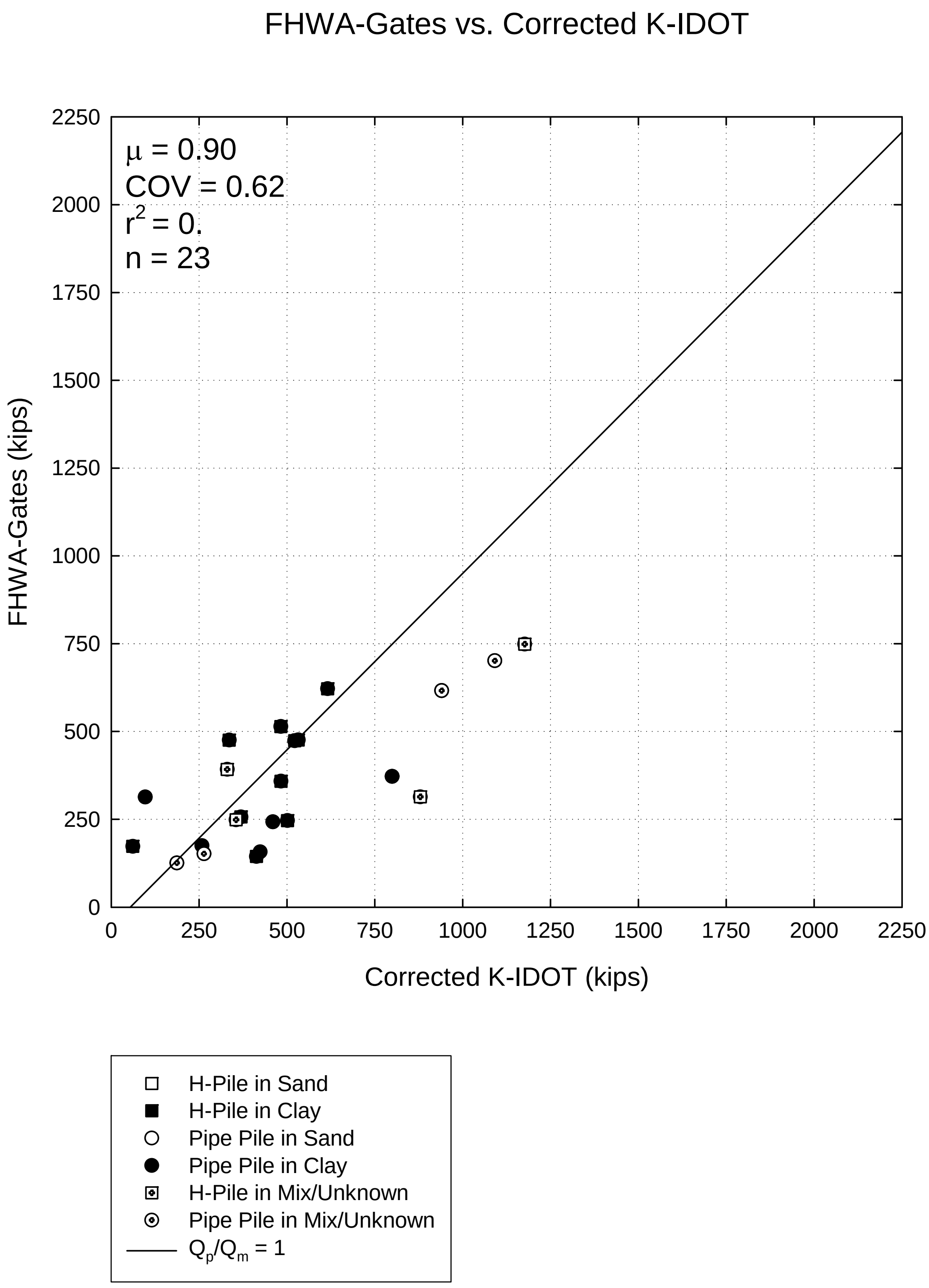

Figure E.15. FHWA-Gates vs. Corrected K-IDOT, Comprehensive Database.

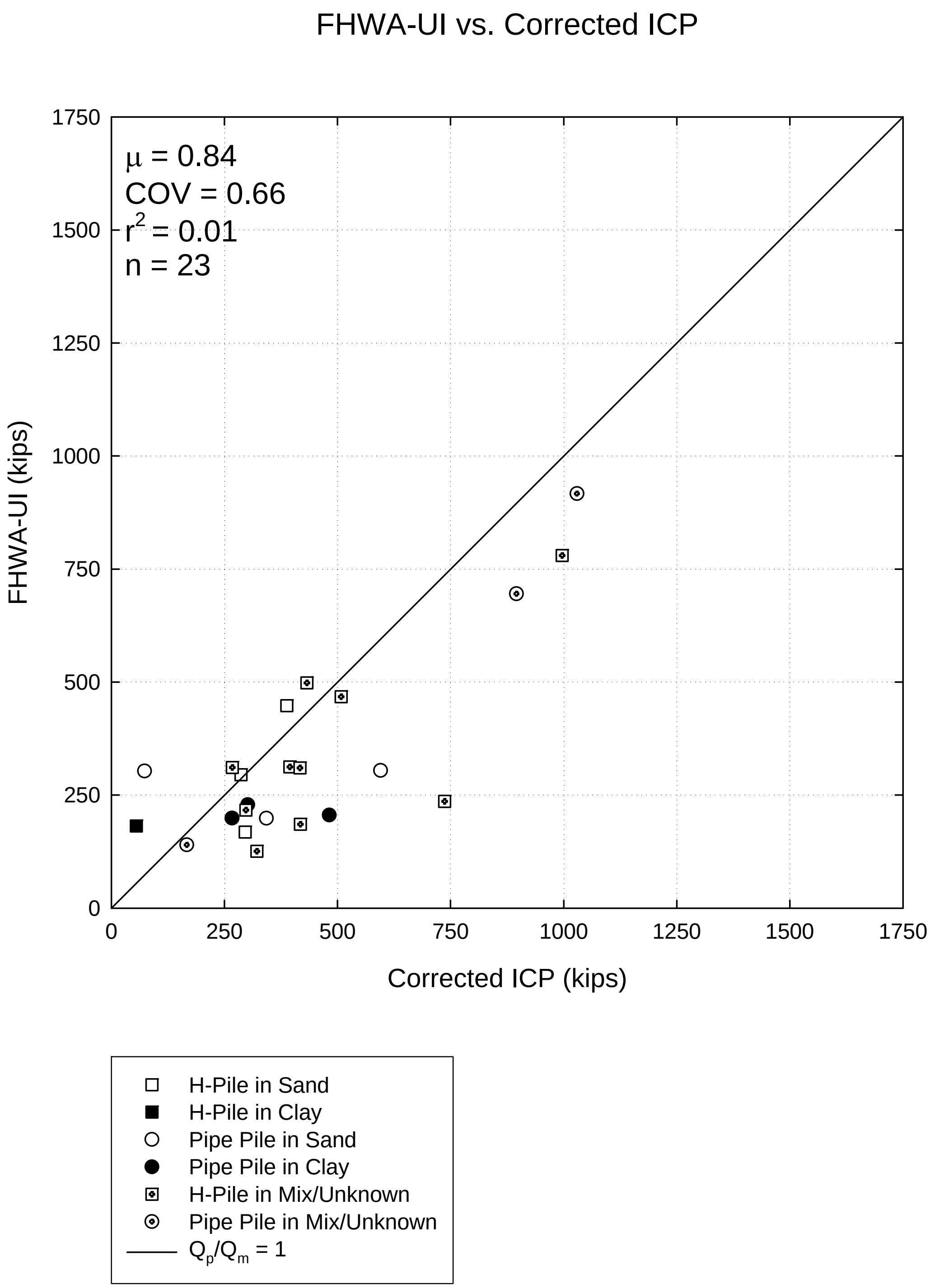

Figure E.16. FWHA-UI vs. Corrected ICP, Comprehensive Database.

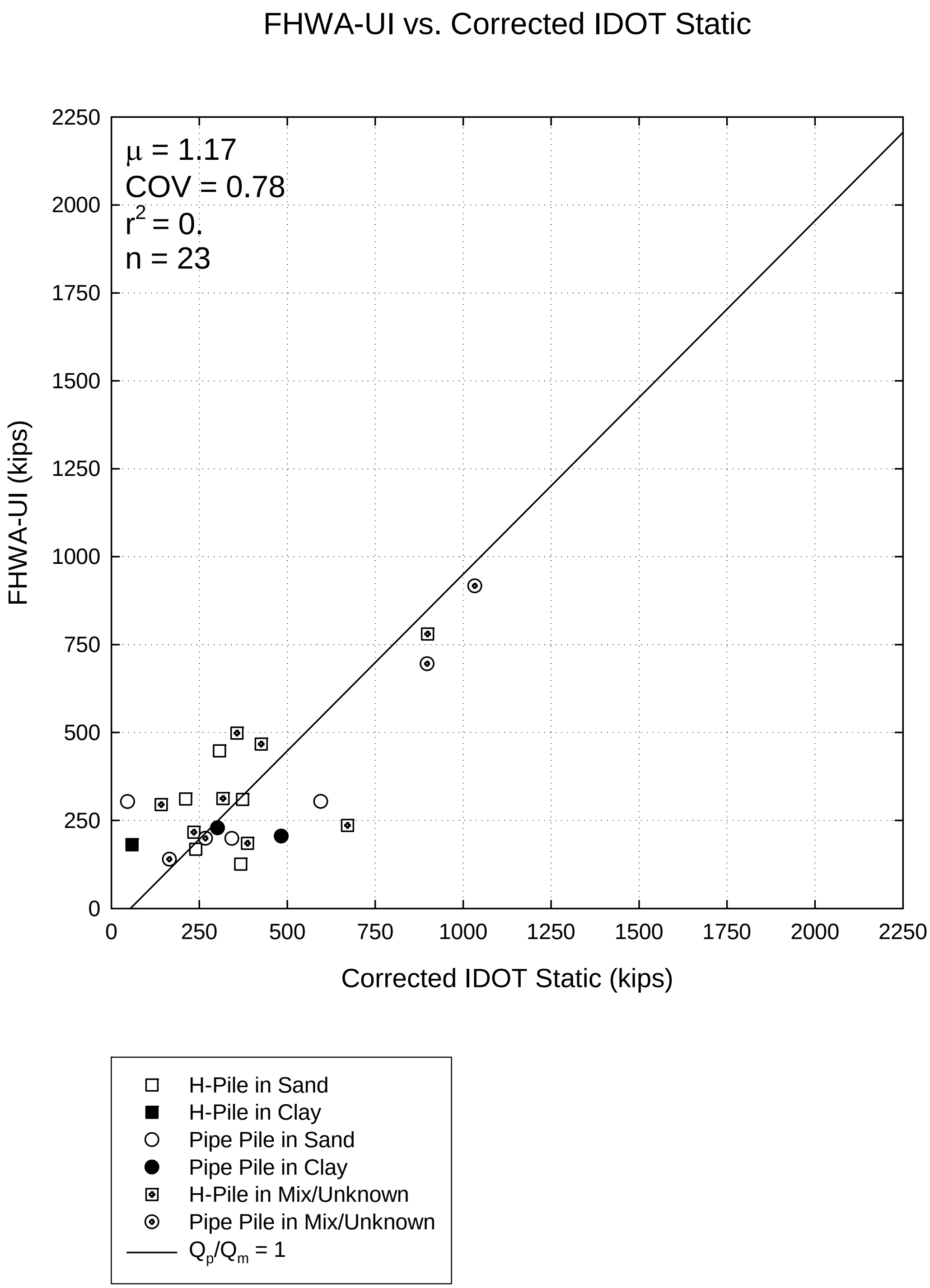

Figure E.17. FHWA-UI vs. Corrected IDOT Static, Comprehensive Database.

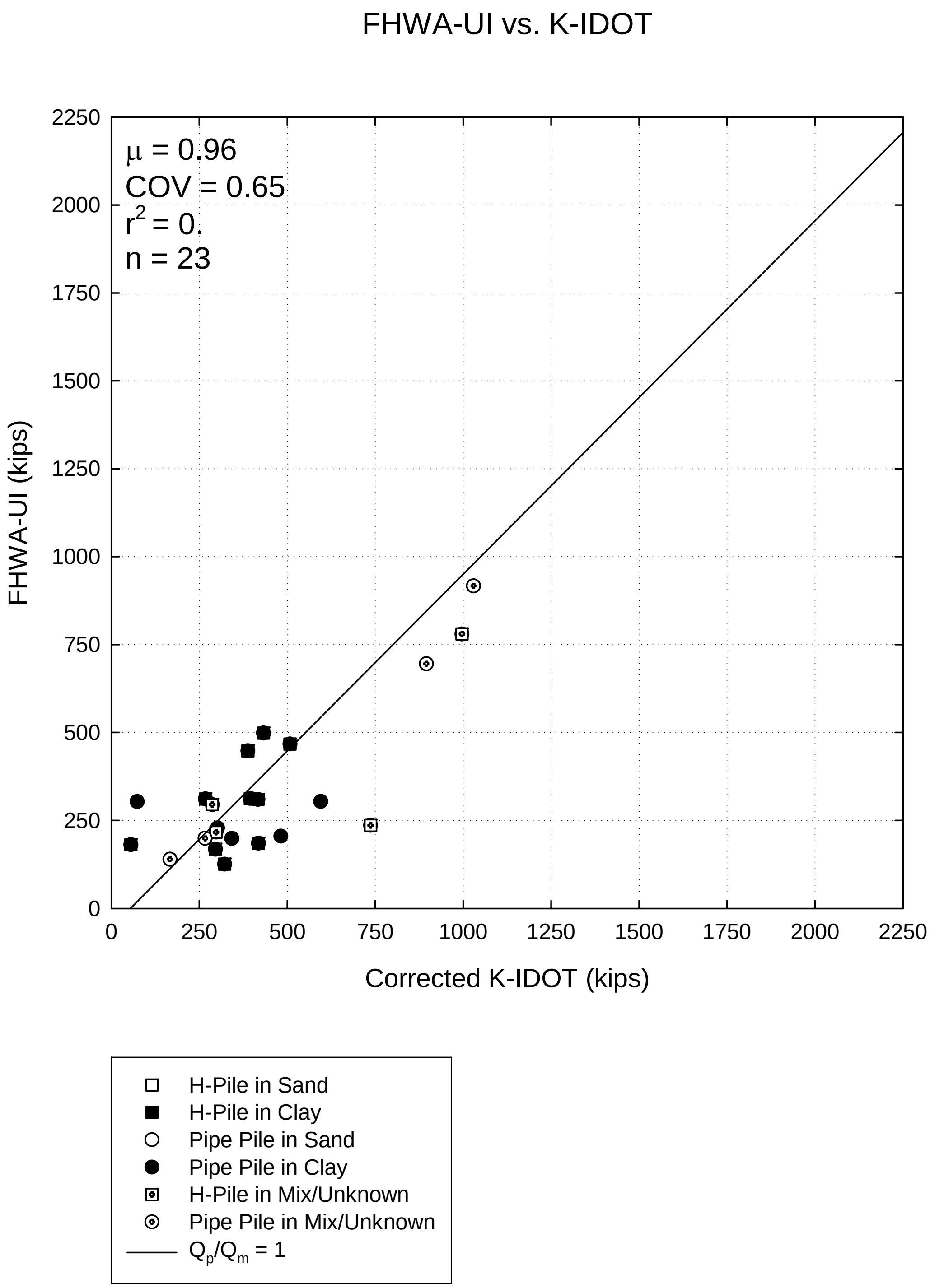

Figure E.18. FHWA-UI vs. Corrected K-IDOT, Comprehensive Database.