Comparison of Five Different Methods for Determining Pile Bearing Capacities

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Final Report

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16. Abstract

The purpose of this study is to assess the accuracy and precision with which five methods can predict axial pile capacity. The methods are the Engineering News formula currently used by Wisconsin DOT, the FHWA-Gates formula, the Pile Driving Analyzer, the Washington State DOT. Further analysis was conducted on the FHWA-Gates method to improve its ability to predict axial capacity. Improvements were made by restricting the application of the formula to piles with axial capacity less than 750 kips, and to apply adjustment factors based on the pile being driven, the hammer being used, and the soil into which the pile is being driven. Two databases of pile driving information and static or dynamic load tests were used evaluate these methods.

Analysis is conducted to compare the impact of changing to a more accurate predictive method, and incorporating LRFD. The results of this study indicate that a "corrected" FHWA-Gates and the WSDOT formulas provide the greatest precision. Using either of these two methods and changing to LRFD should increase the need for foundation (geotechnical) capacity by less than 10 percent.

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Executive Summary

Project Summary

This study was conducted to assess the accuracy and precision with which four methods can predict axial pile capacity. The methods are the Engineering News formula currently used by Wisconsin DOT, the FHWA-Gates formula, the Pile Driving Analyzer, and the method developed by Washington State DOT. Additional analysis was conducted on the FHWA-Gates method to improve its ability to predict axial capacity. Improvements were made by restricting the application of the formula to piles with axial capacity less than 750 kips, and to apply adjustment factors based on the pile being driven, the hammer being used, and the soil into which the pile is being driven. Two databases of pile driving information and static or dynamic load tests were used evaluate these methods.

Analyses were conducted to compare the impact of changing to a more accurate predictive method, and incorporating LRFD. The results of this study indicate that a "corrected" FHWA-Gates and the WSDOT formulas provide the greatest precision. Using either of these two methods and changing to LRFD should increase the need for foundation (geotechnical) capacity by less than 10 percent.

Background

The Wisconsin Department of Transportation (WisDOT) often drives piling in the field based on the dynamic formula known as the Engineering News (EN) Formula. The Federal Highway Administration (FHWA), as well as others, have provided some evidence and encouragement for state DOTs to migrate from the EN formula to a more accurate dynamic formula known as the FHWA-modified Gates formula. The behavior and limitations of the FHWA-modified Gates formula need to be defined more quantitatively to allow WisDOT to assess when use of the Gates method is appropriate. For example, there is evidence that the Gates method may be applicable only over a limited range of pile capacity. Furthermore, there needs to be a clear quantitative comparison of predictions made with FHWA-modified Gates and predictions made with the EN-Wisc, so that WisDOT can better assess the impact that transition will make to the practice and economics of design and construction of driven pile foundations.

The Department of Civil Engineering at the University of Illinois at Urbana/Champaign conducted the project through the Wisconsin Highway Research Program. The research team included James H. Long (Professor and Principal Investigator), Joshua Hendrix (Graduate Student), and David Jaromin (Graduate Student). The technical oversight committee consisted of Mr. Robert Andorfer, Mr. Finn Hubbard, Mr. Steve Maxwell, and was chaired by Mr. Jeffrey Horsfall. All members of the technical oversight committee were members of the Wisconsin Department of Transportation.

Process

This study focused on four methods that use driving resistance to predict capacity: the Engineering News (EN-Wisc) formula, the FHWA-modified Gates formula (FHWA-Gates), the Washington State Department of Transportation formula (WSDOT), the Pile Driving Analyzer (PDA), and developed a fifth method, called the "corrected" FHWA-Gates. Major emphasis was given to load test results in which predicted capacity could be compared with capacity measured from a static load test.

The first collection of load tests compiles results of several smaller load test databases. The databases include those developed by Flaate (1964), Olson and Flaate (1967), Fragaszy et al. (1988), by the FHWA (Rausche et al. 1996), and by Allen (2007) and Paikowsky (NCHRP 507, 2004). A total of 156 load tests were collected for this database. Only steel H-piles, pipe piles, and metal shell piles are collected and used in this database.

The second collection was compiled from data provided by the Wisconsin Department of Transportation. The data comes from several locations within the State. A total of 316 piles were collected from the Marquette Interchange, the Sixth

Street Viaduct, Arrowhead Bridge, Bridgeport, Prescott Bridge, the Clairemont Avenue Bridge, the Fort Atkinson Bypass, the Trempeauleau River Bridge, the Wisconsin River Bridge, the Chippewa River Bridge, La Crosse, and the South Beltline in Madison. Only steel H-piles, pipe piles, and metal shell piles are collected and used in this database.

The ratio of predicted capacity (Q_P) to measured capacity (Q_M) was used as the metric to quantify how well or poorly a predictive method performs. Statistics for each of the predictive methods were used to quantify the accuracy and precision for several pile driving formulas. In addition to assessing the accuracy of existing methods, modifications were imposed on the FHWA-Gates method to improve its predictions. The FHWA-Gates method tended to overpredict at low capacities and underpredict at capacities greater than 750 kips. Additionally, the performance was also investigated for assessing the effect of different pile types, pile hammers, and soil. All these factors were combined to develop a "corrected" FHWA Gates method. The corrected FHWA-Gates applies adjustment factors to the FHWA-Gates method as follows: 1) F_O - an overall correction factor, 2) F_H - a correction factor to account for the hammer used to drive the pile, 3) F_S - a correction factor to account for the soil surrounding the pile, 4) F_P - a correction factor to account for the type of pile being driven. The specific correction factors are given in Table 4.10 in the report.

A summary of the statistics (for Q_P/Q_M) associated with each of the methods is given below:

Mean	COV	Method
0.43	0.47	Wisc-EN
1.11	0.39	WSDOT
1.13	0.42	FHWA-Gates
0.73	0.40	PDA
1.20	0.40	FHWA-Gates for all piles <750 kips
1.02	0.36	"corrected" FHWA-Gates for piles <750 kips

The second database contains records for 316 piles driven only in Wisconsin. Only a few cases contained static load tests but there were several cases in which CAPWAP analyses were conducted on restrikes. The limited number of static load tests and CAPWAP analyses for piles with axial capacities less than 750kips were not enough to develop correction factors for the corrected-FHWA Gates. However, predicted and measured capacities for these cases were in good agreement with the results from the first database.

Findings and Conclusions

The predictive methods listed in order of increasing efficiency are as follows: EN-Wisc, Gates-FHWA, PDA, WSDOT, and "corrected" FHWA-Gates.

The Wisc-EN formula significantly under-predicts capacity (mean = 0.43), and this is expected because it is the only method herein that predicts a safe bearing load (a factor of safety inherent with its use). The other methods predict ultimate bearing capacity. The scatter (COV = 0.47)) associated with the EN-Wisc method is the greatest and therefore, the EN-Wisc method is the least precise of all the methods.

The FHWA-Gates method tends to overpredict axial pile capacity for small loads and underpredict capacity for loads greater than 750 kips. The method results in a mean value of 1.13 and a COV equal to 0.42. The degree of scatter, as indicated by the value of the COV, is greater than the WSDOT method, but significantly less than the EN-Wisc method.

The PDA capacity determined for end-of-driving conditions tends to underpredict axial pile capacity. The ratio of predicted to measured capacity was 0.7 and the method exhibits a COV of 0.40 which is very close to the scatter observed for WSDOT, FHWA-Gates and "corrected" FHWA-Gates.

The WSDOT method exhibited a slight tendency to overpredict capacity and exhibited the greatest precision (lowest COV) for all the method except the corrected FHWA-Gates. The WSDOT method seemed to predict capacity with equal adeptness across the range of capacities and deserves consideration as a simple dynamic formula.

The corrected FHWA-Gates method predicts axial pile capacity with the greatest degree of precision; however, the method is restricted for piles with axial capacity less than 750 kips. The method results in a mean value of 1.02 and a COV equal to 0.36 which is the smallest COV for all the methods investigated.

Resistance factors were determined for each of the methods for reliability index values (β_T) equal to 2.33 and 3.0 (given in Tables 6.1 and 6.2 in the report) for the First Order Second Moment (FOSM) method and for the Factor of Reliability Method (FORM), respectively. Using a target reliability index of 2.33 and FORM result in the following values for resistance factors for the different methods:

Method	Resistance Factor
EN-Wisc	0.9
FHWA-Gates	0.42
PDA	0.64
WSDOT	0.46
Corrected FHWA-Gates	0.54

However, a more detailed investigation was performed on the top three methods (UI-Gates, WSDOT, and FHWA-Gates). The cumulative distribution for the ratio Q_P/Q_M was found to be approximately log-normal, however, a fit to the extremal data resulted in a more accurate representation for portion of the distribution that affects the determination of the resistance factor. Fitting to the extremal data results in greater resistance factors. The results for FORM at a target reliability index of 2.33 results in the following resistance factors

Method	Resistance Factor
FHWA-Gates	0.47
WSDOT	0.55
Corrected FHWA-Gates	0.61

Comparisons were also conducted to show the differences between design based on Factors of Safety (existing Wisconsin DOT approach) and LRFD. The impact of moving from current foundation practice to LRFD will significantly increase the demand for foundation capacity by about fifty percent if the EN-Wisc method continues to be used with LRFD. However, the increase in capacity can be mitigated to a considerable degree by replacing the EN-Wisc method with a more efficient method, such as the “corrected” FHWA-Gates method or the WSDOT method. If the more accurate methods are used, the change in overall demand for foundation capacity should less than 15 percent.

Chapter 1

1.0 INTRODUCTION

The Wisconsin Department of Transportation (WisDOT) often drives piling in the field based on the dynamic formula known as the Engineering News (EN) Formula. The Federal Highway Administration (FHWA) and others have provided some evidence and encouragement for state DOTs to migrate from the EN formula to a more accurate dynamic formula known as the FHWA-modified Gates formula. This report collects pile load test data and uses the information to investigate and quantify the accuracy and precision with which five different methods can predict axial pile capacity due to behavior during pile driving. These predictive methods are the Engineering News formula with modifications used by Wisconsin DOT (EN-Wisc), the FHWA-modified version of the Gates formula (FHWA-Gates), the Pile Driving Analyzer (PDA), the Washington State Department of Transportation (WSDOT) formula. A fifth method was developed as part of this study and is termed the "corrected" FHWA-Gates method. This study provides information which will allow Wisconsin DOT to assess when or if it is appropriate to use each of the methods and to estimate the reliability/safety and economy associated with each method.

Chapter 2 presents the equations, some history, advantages and disadvantages for four predictive methods being investigated: EN-Wisc, FHWA-Gates, PDA, and WSDOT. Chapter 3 discusses the sources and collection efforts for the databases and the selection process for load tests to emphasize cases that are relevant for Wisconsin DOT. Lists of each load test for both databases (the nationwide database with 156 load tests, and the database with 316 piles driven in Wisconsin) are provided in this chapter. Only steel piles were used in these databases. A major difference between the two databases is that 156 static load test results are available for each of the piles in the first database (the nationwide database), whereas only 12 static load tests were available for the Wisconsin database. Chapter 4 uses the first database to evaluate the accuracy and precision with which the four methods can predict pile capacity. The fifth method (corrected FHWA-Gates) is developed and assessed in this chapter using this database. Chapter 5 investigates the statistical agreement between the predictive methods and confirms, with reasonable agreement, the trends observed in the first database. Chapter 6 uses the statistics in previous chapters to determine resistance factors suitable for use in LRFD. In addition, comparisons are made between foundation loads and capacities using current Wisconsin DOT practice with load and capacity demands for LRFD and simple analyses are presented to assess the impact of using LRFD and switching to a more accurate predictive method. Recommendations for appropriate resistance factors are given for each predictive method. Each of the methods are ranked to assist use of the more efficient methods. Chapter 7 provides a summary of the findings and chapter 8 includes the references made in this report.

Chapter 2

2.0 METHODS FOR PREDICTING AXIAL PILE CAPACITY

2.1 INTRODUCTION

Several methods are available for predicting axial pile capacity based upon the resistance of the pile during driving or during retapping. This chapter introduces some selected methods that use the behavior of the pile during driving to determine capacity. This chapter focuses on four methods that use driving resistance to predict capacity: the Engineering News (EN-Wisc) formula, the Gates formula, the Washington State Department of Transportation formula (WSDOT), and the Pile Driving Analyzer (PDA).

The EN-Wisc, Gates, and WSDOT formulae estimate pile capacity based on simple field measurements of driving resistance. These methods are simple dynamic formulae that require hammer energy and pile set (or blow count) to estimate axial pile capacity (the WSDOT method also requires information on the type of pile hammer). The PDA method requires detailed measurements of the temporal variation of pile force and velocity during driving.

2.2 ESTIMATES USING DYNAMIC FORMULAE

The dynamic formula is an energy balance equation. The equation relates energy delivered by the pile hammer to energy absorbed during pile penetration. Dynamic formulae are expressed generally in the form of the following equation:

$$eWH = Rs \qquad (2.1)$$

where e = efficiency of hammer system, W = ram weight, H = ram stroke, R = pile resistance, and s = pile set (permanent pile displacement per blow of hammer). The pile resistance, R, is assumed to be related directly to the ultimate static pile capacity, Q_u.

Dynamic formulae provide a simple means to estimate pile capacity; however, there are several shortcomings associated with their simplified approach (FHWA, 1995):

- dynamic formulae focus only on the kinetic energy of driving, not on the driving system,
- dynamic formulae assume constant soil resistance rather than a velocity dependent resistance, and
- the length and axial stiffness of the pile are ignored.

Although hundreds of dynamic formulae have been proposed, only a few of them are used commonly (Fragaszy, 1989). An extensive study of all dynamic formulae is beyond the scope of this study; however, the EN-Wisc, the FHWA-Gates, and the WSDOT formulae are described herein.

2.2.1 The Engineering News (EN) Formula

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

$$Q_u = \frac{WH}{(s+c)} \tag{2.2}$$

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 pile to the weight of hammer ram.

The EN formula is often used to define an allowable capacity by dividing the ultimate pile capacity (Eqn. 2.2) by factor of safety (FS) equal to 6. The reader should recognize 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. The formula used by Wisconsin DOT is defined herein as EN-Wisc and is defined below:

$$Q_{all} = \frac{2WH}{(s+c)} \tag{2.3}$$

where Q_{all} = the allowable pile load (safe bearing load in kips), W = weight of hammer (kips), H = drop of hammer (ft), s = pile penetration for the last blow (in) and c is a constant equal to 0.2 for air/steam and diesel hammers.

2.2.2 Original Gates Equation

Gates originally developed his pile driving formula in 1957. The empirical equation is as follows:

$$Q_u = \tfrac{6}{7}\sqrt{eE_r}\,\log(10N_b) \tag{2.4}$$

where Q_u = ultimate capacity (kips), E_r = 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), N_b is the number of hammer blows to penetrate the pile one inch. A factor of safety equal to 3 is recommended by Gates (1957) to achieve the allowable bearing capacity. Adjustments to the original Gates equations were proposed by Olson and Flaate (1967), the FHWA, and others (Long, 2001) and are discussed further below.

2.2.3 Modified Gates Equation (Olson and Flaate)

Olson and Flaate (1967) offered a modified version of the original Gates equation. The modifications were based on a statistical fit through the predicted versus measured data. Their modifications are as follows:

$$R_u = 1.11\sqrt{eE_r}\,\log(10N_b) - 34 : \text{for timber piles} \qquad (2.5)$$

$$R_u = 1.39\sqrt{eE_r}\,\log(10N_b) - 54 : \text{for concrete piles} \qquad (2.6)$$

$$R_u = 2.01\sqrt{eE_r}\,\log(10N_b) - 166 : \text{for steel piles} \qquad (2.7)$$

$$R_u = 1.55\sqrt{eE_r}\,\log(10N_b) - 96 : \text{for all piles} \qquad (2.8)$$

As before, units of R_u are in kips, E_r is in units of ft-lbs, and N_b is in blows per inch.

2.2.4 FHWA-Modified Gates Equation (USDOT)

The FHWA pile manual (2006) recommends a modified Gates formula that is herein referred to as FHWA-Gates. Their equation is as follows:

$$R_u = 1.75\sqrt{eE_r}\,\log(10N_b) - 100 \qquad (2.9)$$

A similar equation can be obtained by averaging the equations for steel and concrete piles proposed by Olson and Flaate.

2.2.5 Long (2001) Modification to Original Gates Method

Modifications to the Gates formula made by Olson and Flaate, and by the FHWA have a shortcoming. At low energy levels, the intercept portion of the correction dominates the capacity. Thus it is possible for both the Olson and Flaate and the FHWA to predict a negative pile capacity. Long (2001) proposed a correction to the original Gates equation using a power function which predicts positive pile capacity for all combinations of energy and pile penetration resistance. The equation developed by Long (2001) is as follows:

$$Q_{Gates(\mathrm{mod}ified)} = 0.25 * Q_{Gates(original)}^{1.35} \qquad (2.10)$$

2.2.6 Washington Department of Transportation (WSDOT) method

The original intention of the Department of Transportation in the State of Washington was to improve the Gates Formula; however, significant changes were made to the formula (Allen, 2005, 2007). The formula is referred to herein as the WSDOT method and is given as:

$$R_n = 6.6 F_{eff} W H \ln(10N) \tag{2.11}$$

where R_n = ultimate axial 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 at the end of driving.

The factor, F_{eff} , is a factor that depends on the type of pile hammer used and the pile being driven. A value for F_{eff} equal to 0.55 is suggested for all pile types driven with an air/steam hammer, 0.37 for open-ended diesel hammers for concrete and timber piles, 0.47 for steel piles driven with an open-ended diesel hammer, and 0.35 for all piles driven with a closed-ended diesel hammer.

2.3 ESTIMATES USING PILE DRIVING ANALYZER (PDA)

The PDA method refers to a procedure for determining pile capacity based on the temporal variation of pile head force and velocity. The PDA monitors instrumentation attached to the pile head, and measurements of strain and acceleration are recorded versus time. Strain measurements are converted to pile force, and acceleration measurements are converted to velocities. A simple dynamic model (CASE model) is applied to estimate the pile capacity. The calculations for the CASE model are simple enough for static pile capacity to be estimated during pile driving operations. Several versions of the CASE method exist, and each method will yield a different static capacity. A more detailed presentation of CASE methods are presented by Hannigan (1990).

PDA measurements are used to estimate total pile capacity as:

$$R_{TL} = \frac{F_{T1} + F_{T1+2L/c}}{2} + \left[V_{T1} - V_{T1+2L/c}\right]\frac{Mc}{2L} \qquad (2.12)$$

where R_{TL} = total pile resistance, F_{T1} = measured force at the time T1, $F_{T1+2L/c}$ = measured force at the time T1 plus 2L/c, V_{T1} = measured velocity at the time T1, $V_{T1+2L/c}$ = measured velocity at the time T1 plus 2L/c, L = length of the pile, c = speed of wave propagation in the pile, and M is the pile mass per unit length. The value, 2L/c is the time required for a wave to travel to the pile tip and back. Terms for force and velocity are illustrated in Fig. 2.1.

The total pile resistance, R_{TL}, includes a static and dynamic component of resistance. Therefore, the total pile resistance is:

$$R_{TL} = R_{static} + R_{dynamic} \qquad (2.13)$$

where R_{static} is the static resistance and $R_{dynamic}$ is the dynamic resistance. The dynamic resistance is assumed viscous and therefore is velocity dependent. The dynamic resistance is estimated as:

$$R_{dynamic} = J\frac{Mc}{L}V_{toe} \qquad (2.14)$$

where J is the CASE damping constant and V_{toe} is the velocity at the toe of the pile. The velocity at the toe of the pile can be estimated from PDA measurements of force and velocity as:

$$V_{toe} = V_{T1} + \frac{F_{T1} - R_{TL}}{\frac{Mc}{L}} \qquad (2.15)$$

Substituting Eqns. 2.14 and 2.15 into Eqn. 2.13 and rearranging terms results in the expression for static load capacity of the pile as:

$$R_{static} = R_{TL} - J\left[V_{T1}\frac{Mc}{L} + F_{T1} - R_{TL}\right] \quad (2.16)$$

The calculated value of R_{TL} can vary depending on the selection of T1. T1 can occur at some time after initial impact:

$$T1 = TP + \delta \quad (2.17)$$

where TP = time of impact peak, and δ = time delay. The two most common CASE methods are the RSP method and the RMX method. The RSP method uses the time of impact as T1 (corresponds to $\delta = 0$ in Eqn. 2.17). The RMX method varies δ to obtain the maximum value of R_{static}.

2.4 EFFECT OF TIME ON PILE CAPACITY

The axial capacity of a pile is temporal. The process of pile penetration subjects the soil surrounding the pile to large strains and vibrations changing the soil's properties and state of stress. The soil may respond to the new conditions by changing soil density, by dissipation of excess pore water pressure, and by changing the state of stress in the soil. The time required for the changes to occur may be hours, days, or months, or years, depending on the soil type (Long, 2001). The increase on pile capacity with time is referred to as "setup."

Typically, the axial capacity for a pile is least immediately after the End of Driving (EOD). Reconsolidation of the surrounding soil after driving typically increases the axial capacity of the pile with time. Axial pile capacity may continue to increase with time beyond that required for 100 percent consolidation, but at a smaller rate.

Although less common, pile capacities may also decrease with time (relaxation) for piles driven into dense saturated sands and silts and some shales . Accordingly, pile driving operations in the field may be conducted specifically to determine and quantify setup or relaxation. Normal pile driving operations are conducted to drive the pile to the design length or penetration resistance. The penetration resistance is recorded at the end of driving. The pile is allowed to remain in the ground undisturbed for a specified period of time such as hours, days, or weeks. The pile is then re-driven and the penetration resistance is recorded for the Beginning of Restrike (BOR). Comparing the driving resistance exhibited by the pile for EOD and BOR conditions provides a means to qualify and quantify setup or relaxation occurring at a site.

Dynamic formulae, such as EN-Wisc, Gates, and WSDOT use EOD data for predicting capacity and have been calibrated with static load tests. Accordingly, these dynamic formulae implicitly include time effects (albeit approximately) because static load tests are usually conducted on driven piles several days after driving. Methods that use PDA measurements at EOD may indeed predict pile capacity more accurately, but the estimate is for axial capacity at the EOD and does not account for time effects. A significant improvement for methods that use PDA measurements is to predict axial capacity based on BOR results.

2.5 CAPWAP (CASE Pile Wave Analysis Program)

CAPWAP employs PDA measurements obtained during driving with more realistic modeling capabilities (similar to WEAP) to estimate ultimate capacity. The method uses the acceleration history measured at the top of the pile as a boundary condition for analyses. The result of the analyses is a predicted force versus time response at the top of the pile. Comparison of predicted and measured force response allows the user to determine the accuracy of the wave equation model, and model parameters are modified until the measured and predicted force versus time plots are in close agreement. The method often predicts capacity well; however, like the PDA, the prediction for capacity is at the time of driving. Accordingly, CAPWAP analyses for beginning of restrike (BOR) conditions (rather than EOD) are recommended for estimating ultimate axial capacity.

2.6 SUMMARY AND DISCUSSION

Several methods for predicting axial pile capacity have been presented and discussed. Predictions of pile capacity can be made with simple measurements from visual observation for the EN formula and the Gates formula. However, the PDA method requires special equipment to monitor, record and interpret the pile head accelerations and strains during driving. The simple dynamic formulae are simple to use; however, they do not model the mechanics of pile driving. Furthermore, energy delivered by the pile hammer (an important parameter that affects the prediction of pile capacity) is based on estimates rather than measurements. The PDA method uses pile dynamic monitoring to determine energy delivered to the pile head and displacements of the pile.

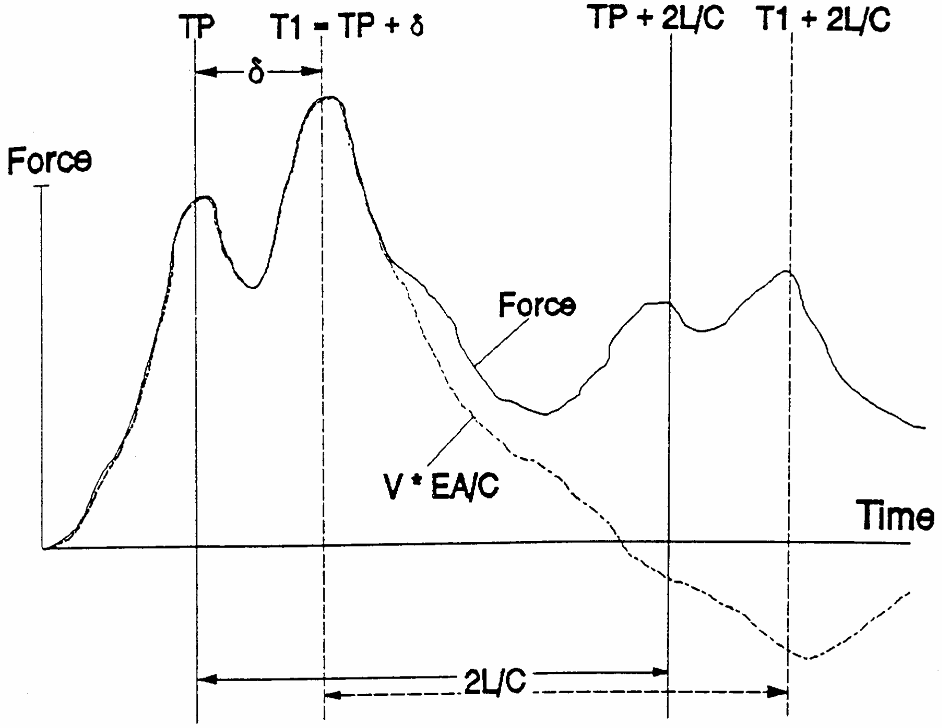


Figure 2.1 Force and velocity traces showing two impact peaks indicative of driving in soils capable of large deformations (after Paikowsky et al. 1994).

Chapter 3

3.0 DATABASES, NATIONWIDE COLLECTION AND WISCONSIN DATA

3.1 INTRODUCTION

Several datasets have been collected to investigate how well methods predict axial capacity of piles. This chapter presents a discussion of the collections that are relevant to this study. Several databases were collected and interpreted that contained information on the driving behavior during driving. These methods include dynamic formulae, methods that model the mechanics of the pile and pile driving system, and methods that require measurements of acceleration and strain at the pile head during driving. This chapter introduces the databases and the data from these collections.

All data given in the tables are for cases relevant to the study herein. Only steel H-piles, pipe piles, and metal shell piles are presented; however, the original datasets included many additional pile types. Furthermore, some of these studies investigated several dynamic formulae, many of which are not relevant to this study. Accordingly, only predictive methods relevant to this study (EN-Wisc, FHWA-Gates, WsDOT, PDA, and CAPWAP) are reported herein.

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 end of driving (EOD). Hiley, Janbu, and Engineering News formulae were selected for evaluation. Flaate reported 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. Measured and predicted pile capacities relevant to this study are given in Table 3.1.

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. 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 effects on the conclusions. An additional column is added in the summary table (Table 3.1) to identify hammer type.

Olson and Flaate compared seven different dynamic pile-driving formulae: Engineering News, Gow, Hiley, Pacific Coast Uniform Building Code, Janbu, Danish and Gates. Janbu was found to be the most accurate of the seven formulae for timber and steel piles. However, it was concluded that no formula was clearly superior. Danish, Janbu, and Gates exhibited the highest average correlation factors; however, since the Gates formula was simpler than the other formulae, Gates was recommended as the most reasonable formula. It is noteworthy that 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 individual pile load tests which were driven into a variety of soil types (Table 3.2). Thirty-eight of these piles had incomplete data, while 2 of them were damaged during driving. The remaining 63 piles were used by Fragaszy et al. The data are believed to be representative of driving resistances at the end of initial driving (EOD). 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 method performed well, and (4) the pile type and soil conditions can influence the accuracy of the formulae.

3.5 DATABASE FROM FHWA

The Federal Highway Administration (FHWA) made available their database on driven piling as developed and described in Rausche et al. (1996). Although the database includes details for 200 piles, only 35 load tests present enough information to be useful for this study.

The database includes several pile types, lengths, soil conditions, and pile driving hammers. Unique features of this database include the predictions based on PDA and CAPWAP as well as the dynamic formulae. Measured capacity, along with predicted capacity using six methods are given in Table 3.3 for the driving resistance at the end of driving (EOD).

3.6 ALLEN (2005) and NCHRP 507

This dataset was expanded by Paikowsky from the FHWA database described earlier. However, the stroke height for variable stroke hammers (diesel) was not reported. Allen(2005) used this database to infer hammer stroke information and to develop a dynamic formula for Washington State DOT. A summary of test results is given in Table 3.4. Of the 141 tests reported, 84 were useful for this study.

3.7 WISCONSIN DOT DATABASE

A database of piles was compiled from data provided by the Wisconsin Department of Transportation (Table 3.5). The data comes from several locations within the State (Fig. 3.1). Results from a total of 316 piles were collected from the Marquette Interchange, the Sixth Street Viaduct, Arrowhead Bridge, Bridgeport, Prescott Bridge, the Clairemont Avenue Bridge, the Fort Atkinson Bypass, the Trempeauleau River Bridge, the Wisconsin River Bridge, the Chippewa River Bridge, La Crosse, and the South Beltline in Madison.

The data encompass several different soil types and are classified as sand, clay, or a mixture of the two. Soil that behaves in a drained manner is categorized as sand. Soil that behaves in an undrained manner is identified as clay. The soil type for each pile is classified according to the soil along the sides of the pile and the soil at the tip of the pile.

3.8 SUMMARY

Loadtest results and background have been presented for several collections of load test databases. The databases include those developed by Flaate (1964), Olson and Flaate (1967), Fragaszy et al. (1988), by the FHWA (Rausche et al. 1996), and by Allen(2007) and NCHRP 507 (Paikowsky, 2004).

Table 3.1 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 3.2 Load test data from Fragaszy et al. (1988)

LTN	Pile Type	Measured Capacity (kips)	Predicted Capacities		
			$Q_{\text{EN-Wisc}}$ (kips)	$Q_{\text{FHWA-Gates}}$ (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 3.3 Load test data from Rausche et al. (1996)

LTN	Pile Type	Meas. Cap. (kips)	Predicted Capacity (kips)					
			$Q_{EN\text{-}Wisc}$	$Q_{FHWA\text{-}Gates}$	Q_{WsDOT}	$Q_{PDA\text{-}EOD}$	$Q_{PDA\text{-}BOR}$	Q_{CAPWAP}
1	CEP	109	18	71	97	61	167	99
2	CEP	114	18	71	97	37	124	70
3	G	158	86	289	222	91	250	250
4	M	240	82	280	194	111	121	239
5	CEP	287	125	374	376	351	413	288
6	H	296	240	554	680	320	441	308
7	H	306	138	397	397	378	469	431.1
8	H	308	151	416	380	311	321	300
9	H	313	132	394	493	222	346	341
10	CEP	347	83	282	218	163	209	205
11	CEP	375	163	436	414			
12	CEP	380	30	121	162			400
13	CEP	380	46	191	214			340
14	M	383	92	304	230	239	213	250
15	CEP	470	255	613	524			528
16	H	474	261	582	722	394	481	472
17	CEP	497	76	270	236			277
18	H	509	138	395	367			
19	H	575	383	724	913	425	468	473
20	H	576	514	962	1062	570	527	543
22	CEP	580	74	269	297	324	506	530
23	CEP	600	50	204	223		450	454
24	CEP	600	316	647	783	500	820	700
25	H	618	91	287	499	118	627	629
26	H	635	286	615	646	430	587	582
27	CEP	656	280	685	578		642	635
28	CEP	657	46	191	214			575
29	CEP	659	387	774	799			518
30	CEP	660	193	485	452			521.4
31	H	757	232	550	780	336	710	652
32	H	770	550	940	1135	579		566
33	CEP	784	164	449	351	366		351
34	H	932	154	423	420			730.6
35	H	1378	641	1088	1324	1411	1236	1221

Table 3.4 Load test data from Allen (2007)

LTN	Pile Type	Meas. Cap. (kips)	Predicted Capacity (kips)			
			$Q_{EN\text{-}Wisc}$	$Q_{FHWA\text{-}Gates}$	Q_{WsDOT}	Q_{CAPWAP}
1. FWA-EOD	CEP 48 "	1300	813	1303	1718	295
2. FWB-EOD	CEP 48 "	1225	771	1200	1592	
3. ST46-EOD	CEP 10 "	104	52	206	153	82
4. CHA1-EOD	CEP 12.75 "	647	388	775	800	390
5. CHA4-EOD	CEP 12.75 "	504	215	517	564	271
6. CHB2-EOD	HP12x63	315	42	176	203	110
7. CHB3-EOD	HP12x63	214	54	215	232	105
8. CHC3-EOD	CEP14 "	237	84	292	289	110
9. CH4-EOD	CEP9.63 "	364	46	190	213	150
10. CH39-EOD	CEP9.63 "	656	46	190	213	187
11. CH6-5B-EOD	CEP9.63 "	372	30	121	162	
12. CH95B-EOD	CEP9.63 "	554	62	237	248	221
13. S1-EOD	OEP 24 "	586	257	575	675	460
14. S2-EOD	HP14x73	318	133	394	494	215
15. DD23-EOD	CEP 12.75	476	76	270	237	153
16. NBTP2-EOD	HP12X74	416	188	478	528	304
17. NBTP3-EOD	HP12X74	448	222	527	572	315
18. NBTP5-EOD	CEP12.75 "	400	188	478	528	320
19. DD29-EOD	CEP 12.75 "	737	164	450	351	351
20. NYSP-EOD	HP10X42	313	141	417	294	132
21. FN1-EOD	HP10x42	300	173	456	497	230
22. FN4-EOD	CEP12.75 "	280	158	433	474	244
23. FIA-EOD	HP14x89	930	167	445	455	367
24. FIB-EOD	CEP 14 "	650	233	542	545	511
25. FO1-EOD	CEP 26 "	557	489	831	1154	496
26. FO3-EOD	HP14x117	820	756	1119	1560	566
27. FM5-EOD	CEP 18 "	420	146	418	564	346
28. FM17-EOD	CEP 18 "	447	158	439	588	424
29. FM23-EOD	CEP 18 "	340	150	425	572	323
30. FC1-EOD	CEP12.75 "	340	173	453	462	270

Table 3.4 (continued) Load test data from Allen (2007)

LTN	Pile Type	Meas. Cap. (kips)	EOD - Predicted Capacity (kips)			
			$Q_{EN\text{-}Wisc}$	$Q_{FHWA\text{-}Gates}$	Q_{WsDOT}	Q_{CAPWAP}
31. FC2-EOD	CEP12.75 "	376	178	461	469	375
32. FV15-EOD	HP14x73	315	79	273	200	194
33. FV10-EOD	HP14x73	313	58	224	171	159
34. CA1-EOD	CEP 9.6 "	533	331	723	679	410
35. T1/A-EOD	OEP 60 "	1984	633	966	1418	1775
36. T2/A-EOD	OEP 48 "	1470	510	849	1247	1252
37. GZB22-EOD	OEP 36 "	1060	729	1049	1596	1109
38. EF62-EOD	CP 9.625 "	477	341	678	791	522
39. 33P1-EOD	HP 12x74	800	278	622	585	439
40. 33P2-EOD	CP 12.75 "	490	375	833	783	290
41. TRD22-EOD	HP 12x74	350	187	540	386	432
42. TRE22-EOD	HP 12x74	570	301	687	617	575
43. TRP5X-EOD	HP 12x53	475	195	571	407	484
44. PX3-EOD	HP14X117	1239	456	884	937	554
45. PX4-EOD	CEP 14 "	767	536	1083	1160	508
46. TSW/D62/2-EOD	HP12X120?	1011	585	917	1469	1091
47. OD1J-EOD	OEP 24 "	1691	296	635	1033	786
48. OD2P-EOD	OEP 24 "	655	177	469	784	350
49. OD2T-EOD	CEP 24 "	745	384	725	1021	817
50. OD3H-EOD	OEP 42 "	1124	177	469	784	324
51. OD4L-EOD	CEP 24 "	959	259	589	963	504
52. OD4P-EOD	CEP 24 "	684	176	464	555	273
53. OD4T-EOD	CEP 24 "	740	131	391	478	301
54. OD4W-EOD	CEP 24 "	903	173	464	677	397
55. FMN2-EOD	HP14x73	740	210	519	707	342
56. FMI1-EOD	CEP 14 "	310	126	375	356	285
57. FMI2-EOD	CEP 14 "	160	72	265	269	184
58. GZA3-EOD	CEP13.38 "	480	291	668	598	365
59. GZA5-EOD	CEP 9.75 "	296	189	480	441	293
60. GZA6-EOD	CEP 9.75 "	326	270	623	560	275

Table 3.4 (continued) Load test data from Allen (2007)

LTN	Pile Type	Meas. Cap. (kips)	Predicted Capacity (kips)			
			$Q_{EN\text{-}Wisc}$	$Q_{FHWA\text{-}Gates}$	Q_{WsDOT}	Q_{CAPWAP}
61. GZBBC-EOD	CEP 10 "	530	291	668	598	413
62. GZBP2-EOD	CEP13.38 "	320	291	668	598	317
63. GZB6-EOD	CEP13.38 "	390	244	573	518	341
64. GZZ5-EOD	CEP 14 "	440	279	602	708	214
65. GZO5-EOD	CEP 14 "	486	279	602	708	205
66. GZCC5-EOD	CEP 14 "	490	321	654	765	492
67. GZL2-EOD	CEP 14 "	660	405	758	879	267
68. GZP14-EOD	CEP 14 "	420	308	638	748	305
69. GZP11-EOD	CEP 14 "	386	317	650	760	239
70. GZP12-EOD	CEP 14 "	560	457	829	959	520
71. GF19-EOD	HP10x42	397	189	519	388	398
72. GF110-EOD	HP12x74	550	218	621	459	457
73. GF222-EOD	HP12x74	570	291	668	598	512
74. GF312-EOD	HP12x74	310	184	505	379	405
75. GF313-EOD	HP10x57	330	189	519	388	446
76. GF412-EOD	HP12x74	272	215	605	448	455
77. GF413-EOD	HP10x57	300	215	605	448	428
78. GF414-EOD	HP10x57	390	341	811	722	524
79. GF415-EOD	HP12x74	500	313	723	645	561
80. TSW/HHK9/ 1-EOD	OEP 60 "	1021	343	679	888	857
81. TSW/HHK9/ 2-EOD	OEP 48 "	1055	329	663	870	947
82. TSW/HHK9/ 2-BOR	HP12X120?	1055	442	787	1012	978
83. D3-BORb	HP12X120?	223	100	322	288	156
84. CHC3-BORL	CEP11.73 "	237	111	351	403	390

Table 3.5 Wisconsin DOT Load test data.

Load Test	Pile Name	Pile Type	Soil Along Side	Soil at Tip	Hammer Type	PDA EOD Capacity (kips)	CAPWAP Capacity (kips)	Wisc ENR (kips)	FHWA Gates (kips)	WsDOT Method (kips)	Load Test Source
1	IPS-01-12	Closed-End Pipe	Mix	Mix	OED	683	896	361	699	928	Pile Test Program Data Report
2	IPS-02-12	Closed-End Pipe	Mix	Fine	OED	626	1776	401	743	946	Pile Test Program Data Report
3	IPS-03-12	Closed-End Pipe	Mix	Coarse	OED	742	773	418	759	1027	Pile Test Program Data Report
4	IPS-03-16F	Closed-End Pipe	Mix	Coarse	OED	948	1648	613	949	1362	Pile Test Program Data Report
5	IPS-04-12	Closed-End Pipe	Fine	Coarse	OED	683	1716	494	847	1079	Pile Test Program Data Report
6	IPS-06-12	Closed-End Pipe	Mix	Fine	OED	715	1195	542	887	1205	Pile Test Program Data Report
7	IPS-12-12	Closed-End Pipe	Fine	Fine	OED	607	1394	289	619	845	Pile Test Program Data Report
8	IPS-14-12	Closed-End Pipe	Mix	Fine	OED	627	1401	261	586	803	Pile Test Program Data Report
9	IPS-15-12	Closed-End Pipe	Mix	Coarse	OED	608	1065	394	736	917	Pile Test Program Data Report
10	IPS-16-12	Closed-End Pipe	Mix	Coarse	OED	710	1270	432	773	1087	Pile Test Program Data Report
11	IPS-20-12	Closed-End Pipe	Fine	Coarse	OED	593	1437	325	659	859	Pile Test Program Data Report
12	IPS-21-12	Closed-End Pipe	Fine	Fine	OED	563	959	439	781	1048	Pile Test Program Data Report
13	IPS-21-16P	Closed-End Pipe	Fine	Fine	OED	830	1859	519	859	1224	Pile Test Program Data Report
14	IPS-24-12	Closed-End Pipe	Mix	Coarse	OED	644	1204	289	619	846	Pile Test Program Data Report
15	IPS-25-12	Closed-End Pipe	Mix	Mix	OED	634	897	295	625	830	Pile Test Program Data Report
16	IPS-26-12	Closed-End Pipe	Fine	Fine	OED	591	1155	511	856	1158	Pile Test Program Data Report
17	IPS-26-16F	Closed-End Pipe	Fine	Fine	OED	564	1327	258	582	793	Pile Test Program Data Report
18	IPS-29-12	Closed-End Pipe	Mix	Coarse	OED	654	1047	479	829	1059	Pile Test Program Data Report
19	IPS-29-16F	Closed-End Pipe	Mix	-	OED	631	1508	576	921	1265	Pile Test Program Data Report
20	IPS-30-12	Closed-End Pipe	Mix	Coarse	OED	761	831	568	916	1233	Pile Test Program Data Report
21	IPS-31-12	Closed-End Pipe	Mix	-	OED	674	986	676	1034	1411	Pile Test Program Data Report
22	IPS-32-12	Closed-End Pipe	Mix	Coarse	OED	733	1008	556	921	1170	Pile Test Program Data Report
23	IPS-32-16F	Closed-End Pipe	Mix	Coarse	OED	1010	1213	639	977	1395	Pile Test Program Data Report
24	IPS-33-12	Closed-End Pipe	Mix	Coarse	OED	681	1154	444	788	1034	Pile Test Program Data Report
25	IPS-34-12	Closed-End Pipe	Mix	Coarse	OED	782	978	612	964	1304	Pile Test Program Data Report
26	IPS-35-12	Closed-End Pipe	Mix	Coarse	OED	655	1318	352	688	886	Pile Test Program Data Report
27	IPS-41-12	Closed-End Pipe	-	-	OED	369	955	156	434	544	Pile Test Program Data Report
28	IPS-42-12	Closed-End Pipe	-	-	OED	420	712	274	598	746	Pile Test Program Data Report
29	IPS-43-12	Closed-End Pipe	Mix	-	OED	629	-	373	713	985	Pile Test Program Data Report
30	IPS-43-12A	Closed-End Pipe	Mix	Fine	OED	680	1203	437	779	1079	Pile Test Program Data Report
31	SLT-B-12-1A	Closed-End Pipe	Mix	Coarse	OED	558	1778	337	671	832	Pile Test Program Data Report
32	SLT-B-12-2	Closed-End Pipe	Mix	Coarse	OED	669	1474	506	855	1118	Pile Test Program Data Report
33	SLT-B-14-3S	Closed-End Pipe	Mix	Coarse	OED	623	1507	287	616	840	Pile Test Program Data Report
34	SLT-B-16F-4	Closed-End Pipe	Mix	Coarse	OED	922	1890	598	936	1329	Pile Test Program Data Report
35	SLT-B-16P-5	Closed-End Pipe	Mix	Coarse	OED	950	1864	679	1019	1450	Pile Test Program Data Report
36	SLT-B-14-6C	Closed-End Pipe	Mix	Coarse	OED	547	1748	230	546	749	Pile Test Program Data Report
37	SLT-B-14-7C	Closed-End Pipe	Mix	Coarse	OED	380	1571	120	370	515	Pile Test Program Data Report
38	SLT-D-16F-1	Closed-End Pipe	Mix	Fine	OED	482	1332	245	566	795	Pile Test Program Data Report
39	SLT-D-14-2	Closed-End Pipe	Mix	Fine	OED	671	1327	502	845	1156	Pile Test Program Data Report
40	SLT-D-12-3S	Closed-End Pipe	Mix	Fine	OED	448	692	270	592	733	Pile Test Program Data Report
41	SLT-D-16P-4	Closed-End Pipe	Mix	Fine	OED	718	1533	453	795	1118	Pile Test Program Data Report
42	SLT-D-14-5	Closed-End Pipe	Mix	Fine	OED	554	1628	369	707	949	Pile Test Program Data Report
43	SLT-D-12-6C	Closed-End Pipe	Mix	Fine	OED	683	964	456	798	1089	Pile Test Program Data Report
44	SLT-E-12-1	Closed-End Pipe	Mix	Coarse	OED	598	1427	315	647	812	Pile Test Program Data Report
45	SLT-E-16P-2	Closed-End Pipe	Mix	Coarse	OED	391	1786	187	484	651	Pile Test Program Data Report
46	SLT-E-14-3S	Closed-End Pipe	Mix	Coarse	OED	668	1467	356	695	941	Pile Test Program Data Report
47	SLT-E-12-4	Closed-End Pipe	Mix	Coarse	OED	584	1034	378	718	904	Pile Test Program Data Report
48	SLT-E-16F-5	Closed-End Pipe	Mix	Coarse	OED	506	1299	249	570	766	Pile Test Program Data Report
49	SLT-E-14-6C	Closed-End Pipe	Mix	Coarse	OED	464	1364	152	429	581	Pile Test Program Data Report
50	SLT-A-12-3S	Closed-End Pipe	Fine	Fine	Hydraulic	497	500				Pile Test Program Data Report
51	SLT-C-14-3S	Closed-End Pipe	Mix	Coarse	Hydraulic	514	840				Pile Test Program Data Report
52	SLT-F-12-3S	Closed-End Pipe	Fine	Coarse	Hydraulic	501	794				Pile Test Program Data Report
53	S-11 #7	Closed End Pipe	Mix	Mix	OED	578	908	589	929	1310	Structure B-40-285 SB - GRL Final Report
54	S-12 #4	Closed End Pipe	Mix	Mix	OED	678	835	311	654	1085	Structure B-40-285 SB - GRL Final Report

Table 3.5 (continued) Wisconsin DOT Load test data.

Load Test	Pile Name	Pile Type	Soil Along Side	Soil at Tip	Hammer Type	PDA EOD Capacity (kips)	CAPWAP Capacity (kips)	Wisc ENR (kips)	FHWA Gates (kips)	WsDOT Method (kips)	Load Test Source
55	S-13 #4	Closed End Pipe	Mix	Fine	OED	663	797	532	870	1292	Structure B-40-285 SB - GRL Final Report
56	S-14 #4	Closed End Pipe	Fine	Fine	OED	567	1064	490	830	1209	Structure B-40-285 SB - GRL Final Report
57	S-15 #1	Closed End Pipe	Mix	-	OED	580	923	410	753	1114	Structure B-40-285 SB - GRL Final Report
58	S-15 #10	Closed End Pipe	Mix	-	OED	574	920	422	765	1147	Structure B-40-285 SB - GRL Final Report
59	S-16 #1	Closed End Pipe	Mix	Fine	OED	675	1091	672	995	1532	Structure B-40-285 SB - GRL Final Report
60	S-16 #12	Closed End Pipe	Mix	Fine	OED	696	1061	784	1100	1680	Structure B-40-285 SB - GRL Final Report
61	S-17 #3	Closed End Pipe	Mix	-	OED	601	867	680	1007	1502	Structure B-40-285 SB - GRL Final Report
62	S-18 #12	Closed End Pipe	Mix	-	OED	747	1174	846	1124	2022	Structure B-40-285 SB - GRL Final Report
63	S-18 #24	Closed End Pipe	Mix	-	OED	877	1292	1256	1424	2671	Structure B-40-285 SB - GRL Final Report
64	S-19 #3	Closed End Pipe	Coarse	Coarse	OED	450	762	238	557	773	Structure B-40-285 SB - GRL Final Report
65	S-20 #13	Closed End Pipe	Mix	Coarse	OED	472	768	218	531	761	Structure B-40-285 SB - GRL Final Report
66	ES-1 #7	Closed-End Pipe	Mix	Coarse	OED	179	993	151	417	756	B-40-1423 - GRL Revised Final Report
67	ES-2 #5	Closed-End Pipe	Fine	Fine	OED	681	1064	418	770	1358	B-40-1423 - GRL Revised Final Report
68	ES-2 #9	Closed-End Pipe	Fine	Fine	OED	442	1144	340	685	1104	B-40-1423 - GRL Revised Final Report
69	ES-3 #1	Closed-End Pipe	Mix	Coarse	OED	481	856	342	683	1002	B-40-1423 - GRL Revised Final Report
70	ES-3 #14	Closed-End Pipe	Mix	Coarse	OED	451	853	275	607	895	B-40-1423 - GRL Revised Final Report
71	TP-15	Closed-End Pipe	Coarse	Coarse	OED	367	700	460	861	945	Sixth Street Viaduct Rep Pile Test
72	TP-16	Closed-End Pipe	Coarse	Coarse	OED	379	762	465	862	957	Sixth Street Viaduct Rep Pile Test
73	TP-17	Closed-End Pipe	Coarse	Coarse	OED	355	826	343	683	774	Sixth Street Viaduct Rep Pile Test
74	TP-18	Closed-End Pipe	Coarse	Coarse	OED	324	677	176	464	542	Sixth Street Viaduct Rep Pile Test
75	TP-19	Closed-End Pipe	Coarse	Coarse	OED	262	773	179	466	524	Sixth Street Viaduct Rep Pile Test
76	N11 Pile #5	Closed End Pipe	Mix	Fine	OED	708	903	352	696	1080	B-40-285 NB - GRL Final Report
77	N12 Pile #5	Closed End Pipe	Fine	Coarse	OED	706	778	395	739	1113	B-40-285 NB - GRL Final Report
78	N13 Pile #4	Closed End Pipe	Fine	Fine	OED	653	876	532	870	1292	B-40-285 NB - GRL Final Report
79	N14 Pile #1	Closed End Pipe	Mix	-	OED	716	778	750	1074	1608	B-40-285 NB - GRL Final Report
80	N14 Pile #10	Closed End Pipe	Mix	-	OED	691	987	756	1073	1642	B-40-285 NB - GRL Final Report
81	N15 Pile #13	Closed End Pipe	Mix	Mix	OED	563	707	502	842	1218	B-40-285 NB - GRL Final Report
82	N16 Pile #1	Closed End Pipe	Mix	-	OED	560	887	717	1047	1535	B-40-285 NB - GRL Final Report
83	N16 Pile #15	Closed End Pipe	Mix	-	OED	406	859	669	1009	1434	B-40-285 NB - GRL Final Report
84	N17 Pile #5	Closed End Pipe	Mix	-	OED	571	794	659	979	1628	B-40-285 NB - GRL Final Report
85	N18 Pile #6	Closed End Pipe	Mix	-	OED	462	712	608	959	1298	B-40-285 NB - GRL Final Report
86	N19 Pile #13	Closed End Pipe	Fine	Fine	OED	535	703	513	853	1226	B-40-285 NB - GRL Final Report
87	N20 Pile #2	Closed End Pipe	Mix	Fine	OED	553	769	408	750	1076	B-40-285 NB - GRL Final Report
88	N21 Pile #1	Closed End Pipe	Mix	-	OED	492	714	502	842	1218	B-40-285 NB - GRL Final Report
89	N21 Pile #8	Closed End Pipe	Mix	-	OED	465	771	723	1053	1550	B-40-285 NB - GRL Final Report
90	SE/SP1 #7	Closed-End Pipe	Mix	-	OED	478	758	561	896	1480	Structure B-40-1121 - GRL Final Report
91	SE/SP2 #12	Closed-End Pipe	Mix	-	OED	419	659	408	750	1076	Structure B-40-1121 - GRL Final Report
92	SE/SP3 #17	Closed-End Pipe	Mix	Coarse	OED	458	682	210	520	734	Structure B-40-1121 - GRL Final Report
93	SE/SP4 #7	Closed-End Pipe	Mix	Fine	OED	625	632	499	839	1233	Structure B-40-1121 - GRL Final Report
94	SE/SP4 #15	Closed-End Pipe	Mix	Mix	OED	511	795	539	877	1288	Structure B-40-1121 - GRL Final Report
95	SE/SP5 #7	Closed-End Pipe	Mix	Coarse	OED	621	753	460	802	1184	Structure B-40-1121 - GRL Final Report
96	SE/SP5 #15	Closed-End Pipe	Mix	Coarse	OED	560	739	410	753	1114	Structure B-40-1121 - GRL Final Report
97	Bridge Port, Pier 5, Pile8	CIP	sand	sand	OED	310		127	379	406	Bridgeport
98	Bridge Port, Pier 5, Pile11	CIP	sand	sand	OED	305		107	341	374	Bridgeport
99	Bridge Port, Pier 5, Pile20	CIP	sand	sand	OED	310		127	379	406	Bridgeport
100	Bridge Port, Pier 5, Pile23	CIP	sand	sand	OED	290		138	397	422	Bridgeport
101	Bridge Port, Pier 6, Pile8	CIP	sand	sand	OED	310		110	348	380	Bridgeport
102	Bridge Port, Pier 6, Pile11	CIP	sand	sand	OED	310		93	314	351	Bridgeport
103	Bridge Port, Pier 6, Pile20	CIP	sand	sand	OED	300		112	352	383	Bridgeport
104	Bridge Port, Pier 6, Pile23	CIP	sand	sand	OED	305		97	322	358	Bridgeport
105	Bridge Port, Pier 7, Pile8	CIP	sand	sand	OED	300		114	355	386	Bridgeport
106	Bridge Port, Pier 7, Pile11	CIP	sand	sand	OED	310		123	371	399	Bridgeport
107	Bridge Port, Pier 7, Pile20	CIP	sand	sand	OED	310		112	352	383	Bridgeport
108	Bridge Port, Pier 7 Pile23	CIP	sand	sand	OED	310		118	363	392	Bridgeport

Table 3.5 (continued) Wisconsin DOT Load test data.

Load Test	Pile Name	Pile Type	Soil Along Side	Soil at Tip	Hammer Type	PDA EOD Capacity (kips)	CAPWAP Capacity (kips)	Wisc ENR (kips)	FHWA Gates (kips)	WsDOT Method (kips)	Load Test Source
109	Bridge Port, Pier 8, Pile8	CIP	sand	sand	OED	310		110	349	393	Bridgeport
110	Bridge Port, Pier 8, Pile11	CIP	sand	sand	OED	330		118	363	405	Bridgeport
111	Bridge Port, Pier 8, Pile20	CIP	sand	sand	OED	300		98	324	372	Bridgeport
112	Bridge Port, Pier 8, Pile23	CIP	sand	sand	OED	300		118	363	405	Bridgeport
113	Bridge Port, Pier 9, Pile8	CIP	sand	sand	OED	300		119	363	365	Bridgeport
114	Bridge Port, Pier 9, Pile11	CIP	sand	sand	OED	310		174	458	503	Bridgeport
115	Bridge Port, Pier 9, Pile20	CIP	sand	sand	OED	310		125	372	373	Bridgeport
116	Bridge Port, Pier 9, Pile23	CIP	sand	sand	OED	310					Bridgeport
117	Bridge Port, Pier 10, Pile8	CIP	sand	sand	OED	345		126	378	419	Bridgeport
118	Bridge Port, Pier 10, Pile11	CIP	sand	sand	OED	300		120	367	408	Bridgeport
119	Bridge Port, Pier 10, Pile20	CIP	sand	sand	OED	315		128	382	422	Bridgeport
120	Bridge Port, Pier 10, Pile23	CIP	sand	sand	OED	318		107	343	387	Bridgeport
121	Bridge Port, Pier 11, Pile8	CIP	sand	sand	OED	310		129	385	437	Bridgeport
122	Bridge Port, Pier 11, Pile11	CIP	sand	sand	OED	300		130	386	432	Bridgeport
123	Bridge Port, Pier 11, Pile20	CIP	sand	sand	OED	300		123	374	421	Bridgeport
124	Bridge Port, Pier 11, Pile23	CIP	sand	sand	OED	300		137	398	443	Bridgeport
125	Bridge Port, Pier 12, Pile9	CIP	sand	sand	OED	320		101	331	383	Bridgeport
126	Bridge Port, Pier 12, Pile11	CIP	sand	sand	OED	320					Bridgeport
127	Bridge Port, Pier 12, Pile20	CIP	sand	sand	OED	310		114	356	399	Bridgeport
128	Bridge Port, Pier 12, Pile23	CIP	sand	sand	OED	300					Bridgeport
129	Bridge Port, South Abutment, Pile2	CIP	sand	sand	OED	300		122	370	412	Bridgeport
130	Bridge Port, South Abutment, Pile6	CIP	sand	sand	OED	320		131	386	426	Bridgeport
131	Bridge Port, South Abutment, Pile10	CIP	sand	sand	OED	315		131	386	426	Bridgeport
132	Arrowhead Bridge - Site 1	H-Pile	mixed	sand/stiff clay	air/steam	760		446	933	979	Arrowhead Bridge
133	Arrowhead Bridge - Site 1	C.I.P.	mixed	sand/stiff clay	air/steam	360		409	923	916	Arrowhead Bridge
134	Arrowhead Bridge - Site 3	H-Pile	mixed	sand/stiff clay	air/steam	660		228	535	582	Arrowhead Bridge
135	Arrowhead Bridge - Site 4	H-Pile	mixed	dense sand	air/steam	550		451	1123	1121	Arrowhead Bridge
136	Arrowhead Bridge - Site 4	C.I.P.	mixed	dense sand	air/steam	460		343	712	744	Arrowhead Bridge
137	Prescott Bridge	CIP 13.375x0.375	loose sand	loose sand/gravel	OED	300		82	289	349	Arrowhead Bridge
138	Pile 12 - South Abutment - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	254		103	332	231	Arrowhead Bridge
139	Pile 17 - South Abutment - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	255		123	386	260	Prescott Bridge
140	Pile 20 - South Abutment - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	270		128	402	269	Clairemont Avenue Bridge
141	Pile 19 - Pier 1 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	256		114	360	246	Clairemont Avenue Bridge
142	Pile 5 - Pier 1 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	262		110	350	241	Clairemont Avenue Bridge
143	Pile 23 - Pier 1 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	256		121	374	260	Clairemont Avenue Bridge
144	Pile 29 - Pier 2 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	255		139	395	341	Clairemont Avenue Bridge
145	Pile 1 - Pier 2 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	260		111	344	301	Clairemont Avenue Bridge
146	Pile 22 - Pier 2 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	264		115	352	331	Clairemont Avenue Bridge
147	Pile 35 - Pier 3 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	268		124	370	339	Clairemont Avenue Bridge
148	Pile 1 - Pier 3 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	258		117	356	309	Clairemont Avenue Bridge
149	Pile 29 - Pier 3 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	268		121	362	313	Clairemont Avenue Bridge
150	Pile 4 - Pier 4 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	283		129	379	345	Clairemont Avenue Bridge
151	Pile 29 - Pier 4 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	282		133	385	350	Clairemont Avenue Bridge
152	Pile 19 - Pier 4 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	300		141	399	360	Clairemont Avenue Bridge
153	Pile 34 - Pier 5 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	283		125	370	329	Clairemont Avenue Bridge
154	Pile 16 - Pier 5 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	285		109	339	307	Clairemont Avenue Bridge
155	Pile 14 - Pier 5 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	268		117	355	319	Clairemont Avenue Bridge
156	Pile 33 - Pier 6 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	260		108	346	239	Clairemont Avenue Bridge
157	Pile 15 - Pier 6 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	253		106	338	235	Clairemont Avenue Bridge
158	Pile 7 - Pier 6 - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	263		110	350	241	Clairemont Avenue Bridge
159	Pile 19 - North Abutment - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	258		119	358	321	Clairemont Avenue Bridge
160	Pile 15 - North Abutment - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	260		119	359	311	Clairemont Avenue Bridge
161	Pile 12 - North Abutment - Clairemont Ave Bridge	CIP 10.75X0.25	sand	sand	OED	262		120	361	332	Clairemont Avenue Bridge
162	Pile 12, South Abutment, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	178		169	452	538	Clairemont Avenue Bridge

Table 3.5 (continued) Wisconsin DOT Load test data.

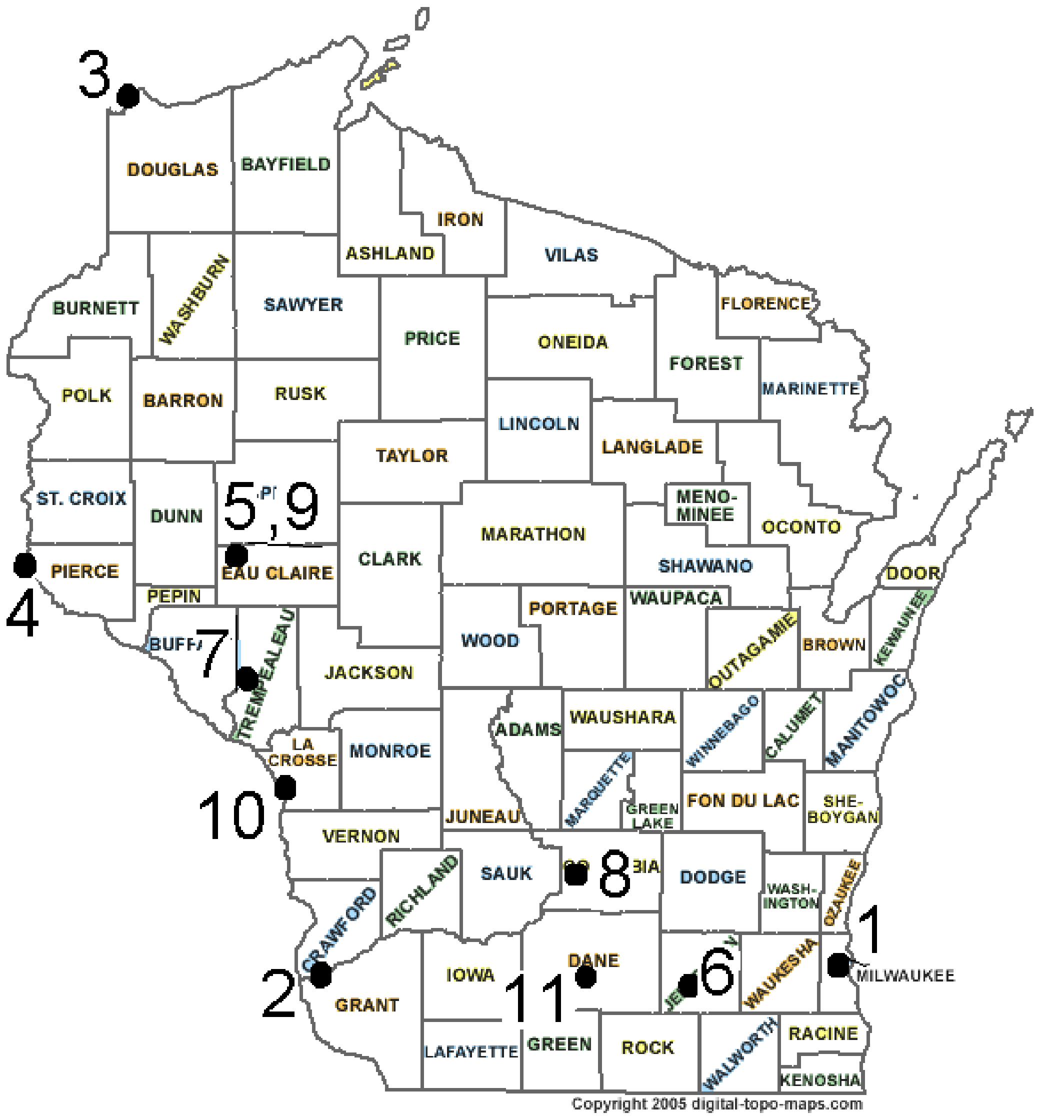
Load Test	Pile Name	Pile Type	Soil Along Side	Soil at Tip	Hammer Type	PDA EOD Capacity (kips)	CAPWAP Capacity (kips)	Wisc ENR (kips)	FHWA Gates (kips)	WsDOT Method (kips)	Load Test Source
163	Pile 32, Pier 1, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	192		319	653	748	Clairemont Avenue Bridge
164	Pile 5, Pier 2, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	178		238	550	660	Fort Atkinson Bypass
165	Pile 8, Pier 2, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	191		267	587	702	Fort Atkinson Bypass
166	Pile 31, Pier 2, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	177		158	436	526	Fort Atkinson Bypass
167	Pile 5, Pier 3, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	176		270	591	690	Fort Atkinson Bypass
168	Pile 8, Pier 3, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	176		270	591	690	Fort Atkinson Bypass
169	Pile 32, Pier 3, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	176		325	662	748	Fort Atkinson Bypass
170	Pile 5, Pier 4, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	176		167	448	532	Fort Atkinson Bypass
171	Pile 8, Pier 4, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	176		167	448	532	Fort Atkinson Bypass
172	Pile 32, Pier 4, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	176		167	448	532	Fort Atkinson Bypass
173	Pile 5, Pier 5, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	188		251	566	659	Fort Atkinson Bypass
174	Pile 29, Pier 5, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	194		255	572	671	Fort Atkinson Bypass
175	Pile 32, Pier 5, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	192		258	576	679	Fort Atkinson Bypass
176	Pile 8, Pier 6, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	174		222	528	620	Fort Atkinson Bypass
177	Pile 29, Pier 6, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	186		209	511	614	Fort Atkinson Bypass
178	Pile 32, Pier 6, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	182		188	482	588	Fort Atkinson Bypass
179	Pile 1, North Abutment, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	194		206	505	591	Fort Atkinson Bypass
180	Pile 4, North Abutment, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	212		327	663	761	Fort Atkinson Bypass
181	Pile 6, North Abutment, Fort Atkinson Bypass	CIP	clay/sand	sand	OED	194		180	469	552	Fort Atkinson Bypass
182	Pile 2, Pier 1,Trempealeau River Bridge		unknown	unknown	OED	240		169	502	356	Fort Atkinson Bypass
183	Pile 5, Pier 1,Trempealeau River Bridge		unknown	unknown	OED	230		169	502	356	Fort Atkinson Bypass
184	Pile 31, Pier 2, Wisconsin River Bridge	pipe - open ended			air/steam	360		173	464	387	Trempealeau River Bridge
185	Pile 26, Pier 8, Wisconsin River Bridge	pipe - open ended			OED	430		291	668	611	Trempealeau River Bridge
186	Pile 16, Pier 4, Wisconsin River Bridge	pipe - open ended			air/steam	320		173	464	387	Wisconsin River Bridge
187	Pile 20, Pier 4, Wisconsin River Bridge	pipe - open ended			air/steam	310		173	464	387	Wisconsin River Bridge
188	Pile 20, Pier 7, Wisconsin River Bridge				OED	550					Wisconsin River Bridge
189	Pile 7, Pier 8, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	148		108	342	349	Wisconsin River Bridge
190	Pile 20, Pier 8, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	140		120	365	375	Wisconsin River Bridge
191	Pile 26, Pier 8, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	150		123	372	386	Chippewa River Bridge
192	Pile 1, Pier 9, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	140		104	330	295	Chippewa River Bridge
193	Pile 7, Pier 9, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	146		109	340	302	Chippewa River Bridge
194	Pile 26, Pier 9, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	140		132	383	332	Chippewa River Bridge
195	Pile 1, Pier 7, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	160		203	499	490	Chippewa River Bridge
196	Pile 7, Pier 7, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	144		110	347	366	Chippewa River Bridge
197	Pile 20, Pier 7, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	148		105	336	357	Chippewa River Bridge
198	Pile 1, Pier 6, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	148		91	308	334	Chippewa River Bridge
199	Pile 20, Pier 6, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	152		100	326	349	Chippewa River Bridge
200	Pile 26, Pier 6, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	156		94	314	339	Chippewa River Bridge
201	Pile 1, Pier 5, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	152		95	311	282	Chippewa River Bridge
202	Pile 7, Pier 5, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	148		77	273	256	Chippewa River Bridge
203	Pile 26, Pier 5, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	160		104	330	295	Chippewa River Bridge
204	Pile 26, Pier 4, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	156		104	330	295	Chippewa River Bridge
205	Pile 1, Pier 3, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	156		99	320	288	Chippewa River Bridge
206	Pile 7, Pier 3, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	156		108	338	301	Chippewa River Bridge
207	Pile 20, Pier 3, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	160		122	365	319	Chippewa River Bridge
208	Pile 1, Pier 2, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	144		95	311	282	Chippewa River Bridge
209	Pile 7, Pier 2, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	156		109	339	301	Chippewa River Bridge
210	Pile 8, Pier 2, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	144		95	311	282	Chippewa River Bridge
211	Pile 1, Pier 1, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	170		140	401	410	Chippewa River Bridge
212	Pile 26, Pier 1, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	170		167	443	445	Chippewa River Bridge
213	Pile 3, East Abut, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	86		51	206	210	Chippewa River Bridge
214	Pile 4, East Abut, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	82		42	179	192	Chippewa River Bridge
215	Pile 9, East Abut, Structure B-18-131, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	88		65	245	237	Chippewa River Bridge
216	Pile 1, Pier 1, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	152		94	314	339	Chippewa River Bridge

Table 3.5 (continued) Wisconsin DOT Load test data.

Load Test	Pile Name	Pile Type	Soil Along Side	Soil at Tip	Hammer Type	PDA EOD Capacity (kips)	CAPWAP Capacity (kips)	Wisc ENR (kips)	FHWA Gates (kips)	WsDOT Method (kips)	Load Test Source
217	Pile 5, Pier 1, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	156		114	355	373	Chippewa River Bridge
218	Pile 24, Pier 1, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	152		106	340	360	Chippewa River Bridge
219	Pile 1, Pier 7, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	148		89	305	332	Chippewa River Bridge
220	Pile 24, Pier 7, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	148		91	308	334	Chippewa River Bridge
221	Pile 28, Pier 7, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	148		100	326	349	Chippewa River Bridge
222	Pile 7, Pier 8, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	158		100	326	349	Chippewa River Bridge
223	Pile 14, Pier 8, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	172		103	333	355	Chippewa River Bridge
224	Pile 22, Pier 8, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	150		96	320	344	Chippewa River Bridge
225	Pile 1, Pier 9, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	140		116	352	310	Chippewa River Bridge
226	Pile 7, Pier 9, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	150		136	391	337	Chippewa River Bridge
227	Pile 28, Pier 9, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	air/steam	148		130	379	329	Chippewa River Bridge
228	Pile 3, West Abut, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	76		77	276	304	Chippewa River Bridge
229	Pile 4, West Abut, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	78		79	281	308	Chippewa River Bridge
230	Pile 9, West Abut, Structure B-18-132, Chippewa River	HP	silty sand w/ gravel and cobbles	silty sand w/ gravel and cobbles	OED	78		75	272	300	Chippewa River Bridge
231	Pile 5, S. Abut, B-32-147, LaCrosse	Pipe	sand	sand	OED	113		152	419	362	Chippewa River Bridge
232	Pile 1, S. Abut, B-32-147, LaCrosse	Pipe	sand	sand	OED	112		178	475	386	Chippewa River Bridge
233	Pile 9, S. Abut, B-32-147, LaCrosse	Pipe	sand	sand	OED	113		127	374	306	LaCrosse
234	Pile 1, S. Abut, B-32-148, LaCrosse	CIP	sand	sand	OED	112		95	311	258	LaCrosse
235	Pile 4, S. Abut, B-32-148, LaCrosse	CIP	sand	sand	OED	114		91	303	261	LaCrosse
236	Pile 8, S. Abut, B-32-148, LaCrosse	CIP	sand	sand	OED	112		105	332	290	LaCrosse
237	Pile 1, Pier, B-32-148, LaCrosse	CIP	sand	sand	OED	110		100	321	272	LaCrosse
238	Pile 6, Pier, B-32-148, LaCrosse	CIP	sand	sand	OED	132		122	365	313	LaCrosse
239	Pile X, Pier, B-32-148, LaCrosse	CIP	sand	sand	OED	112		96	313	267	LaCrosse
240	Pile 2, Pier 2, B-32-149, LaCrosse	CIP	sand	sand	OED	112		105	331	273	LaCrosse
241	Pile 6, Pier 2, B-32-149, LaCrosse	CIP	sand	sand	OED	112		153	431	336	LaCrosse
242	Pile 10, Pier 2, B-32-149, LaCrosse	CIP	sand	sand	OED	112		146	414	325	LaCrosse
243	Pile 3, Pier 1, B-32-149, LaCrosse	CIP	sand	sand	OED	112		108	338	271	LaCrosse
244	Pile 7, Pier 1, B-32-149, LaCrosse	CIP	sand	sand	OED	112		108	338	271	LaCrosse
245	Pile 11, Pier 1, B-32-149, LaCrosse	CIP	sand	sand	OED	112		139	398	321	LaCrosse
246	Pile 2, Pier 2, B-32-150, LaCrosse	CIP	sand	sand	OED	109		119	358	290	LaCrosse
247	Pile 6, Pier 2, B-32-150, LaCrosse	CIP	sand	sand	OED	112		123	366	295	LaCrosse
248	Pile 10, Pier 2, B-32-150, LaCrosse	CIP	sand	sand	OED	112		147	417	327	LaCrosse
249	Pile 1, Pier 1, B-32-150, LaCrosse	CIP	sand	sand	OED	110		110	341	273	LaCrosse
250	Pile 5, Pier 1, B-32-150, LaCrosse	CIP	sand	sand	OED	110		115	352	280	LaCrosse
251	Pile 9, Pier 1, B-32-150, LaCrosse	CIP	sand	sand	OED	112		110	341	273	LaCrosse
252	Pile 1, N. Abut, B-32-147, LaCrosse	CIP	sand	sand	OED	112		124	369	315	LaCrosse
253	Pile 5, N. Abut, B-32-147, LaCrosse	CIP	sand	sand	OED	120		187	486	408	LaCrosse
254	Pile 9, N. Abut, B-32-147, LaCrosse	CIP	sand	sand	OED	118		192	558	407	LaCrosse
255	Pile 1, N. Abut, B-32-148, LaCrosse	CIP	sand	sand	OED	114		105	331	278	LaCrosse
256	Pile 7, N. Abut, B-32-148, LaCrosse	CIP	sand	sand	OED	116		96	313	267	LaCrosse
257	Pile 2, N. Abut., B-32-150, LaCrosse	CIP	sand	sand	OED	112		170	480	359	LaCrosse
258	Pile 5, N. Abut., B-32-150, LaCrosse	CIP	sand	sand	OED	110		155	440	334	LaCrosse
259	Pile 2, N. Abut., B-32-149, LaCrosse	CIP	sand	sand	OED	112		151	429	327	LaCrosse
260	Pile 6, N. Abut., B-32-149, LaCrosse	CIP	sand	sand	OED	112		135	394	305	LaCrosse
261	Pile 5, S. Abut., B-32-149, LaCrosse	CIP	sand	sand	OED	110		124	369	290	LaCrosse
262	Pile 2, S. Abut., B-32-150, LaCrosse	CIP	sand	sand	OED	110		121	364	287	LaCrosse
263	Pile 5, S. Abut., B-32-150, LaCrosse	CIP	sand	sand	OED	112		130	383	299	LaCrosse
264	Pile 9, East Abut, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	268		153	424	459	LaCrosse
265	Pile 9, East Abut, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	504		132	388	414	LaCrosse
266	Pile 10, West Abut, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	460		236	547	639	South Beltline, Madison
267	Pile 1, West Abut, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	436		264	583	674	South Beltline, Madison
268	Pile 1, West Abut, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	428		235	544	617	South Beltline, Madison
269	Pile 2, Pier 1, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	500		281	604	695	South Beltline, Madison
270	Pile 1, Pier 1, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	480		282	607	677	South Beltline, Madison

Table 3.5 (continued) Wisconsin DOT Load test data.

Load Test	Pile Name	Pile Type	Soil Along Side	Soil at Tip	Hammer Type	PDA EOD Capacity (kips)	CAPWAP Capacity (kips)	Wisc ENR (kips)	FHWA Gates (kips)	WsDOT Method (kips)	Load Test Source
271	Pile 1, Pier 2, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	552		187	479	572	South Beltline, Madison
272	Pile 10, Pier 2, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	448		282	607	677	South Beltline, Madison
273	Pile 1, Pier 3, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	400		224	531	623	South Beltline, Madison
274	Pile 12, Pier 3, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	416		201	498	573	South Beltline, Madison
275	Pile 5, Pier 4, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	400		204	503	596	South Beltline, Madison
276	Pile 8, Pier 4, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	476		264	583	674	South Beltline, Madison
277	Pile 10, Pier 5, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	300		235	544	617	South Beltline, Madison
278	Pile 8, Pier 5, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	432		217	520	555	South Beltline, Madison
279	Pile 6, Pier 6, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	260		249	564	656	South Beltline, Madison
280	Pile 7, Pier 6, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	332		208	506	530	South Beltline, Madison
281	Pile 9, Pier 7, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	488		312	658	684	South Beltline, Madison
282	Pile 2, Pier 7, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	466		321	656	746	South Beltline, Madison
283	Pile 8, Pier 8, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	412		234	544	581	South Beltline, Madison
284	Pile 9, Pier 10, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	310		192	485	561	South Beltline, Madison
285	Pile 4, Pier 10, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	424		264	583	654	South Beltline, Madison
286	Pile 7, Pier 11, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	404		214	517	609	South Beltline, Madison
287	Pile 1, Pier 11, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	408		192	485	561	South Beltline, Madison
288	Pile 15, Pier 12, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	390		249	564	656	South Beltline, Madison
289	Pile 8, Pier 13, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	412		299	628	719	South Beltline, Madison
290	Pile 11, Pier 13, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	578		190	485	594	South Beltline, Madison
291	Pile 10, Pier 14, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	334		249	564	656	South Beltline, Madison
292	Pile 2, Pier 14, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	440		264	583	674	South Beltline, Madison
293	Pile 9, Pier 15, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	424		282	607	677	South Beltline, Madison
294	Pile 7, Pier 15, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	552		302	633	702	South Beltline, Madison
295	Pile 10, Pier 16, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	400		249	564	656	South Beltline, Madison
296	Pile 4, Pier 16, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	460		299	628	719	South Beltline, Madison
297	Pile 10, Pier 17, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	376		173	458	551	South Beltline, Madison
298	Pile 4, Pier 18, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	354		187	479	572	South Beltline, Madison
299	Pile 8, Pier 21, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	534		234	544	581	South Beltline, Madison
300	Pile ?, Pier 21, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	526		176	460	490	South Beltline, Madison
301	Pile 3, Pier 22, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	398		179	464	509	South Beltline, Madison
302	Pile 10, Pier 22, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	600		200	496	569	South Beltline, Madison
303	Pile 2, Pier 23, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	518		209	510	582	South Beltline, Madison
304	Pile 5, Pier 23, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	544		189	480	539	South Beltline, Madison
305	Pile 2, Pier 24, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	468		163	440	487	South Beltline, Madison
306	Pile 4, Pier 24, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	386		221	524	580	South Beltline, Madison
307	Pile 3, Pier 25, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	292		198	494	551	South Beltline, Madison
308	Pile 8, Pier 26, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	198		170	452	498	South Beltline, Madison
309	Pile 4, Pier 26, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	394		221	524	547	South Beltline, Madison
310	Pile 10, Pier 27, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	314		187	477	521	South Beltline, Madison
311	Pile 6, Pier 27, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	304		197	491	533	South Beltline, Madison
312	Pile 4, Pier 28, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	506		208	507	548	South Beltline, Madison
313	Pile 12, Pier 29, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	434		187	477	521	South Beltline, Madison
314	Pile 7, Pier 30, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	362		221	524	580	South Beltline, Madison
315	Pile 13, Pier 30, Bridge 315, South Beltline, Madison	CIP	silty sand	silty sand	OED	476		189	480	539	South Beltline, Madison
316	Pile 8, Pier 31, Bridge 316, South Beltline, Madison	CIP	silty sand	silty sand	OED	380		221	524	563	South Beltline, Madison



1. Marquette Interchange, 96 piles
2. Bridgeport, 35 piles
3. Arrowhead Bridge, 5 piles
4. Prescott Bridge, 1 pile
5. Clairemont Ave. Bridge, 24 piles
6. Fort Atkinson Bypass, 20 piles
7. Trempealeau River Bridge, 2 piles
8. Wisconsin River, 5 piles
9. Chippewa River, 42 piles
10. La Crosse, 33 piles
11. South Beltline, Madison, 53 piles

Figure 3.1 Locations for Wisconsin Piles

Chapter 4

4.0 PREDICTED VERSUS MEASURED CAPACITY USING THE NATIONWIDE DATABASE

4.1 INTRODUCTION

Two databases are used in this report to assess the accuracy with which pile capacities can be determined from driving behavior. This chapter focuses on the first database. The first database is a collection of case histories in which a static load test was conducted and behavior of the pile during driving was recorded with sufficient detail to predict pile capacity using simple dynamic formulae. Some of the piles in this database also recorded additional measurements that allowed estimates using the PDA and/or CAPWAP. However, the critical component of this database is that a static load test must have been conducted. This database allows comparisons for 156 piles.

The ratio of predicted capacity (Q_P) to measured capacity (Q_M) is the metric used to quantify how well or poorly a predictive method performs. Statistics for each of the predictive methods are used to quantify the accuracy and precision for several pile driving formulas. Results for driven piles were compiled from the WSDOT (Allen, 2005), Flaate (Olson and Flaate 1967), Fragazy (1988), and FHWA (Long 2001) databases which were discussed in greater detail in Chapter 3. Evaluation for the Wisc-EN, WSDOT, and FHWA-Gates formulae was conducted for the whole database as well as for selective conditions.

4.2 DESCRIPTION OF DATA

It is essential to identify the character of the data when developing and comparing empirical methods. Insight into the character of this collection of pile load tests is provided by Tables 4.1 and 4.2. This investigation is limited to H-piles, open- and closed-ended steel pipe piles, and concrete filled piles. Timber and concrete piles are excluded from this study. Hammer types of interest are air/steam hammers, open and closed ended diesel hammers, and hydraulic hammers. Piles driven with drop hammers are not included in this study. The number of load tests available to assess the effect of different piles, soils, and pile hammers are given in Table 4.1. One can see that of the 156 load tests, results are spread unevenly in the sub-categories. For example, of the 156 load tests, 81 are closed-end pipe piles, while only 13 are open-ended pipe piles. Of the 156 load tests, 73 were driven with single acting air/steam hammers while only 4 were driven with hydraulic hammers. Twenty piles were driven into primarily clay soil, 64 of the piles were driven into predominantly sand, and 56 piles were driven in to both sand and clay layers (mixed). Sixteen piles did not have enough soil information and therefore are identified as unknown.

Table 4.2 provides a detailed accounting for specific sizes of piles, pile hammers, and pile capacities. This table allows the reader to quantify the sizes of piles, hammers, and static pile capacities in this collection. Most of the pile load tests exhibited pile capacities less than 750 kips. The average pile length was in the range of 61-90 ft, but ranged from 9 ft to 200 ft in length. The average H-pile was a 12 inch section, and most of the pipe piles were 12.75 - 14 inches in diameter.

Static load tests (SLT) were conducted to failure for all 156 piles. Pile Dynamic Analysis (PDA) and CAPWAP information was available for only the FHWA database and account for only 20 and 30 piles, respectively. Pile capacities predicted with each of the methods identified in Chapter 2 (Wisc-EN, WSDOT, FHWA-Gates) are compared with static load test capacities in the following sections of this chapter. Predicted capacities are also compared with capacities determined with PDA and CAPWAP for cases where the data are available.

4.3 COMPARISONS OF PREDICTED AND MEASURED CAPACITY

Capacities for all piles in the database were determined using the Wisc-EN, WSDOT, and FHWA-Gates formulae. The predicted capacities are compared with measured pile capacity as determined from a static load test. The predicted capacity (Q_p) divided by the measured capacity (Q_M) is the metric used to quantify the accuracy of a prediction. A value of Q_P/Q_M equal to 1 represents perfect agreement, whereas a value of Q_P/Q_M equal to 1.5 means the method over-predicts capacity by 50%. Values of Q_P/Q_M less than one represent under-prediction of capacity.

Mean, standard deviation, and the coefficient of variation for Q_P/Q_M are used as measures of the accuracy and precision for the methods. Of particular interest is the mean value (μ) which quantifies the overall tendency for the method to under- or over-predict capacity (accuracy). While the standard deviation (σ) identifies the scatter associated with the predictive method and quantifies the precision of the predictive method, the coefficient of variation ($\delta = \mu/\sigma$) is a more useful parameter for comparing precision of methods with different mean values. Thus, this report focuses on the mean and coefficient of variation (cov) to quantify the accuracy and precision of the predictive method. Ideally, good predictive methods exhibit a mean value close to unity and a small coefficient of variation (cov).

Since there are a large number of predicted and measured capacities, there are also a large number of combinations that could be used to assess the agreement between these methods. Comparisons were conducted for the following combinations:

- Dynamic Formulae versus Static Load Test
  - EN-Wisc versus Static Load Test
  - FHWA-Gates versus Static Load Test
  - WSDOT versus Static Load Test
- Dynamic Formula versus PDA (EOD)
  - EN-Wisc versus PDA (EOD)
  - FHWA-Gates versus PDA (EOD)
  - WSDOT versus PDA (EOD)
- Dynamic Formula versus CAPWAP (BOR)
  - EN-Wisc versus CAPWAP (BOR)
  - FHWA-Gates versus CAPWAP (BOR)
  - WSDOT versus CAPWAP (BOR)
- Other comparisons
  - PDA versus SLT
  - CAPWAP versus SLT
  - PDA versus CAPWAP

Each of these combinations were evaluated for the sub-categories of pile driving hammer (single acting Air/Steam, double acting Air/Steam, open-ended diesel, closed-ended diesel, and hydraulic), pile type (H, open-ended pipe, closed-ended pipe), and soil type (primarily sand, primarily clay, mixed, unknown).

Statistics for the above combinations are presented in Tables 4.3, 4.4, and 4.5 and graphs for selected combinations are plotted in Figs. 4.1 - 4.24. The tables and graphs represent a significant amount of data and statistical information that will be discussed in more detail below.

4.4 WISC-EN METHOD

The Wisc-EN formula is described in Chapter 2. This method was used to determine predicted pile capacities using all 156 cases. The predicted capacities are compared with measured capacities statistically in Tables 4.3 to 4.8 and graphically in Figs. 4.1 to 4.6.

4.4.1 Wisc-EN vs. SLT

The results show Wisc-EN significantly under-predicts capacity measured with a static load test. For the entire set of 156 piles, Wisc-EN/SLT is found to have a mean value of Q_P/Q_M equal to 0.44 and a high coefficient of variation value of 0.47 (Table 4.3). When the data are compared for cases in which the measured pile capacity is less than 750 kips (Tables 4.6 through 4.8), the mean and COV values for Q_P/Q_M are 0.44 and 0.46, respectively. The data show no major differences in statistics for all ranges of pile capacity. Also included in Tables 4.3 – 4.8 and Figures 4.1 - 4.6 are results for different hammers, soils, and pile types.

Figure 4.1 illustrates the relationship between the EN-Wisc capacity and the capacity from static load tests. All data fall below the 45° line indicating that the pile capacity measured from a static load test was always larger than the capacity predicted by the EN-Wisc method. This observation is not surprising because the EN-Wisc formula predicts a safe bearing load rather than an ultimate bearing capacity. This is the only method investigated that estimates a safe bearing load rather than an ultimate capacity.

4.4.2 Wisc-EN vs. PDA (EOD) and CAPWAP (BOR)

The Wisc-EN method shows better agreement when compared to PDA than to CAPWAP capacities. Capacities predicted with the Wisc-EN compared with capacities from the PDA (Wisc-EN/PDA) under-predict with a mean value of Q_P/Q_M equal to 0.60 and COV of 0.36 for the 20 piles in which data are available. Wisc-EN/CAPWAP data shows mean values of 0.41 and variation of 0.60 for 30 cases. No major effect is observed for comparisons in which the data are limited to less than 750 kips in capacity.

4.5 WASHINGTON STATE DOT METHOD (WSDOT)

WSDOT method for predicting pile capacities is used to compare predicted vs. measured pile capacities. The data is summarized statistically (Tables 4.3 through 4.8) and graphically (Figures 4.7 to 4.12).

4.5.1 WSDOT vs. SLT

Good correlation is observed between the measured and predicted capacities using the WSDOT method to estimate capacity. The mean value for WSDOT/SLT is 1.11, slightly above unity for the 156 piles. Coefficient of variation shows the least scatter with a value of 0.39. For pile capacities less than 750 kips, the data is similar with a mean of 1.14 and a COV of 0.38. Correlations are also provided for sub-categories based on hammer, pile, and soil type.

4.5.2 WSDOT vs. PDA and CAPWAP

Data for these comparisons are limited simply because this database did not contain a lot of PDA and CAPWAP results for the cases of interest. Predictions with WSDOT were greater than PDA estimates (mean = 1.8) with a COV of 0.44. This is due to the tendency for PDA(EOD) to underpredict capacity, particularly for piles driven into fine-grained soils. WSDOT vs. CAPWAP(BOR) shows good agreement with mean values near unity, $\mu = 1.11$ and COV = 0.43.

4.6 FHWA-GATES METHOD

The FHWA-Gates method was used to predict capacities. The data is summarized statistically (Tables 4.3 to 4.8) and graphically (Figures 4.13-4.18).

4.6.1 FHWA-Gates vs. SLT

Comparisons between the pile capacity predicted using the FHWA-Gates method and the pile capacity determined with a SLT show a reasonably good correlation. A plot of predicted versus measured capacity is shown in Figure 4.13a. The trend of the data is to slightly over-predict at low capacity and under-predict at higher capacity. The method seems to consistently under-predict capacities for measured loads greater than 750 kips. Furthermore, the under-prediction becomes more significant as the pile capacity increases beyond 750 kips. Overall, the FHWA-Gates method tends to over-predict capacity with a mean value for Q_p/Q_m equal to 1.13 with coefficient of variation of 0.42. The mean value is higher at 1.20, when considering only piles with an axial capacity less than 750 kips. The FHWA-Gates/SLT statistics also include a break down by hammer, soil, and pile types (Tables 4.3 to 4.8).

4.6.2 FHWA-Gates vs. PDA(EOD) and CAPWAP(BOR)

PDA and CAPWAP results are significantly different. FHWA-Gates/PDA shows a larger over-predictions with a mean value equal to 1.55 and a COV = 0.35. However, Gates to CAPWAP comparisons result in a mean ratio of 1.03 with a COV at 0.41. This is very good agreement for the limited data sets. The trend observed supports the observation that capacities estimated with PDA(EOD) tend to underestimate capacity while capacity predicted with CAPWAP(BOR) are more representative of the static load test capacity.

4.7 PDA(EOD) AND CAPWAP(BOR)

Prediction of axial capacity using PDA and CAPWAP are compared. The number of cases for the two methods is small, since only 20 PDA and 30 CAPWAP pile tests are used in this analysis. Generally, capacities predicted using PDA(EOD) measurements are lower than capacities predicted using CAPWAP(BOR). PDA vs. CAPWAP statistics show μ = 0.79 and COV = 0.34 with little variation for pile capacities less that 750 kips. Statistics and graphs for PDA and CAPWAP data is given in Tables 4.3 through 4.8 and Figs. 4.19 to 4.24, respectively.

PDA(EOD)/SLT shows mean values of 0.73 with COV of 0.40 whereas CAPWAP(BOR)/SLT shows mean values of 0.92 with COV of 0.25. The results suggest a strong correlation between CAPWAP and SLT since the mean value approaches unity and the statistical scatter is significantly smaller than observed with the other methods. Such a correlation suggests that there is good agreement between static pile capacity and estimates of capacity with CAPWAP(BOR). However, the statistics also indicate that the PDA typically under-predicts pile capacity and exhibits more scatter.

4.8 DEVELOPMENT OF THE "CORRECTED"FHWA-GATES METHOD

The FHWA-Gates predictive method was investigated to determine if the current method could be modified to improve its ability to predict axial capacity. As shown in Figure 4.13a and as discussed previously in this chapter, the trend of the FHWA-Gates method is to slightly over-predict at low capacities and under-predict at higher capacities. This trend is gradual and appears to transitions from over-prediction to under-prediction at an axial capacity of 750 kips. Accordingly, all statistics were re-evaluated to include only piles with capacities less than 750 kips

Overall, the effect of considering only piles with capacities less than 750 kips was to increase the mean values of Q_p/Q_m for the FHWA-Gates method to a value of 1.20 and to decrease the cov to a value of 0.40.

Further improvements to the FHWA-Gates method were implemented by adjusting predictions based on the type of hammer used, the type of pile used and the type of soil surrounding the pile. Statistics for the subcategories are given in Table 4.6 for different hammer types, Table 4.7 for different soil types, and Table 4.8 for different pile types. For example, the mean value of Q_p/Q_m for piles driven with a single acting Air/Steam hammer is 1.07 whereas the value is 1.54 for a closed-end diesel. Studies and statistics for all pile, soil and hammer types were conducted to develop appropriate correction factors for these variables.

Based on the methodology above, FHWA-Gates correction factors were developed and are as follows: 1) F_o - an overall correction factor, 2) F_H - a correction factor to account for the hammer used to drive the pile, 3) F_S - a correction factor to account for the soil surrounding the pile, 4) F_P - a correction factor to account for the type of pile being driven. Table 4.10 shows the values used for each of these correction factors.

Results for the "corrected" FHWA-Gates are given in Table 4.9 and shown in Figs. 4.27 and 4.28. The mean value of Q_p/Q_m reduced from 1.20 to 1.02 with the application of the adjustment factors. The coefficient of variation is also reduced from 0.40 to 0.36 for pile less than 750 kips. Additionally, the difference between mean values for FHWA-Gates/SLT is very small for different soil, hammer, and pile types (difference is a maximum of 0.03 from unity in nearly all circumstances). The outliers, unknown soil type and hydraulic hammer vs. SLT, are the only exceptions since they either do not have an adjustment value or they are the only data point in the dataset.

4.9 SUMMARY AND CONCLUSIONS

A database containing pile load tests from any location was used to determine how well the methods EN-Wisc, FHWA-Gates, WSDOT, and PDA predicted measured capacity. Comparisons focused on predicted capacity verses capacity measured with a static load test. Correction factors were applied to the FHWA-Gates method to improve its ability to predict pile capacity. The ability to predict capacity was quantified with the ratio of predicted to measured capacity (Q_P/Q_M). The mean and coefficient of variation were used to allow quantitative comparisons for each method. Detailed results and graphs are presented within the body of the chapter, but a summary of the methods is given below:

Mean	COV	Method
0.43	0.47	Wisc-EN
1.11	0.39	WSDOT
1.13	0.42	FHWA-Gates
0.73	0.40	PDA
1.20	0.40	FHWA-Gates for all piles <750 kips
1.02	0.36	“corrected” FHWA-Gates for piles <750 kips

The Wisc-EN formula significantly under-predicts capacity (mean = 0.43). This is the (only) method that predicts a safe bearing load; therefore, there is a factor of safety inherent with use of the method. The other methods predict ultimate bearing capacity. The scatter (cov = 0.47)) associated with this method is the greatest and therefore, the EN-Wisc method is the the least precise of all the methods.

The WSDOT method exhibited a slight tendency to overpredict capacity and exhibited the greatest precision (lowest cov). The method seemed to predict capacity with equal adeptness across the range of capacities and deserves consideration as a simple dynamic formula.

The FHWA-Gates method tends to overpredict axial pile capacity for small loads and underpredict capacity for loads greater than 750 kips. The method results in a mean value of 1.13 and a cov equal to 0.42. The degree of scatter, as indicated by the value of the cov, is greater than the WSDOT method, but significantly less than the EN-Wisc method. Improvement in the scatter associated with the FHWA-Gates method can be improved by restricting its use to piles with capacities less than 750 kips.

The pile load test data were used to modify the FHWA-Gates method by correcting for trends observed for different pile types, soil types, and hammer types. The efforts resulted in developing a “corrected” FHWA-Gates method with a mean value of 1.02 and a cov equal to 0.36. This method develops the best statistics with the mean value closest to unity and the lowest cov; however, it is recognized that the data used to develop the correction factors is the same data used to develop the statistics.

The PDA capacity determined for end-of-driving conditions tends to underpredict axial pile capacity. The ratio of predicted to measured capacity was 0.7 and the method exhibits a cov of 0.40 which is very close to the scatter observed for WSDOT, FHWA-Gates and “corrected” FHWA-Gates.

Table 4.1 – Character of Pile Data

PILE COUNTS		**Databases**				
		ALL	**FRAGAZY**	**FLAATE**	**WSDOT**	**FHWA**
Total Number of Piles		156	16	26	82	32
Pile Type	CEP	81	9	11	43	18
	HP	62	5	15	28	14
	OEP	13	2	0	11	0
Soil Type	CLAY	20	0	0	11	9
	MIXED	56	0	0	35	21
	SAND	64	0	26	36	2
	UNKNOWN	16	16	0	0	0
Hammer Type	A/S(DA)	8	0	5	0	3
	A/S(SA)	73	16	21	20	16
	CED	24	0	0	24	0
	HYD	4	0	0	4	0
	OED	47	0	0	34	13
Methods	EN-WISC	156	16	26	82	32
	WSDOT	156	16	26	82	32
	FHWA-GATES	156	16	26	82	32
	PDA	29	0	0	9	20
	CAPWAP	30	0	0	0	30

Table 4.2 – Description of Pile Data

Pile Types	Description	Number	Pile Types	Description	Number
H-Pile	*Total*	62	***Closed-Ended Pipe Pile***	*Total*	81
	Unknown	20		Unknown	20
	10 x 42	4		9.63" x ?	6
	10 x 57	3		9.63" x 0.55	5
	12 x 53	2		9.75" x ?	2
	12 x 63	2		10" x ?	2
	12 x 74	10		12.75" x ?	9
	12 x 120	3		12.75" x 0.25	2
	14 x 73	7		12.75" x 0.31	2
	14 x 89	4		12.75" x 0.38	4
	14 x 117	3		12.75" x 0.5	1
	14 x 142	4		13.38" x ?	3
Open-Ended Pipe Pile	*Total*	13		14" x ?	12
	Unknown	4		14" x 0.5	2
	24"	3		18" x ?	3
	36"	1		24" x ?	5
	42"	1		26" x ?	1
	48"	2		26" x 0.75	1
	60"	2		48" x ?	1

Pile Length	*Unknown*	20	***Measured Capacities***	*(kips)*	*Number*
	1' - 30'	9		0 - 250	24
	31' - 60'	28		251 - 500	67
	61' - 90'	43		501 - 750	41
	91' - 120'	34		751 - 1000	11
	121' - 150'	9		1001 - 1250	8
	151' - 180'	12		1251 - 1500	3
	181' - 210'	1		1501 - 1750	1
Hammer Energy	*(kip-ft)*	*Number*		1751 - 2000	1
	0 - 20	28		> 2000	0
	21 - 40	65			
	41 - 60	27			
	61 - 80	20			
	81 - 100	8			
	101 - 120	7			
	121 +	1			

Table 4.3 – Statistics for All Piles Based on Hammer Type

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
Wisc-En vs. SLT	**Mean:**	0.43	0.46	0.36	0.64	0.38	0.45
	COV:	0.47	0.41	0.50	0.22	0.17	0.45
	n:	156	8	73	24	4	47

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
WSDOT vs. SLT	**Mean:**	1.11	1.00	0.99	1.44	0.99	1.16
	COV:	0.39	0.38	0.42	0.21	0.21	0.38
	n:	156	8	73	24	4	47

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
FHWA-Gates vs. SLT	**Mean:**	1.13	1.34	1.06	1.54	0.87	1.01
	COV:	0.42	0.42	0.47	0.21	0.44	0.38
	n:	156	8	73	24	4	47

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
Wisc-En vs. PDA	**Mean:**	0.60	0.45	0.59	-	-	0.64
	COV:	0.36	-	0.41	-	-	0.34
	n:	20	1	10	0	0	9

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
WSDOT vs. PDA	**Mean:**	1.80	0.96	2.00	-	-	1.67
	COV:	0.44	-	0.48	-	-	0.32
	n:	20	1	10	0	0	9

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
FHWA-Gates vs. PDA	**Mean:**	1.55	1.23	1.75	-	-	1.37
	COV:	0.35	-	0.38	-	-	0.25
	n:	20	1	10	0	0	9

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
Wisc-En vs. CAPWAP	**Mean:**	0.41	0.50	0.32	-	-	0.53
	COV:	0.60	0.48	0.72	-	-	0.45
	n:	30	3	16	0	0	11

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
WSDOT vs. CAPWAP	**Mean:**	1.11	1.13	0.95	-	-	1.34
	COV:	0.43	0.32	0.45	-	-	0.39
	n:	30	3	16	0	0	11

		ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
FHWA-Gates vs. CAPWAP	**Mean:**	1.03	1.25	0.90	-	-	1.15
	COV:	0.41	0.21	0.48	-	-	0.34
	n:	30	3	16	0	0	11

PDA vs SLT

	ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
Mean:	0.73	0.47	0.61	-	-	0.91
COV:	0.40	-	0.43	-	-	0.28
n:	20	1	10	0	0	9

CAPWAP vs SLT

	ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
Mean:	0.92	0.60	0.95	-	-	0.95
COV:	0.25	0.29	0.24	-	-	0.21
n:	30	3	16	0	0	11

PDA vs CAPWAP

	ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
Mean:	0.79	1.04	0.66	-	-	0.92
COV:	0.34	-	0.41	-	-	0.24
n:	20	1	10	0	0	9

Table 4.4 – Statistics for All Piles Based on Soil Type

Wisc-En vs. SLT

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	0.43	0.46	0.36	0.44	0.41
COV:	0.47	0.40	0.64	0.51	0.37
n:	156	64	20	56	16

WSDOT vs. SLT

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	1.11	1.13	1.06	1.12	1.08
COV:	0.39	0.38	0.50	0.39	0.30
n:	156	64	20	56	16

FHWA-Gates vs. SLT

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	1.13	1.31	0.91	1.01	1.15
COV:	0.42	0.41	0.52	0.39	0.24
n:	156	64	20	56	16

Wisc-En vs. PDA

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	0.60	0.45	0.55	0.67	-
COV:	0.36	-	0.38	0.35	-
n:	20	1	9	10	0

WSDOT vs. PDA

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	1.80	0.96	1.75	1.93	-
COV:	0.44	-	0.35	0.48	-
n:	20	1	9	10	0

FHWA-Gates vs. PDA

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	1.55	1.23	1.39	1.73	-
COV:	0.35	-	0.28	0.38	-
n:	20	1	9	10	0

Wisc-En vs. CAPWAP

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	0.41	0.37	0.47	0.39	-
COV:	0.60	0.37	0.47	0.69	-
n:	30	2	9	19	0

WSDOT vs. CAPWAP

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	1.11	0.93	1.39	1.00	-
COV:	0.43	0.11	0.31	0.48	-
n:	30	2	9	19	0

FHWA-Gates vs. CAPWAP

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	1.03	1.13	1.14	0.97	-
COV:	0.41	0.19	0.31	0.48	-
n:	30	2	9	19	0

PDA vs SLT

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	0.73	0.47	0.83	0.68	-
COV:	0.40	-	0.41	0.36	-
n:	20	1	9	10	0

CAPWAP vs SLT

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	0.92	0.50	0.95	0.95	-
COV:	0.25	0.15	0.23	0.23	-
n:	30	2	9	19	0

PDA vs CAPWAP

	ALL Data	Sand	Clay	Mix	Unknown
Mean:	0.79	1.04	0.85	0.72	-
COV:	0.34	-	0.30	0.40	-
n:	20	1	9	10	0

Table 4.5 – Statistics for All Piles Based on Pile Type

Wisc-En vs. SLT

	ALL Data	CEP	HP	OEP
Mean:	0.43	0.42	0.46	0.39
COV:	0.47	0.52	0.41	0.43
n:	156	81	62	13

WSDOT vs. SLT

	ALL Data	CEP	HP	OEP
Mean:	1.11	1.08	1.17	1.03
COV:	0.39	0.42	0.37	0.29
n:	156	81	62	13

FHWA-Gates vs. SLT

	ALL Data	CEP	HP	OEP
Mean:	1.13	1.06	1.29	0.79
COV:	0.42	0.41	0.40	0.39
n:	156	81	62	13

Wisc-En vs. PDA

	ALL Data	CEP	HP	OEP
Mean:	0.60	0.49	0.68	-
COV:	0.36	0.46	0.27	-
n:	20	8	12	0

WSDOT vs. PDA

	ALL Data	CEP	HP	OEP
Mean:	1.80	1.56	1.95	-
COV:	0.44	0.42	0.44	-
n:	20	8	12	0

FHWA-Gates vs. PDA

	ALL Data	CEP	HP	OEP
Mean:	1.55	1.55	1.55	-
COV:	0.35	0.48	0.26	-
n:	20	8	12	0

Wisc-En vs. CAPWAP

	ALL Data	CEP	HP	OEP
Mean:	0.41	0.32	0.54	-
COV:	0.60	0.58	0.50	-
n:	30	17	13	0

WSDOT vs. CAPWAP

	ALL Data	CEP	HP	OEP
Mean:	1.11	0.90	1.39	-
COV:	0.43	0.37	0.37	-
n:	30	17	13	0

FHWA-Gates vs. CAPWAP

	ALL Data	CEP	HP	OEP
Mean:	1.03	0.91	1.18	-
COV:	0.41	0.41	0.37	-
n:	30	17	13	0

PDA vs SLT

	ALL Data	CEP	HP	OEP
Mean:	0.73	0.63	0.81	-
COV:	0.40	0.45	0.36	-
n:	20	8	12	0

CAPWAP vs SLT

	ALL Data	CEP	HP	OEP
Mean:	0.92	0.88	0.96	-
COV:	0.25	0.31	0.18	-
n:	30	17	13	0

PDA vs CAPWAP

	ALL Data	CEP	HP	OEP
Mean:	0.79	0.74	0.83	-
COV:	0.34	0.38	0.33	-
n:	20	8	12	0

Table 4.6 – Statistics for Piles <750^{kips} Based on Hammer Type

Wisc-En vs. SLT

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	0.44	0.50	0.35	0.64	0.45	0.47
COV:	0.46	0.34	0.51	0.22	-	0.38
n:	132	7	70	24	1	30

WSDOT vs. SLT

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	1.14	1.08	0.98	1.44	1.29	1.26
COV:	0.38	0.31	0.43	0.21	-	0.34
n:	132	7	70	24	1	30

FHWA-Gates vs. SLT

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	1.20	1.45	1.07	1.54	1.44	1.16
COV:	0.40	0.35	0.48	0.21	-	0.29
n:	132	7	70	24	1	30

Wisc-En vs. PDA

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	0.61	0.45	0.59	-	-	0.66
COV:	0.36	-	0.41	-	-	0.33
n:	19	1	10	0	0	8

WSDOT vs. PDA

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	1.84	0.96	2.00	-	-	1.76
COV:	0.42	-	0.48	-	-	0.28
n:	19	1	10	0	0	8

FHWA-Gates vs. PDA

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	1.59	1.23	1.75	-	-	1.45
COV:	0.33	-	0.38	-	-	0.19
n:	19	1	10	0	0	8

Wisc-En vs. CAPWAP

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	0.41	0.50	0.32	-	-	0.53
COV:	0.61	0.48	0.72	-	-	0.47
n:	29	3	16	0	0	10

WSDOT vs. CAPWAP

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	1.11	1.13	0.95	-	-	1.37
COV:	0.44	0.32	0.45	-	-	0.40
n:	29	3	16	0	0	10

FHWA-Gates vs. CAPWAP

<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
Mean:	1.03	1.25	0.90	-	-	1.17
COV:	0.41	0.21	0.48	-	-	0.34
n:	29	3	16	0	0	10

	<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
PDA vs SLT	**Mean:**	0.75	-	0.61	-	-	0.99
	COV:	0.41	-	0.43	-	-	0.22
	n:	16	0	10	0	0	6

	<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
CAPWAP vs SLT	**Mean:**	0.95	0.67	0.95	-	-	1.03
	COV:	0.24	0.24	0.24	-	-	0.20
	n:	25	2	16	0	0	7

	<750	**ALL Data**	**A/S (DA)**	**A/S(SA)**	**CED**	**HYD**	**OED**
PDA vs CAPWAP	**Mean:**	0.78	1.04	0.66	-	-	0.89
	COV:	0.34	-	0.41	-	-	0.24
	n:	19	1	10	0	0	8

Table 4.7 – Statistics for Piles <750^{kips} Based on Soil Type

	<750	**ALL Data**	**Sand**	**Clay**	**Mix**	**Unknown**
Wisc-En vs. SLT	**Mean:**	0.44	0.48	0.35	0.44	0.41
	COV:	0.46	0.39	0.71	0.50	0.37
	n:	132	57	15	44	16

	<750	**ALL Data**	**Sand**	**Clay**	**Mix**	**Unknown**
WSDOT vs. SLT	**Mean:**	1.14	1.17	1.08	1.14	1.08
	COV:	0.38	0.36	0.55	0.38	0.30
	n:	132	57	15	44	16

	<750	**ALL Data**	**Sand**	**Clay**	**Mix**	**Unknown**
FHWA-Gates vs. SLT	**Mean:**	1.20	1.38	0.94	1.07	1.15
	COV:	0.40	0.37	0.54	0.37	0.24
	n:	132	57	15	44	16

	<750	**ALL Data**	**Sand**	**Clay**	**Mix**	**Unknown**
Wisc-En vs. PDA	**Mean:**	0.61	0.45	0.56	0.67	-
	COV:	0.36	-	0.39	0.35	-
	n:	19	1	8	10	0

	<750	**ALL Data**	**Sand**	**Clay**	**Mix**	**Unknown**
WSDOT vs. PDA	**Mean:**	1.84	0.96	1.85	1.93	-
	COV:	0.42	-	0.31	0.48	-
	n:	19	1	8	10	0

	<750	**ALL Data**	**Sand**	**Clay**	**Mix**	**Unknown**
FHWA-Gates vs. PDA	**Mean:**	1.59	1.23	1.47	1.73	-
	COV:	0.33	-	0.23	0.38	-
	n:	19	1	8	10	0

	<750	ALL Data	Sand	Clay	Mix	Unknown
Wisc-En vs. CAPWAP	**Mean:**	0.41	0.37	0.46	0.39	-
	COV:	0.61	0.37	0.51	0.69	-
	n:	29	2	8	19	0

	<750	ALL Data	Sand	Clay	Mix	Unknown
WSDOT vs. CAPWAP	**Mean:**	1.11	0.93	1.43	1.00	-
	COV:	0.44	0.11	0.31	0.48	-
	n:	29	2	8	19	0

	<750	ALL Data	Sand	Clay	Mix	Unknown
FHWA-Gates vs. CAPWAP	**Mean:**	1.03	1.13	1.17	0.97	-
	COV:	0.41	0.19	0.31	0.48	-
	n:	29	2	8	19	0

	<750	ALL Data	Sand	Clay	Mix	Unknown
PDA vs SLT	**Mean:**	0.75	-	0.86	0.67	-
	COV:	0.41	-	0.40	0.39	-
	n:	16	0	7	9	0

	<750	ALL Data	Sand	Clay	Mix	Unknown
CAPWAP vs SLT	**Mean:**	0.95	0.56	0.97	0.97	-
	COV:	0.24	-	0.25	0.22	-
	n:	25	1	7	17	0

	<750	ALL Data	Sand	Clay	Mix	Unknown
PDA vs CAPWAP	**Mean:**	0.78	1.04	0.82	0.72	-
	COV:	0.34	-	0.31	0.40	-
	n:	19	1	8	10	0

Table 4.8 – Statistics for Piles <750^{kips} Based on Pile Type

	<750	ALL Data	CEP	HP	OEP
Wisc-En vs. SLT	**Mean:**	0.44	0.42	0.47	0.45
	COV:	0.46	0.52	0.40	0.32
	n:	132	74	52	6

	<750	ALL Data	CEP	HP	OEP
WSDOT vs. SLT	**Mean:**	1.14	1.09	1.20	1.21
	COV:	0.38	0.42	0.35	0.16
	n:	132	74	52	6

	<750	ALL Data	CEP	HP	OEP
FHWA-Gates vs. SLT	**Mean:**	1.20	1.08	1.38	1.03
	COV:	0.40	0.40	0.36	0.23
	n:	132	74	52	6

Wisc-En vs. PDA

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	0.61	0.49	0.70	-
COV:	0.36	0.46	0.26	-
n:	19	8	11	0

WSDOT vs. PDA

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	1.84	1.56	2.04	-
COV:	0.42	0.42	0.41	-
n:	19	8	11	0

FHWA-Gates vs. PDA

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	1.59	1.55	1.63	-
COV:	0.33	0.48	0.21	-
n:	19	8	11	0

Wisc-En vs. CAPWAP

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	0.41	0.32	0.54	-
COV:	0.61	0.58	0.52	-
n:	29	17	12	0

WSDOT vs. CAPWAP

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	1.11	0.90	1.41	-
COV:	0.44	0.37	0.37	-
n:	29	17	12	0

FHWA-Gates vs. CAPWAP

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	1.03	0.91	1.20	-
COV:	0.41	0.41	0.37	-
n:	29	17	12	0

PDA vs SLT

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	0.75	0.65	0.83	-
COV:	0.41	0.45	0.37	-
n:	16	7	9	0

CAPWAP vs SLT

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	0.95	0.91	1.02	-
COV:	0.24	0.28	0.16	-
n:	25	16	9	0

PDA vs CAPWAP

<750	**ALL Data**	**CEP**	**HP**	**OEP**
Mean:	0.78	0.74	0.80	-
COV:	0.34	0.38	0.33	-
n:	19	8	11	0

Table 4.9 – Corrected FHWA-Gates Statistics for Piles <750^{kips} vs. Static Load Tests

<750	ALL Data	Sand	Clay	Mix	Unknown
Mean:	1.02	1.38	0.94	1.07	1.15
COV:	0.36	0.37	0.54	0.37	0.24
n:	132	57	15	44	16

<750	ALL Data	A/S (DA)	A/S(SA)	CED	HYD	OED
Mean:	1.02	1.13	1.02	1.02	1.09	1.02
COV:	0.36	0.37	0.42	0.21	-	0.34
n:	132	8	70	24	1	30

<750	ALL Data	CEP	HP	OEP
Mean:	1.02	1.02	1.02	1.03
COV:	0.36	0.37	0.35	0.29
n:	132	74	52	6

Table 4.10 – Adjustment Factors for Corrected FHWA-Gates Statistics

Adjustment Factors for FHWA-Gates method
FHWA-Gates Capacity *F0*FS*FP*FH

F_0 - Overall adjustment factor

$F_0 = 0.94$

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)

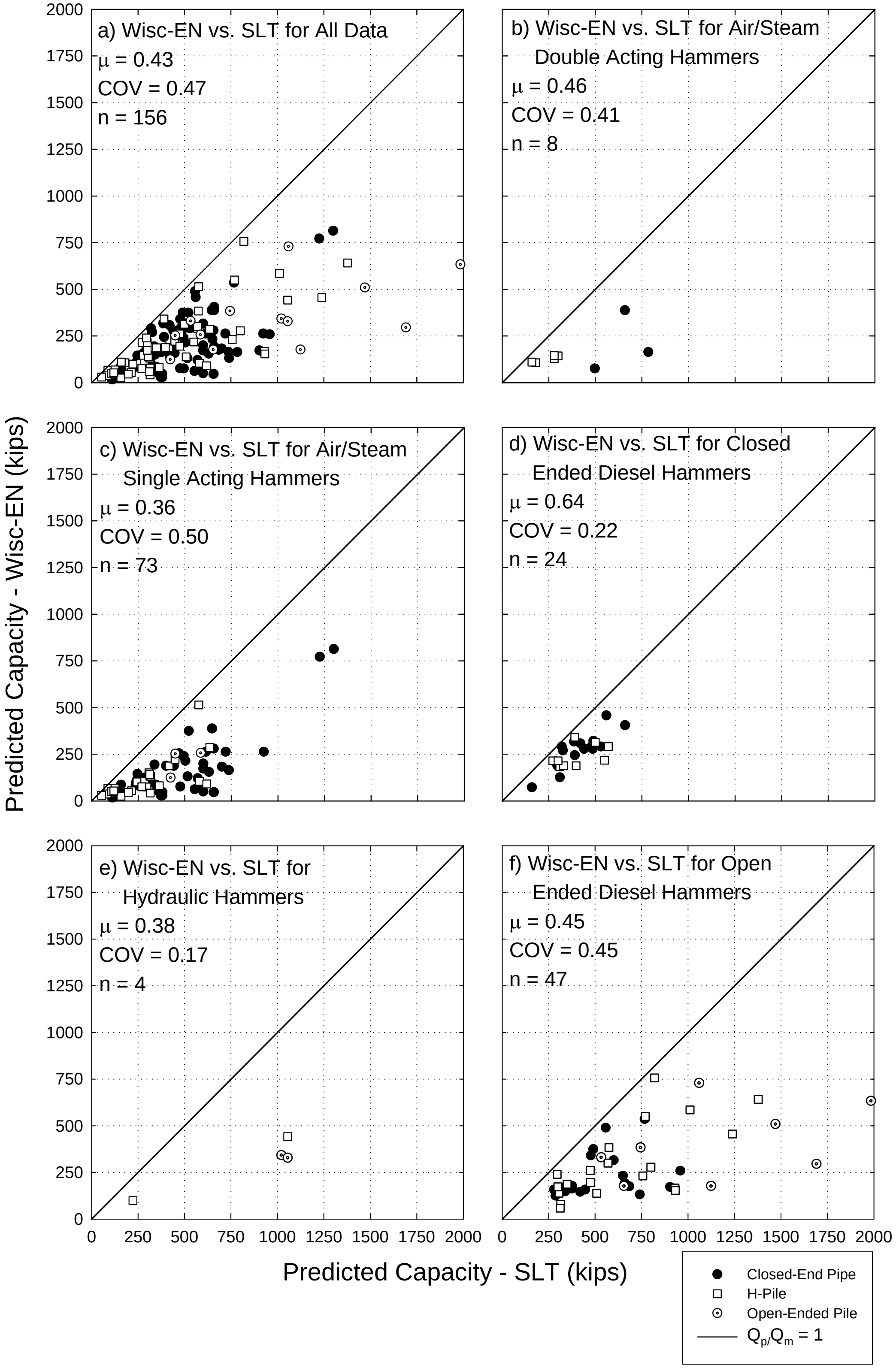


Figure 4.1. Wisc-EN vs SLT Broken Down by Hammer Type

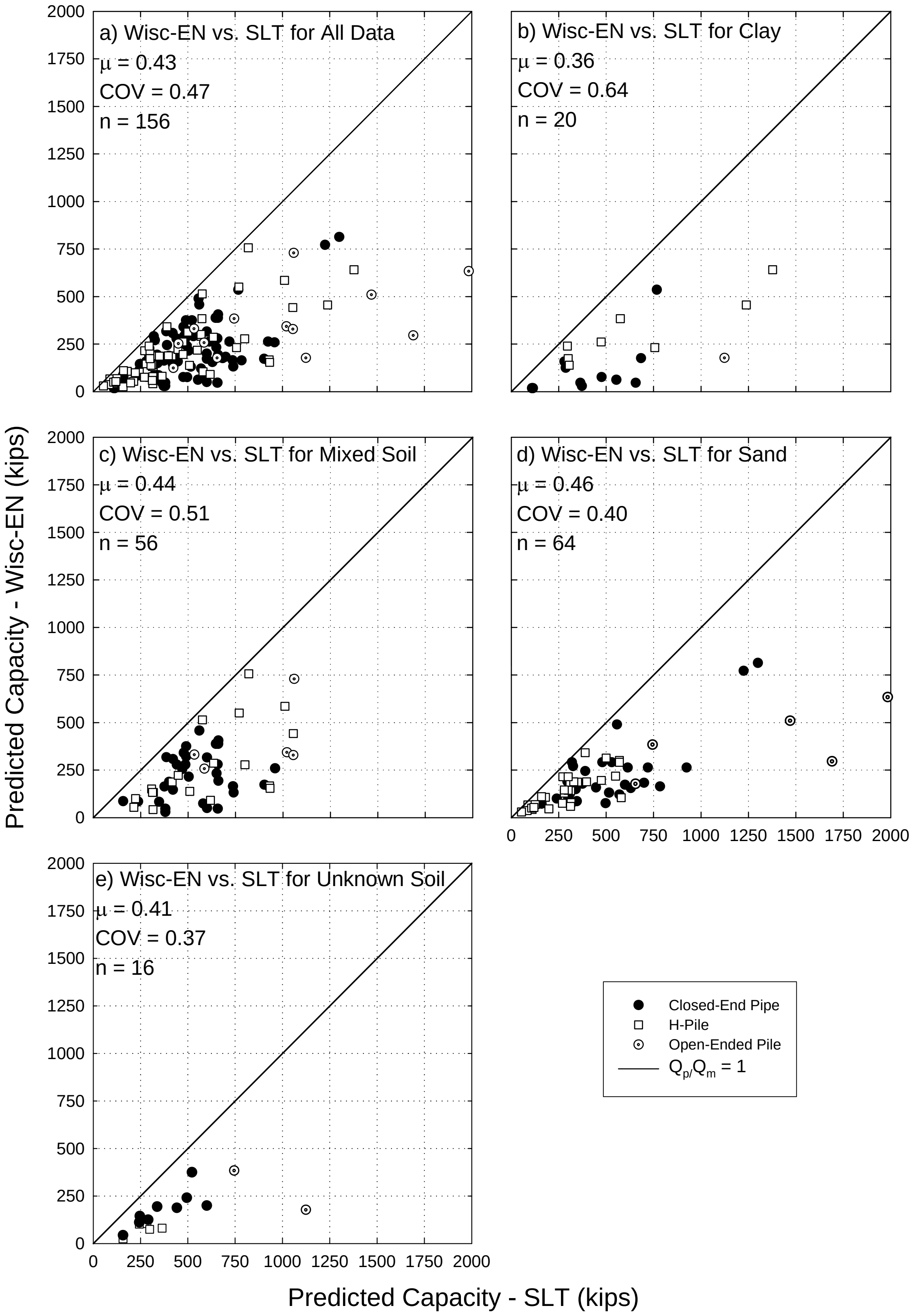


Figure 4.2. Wisc-EN vs SLT Broken Down by Soil Type

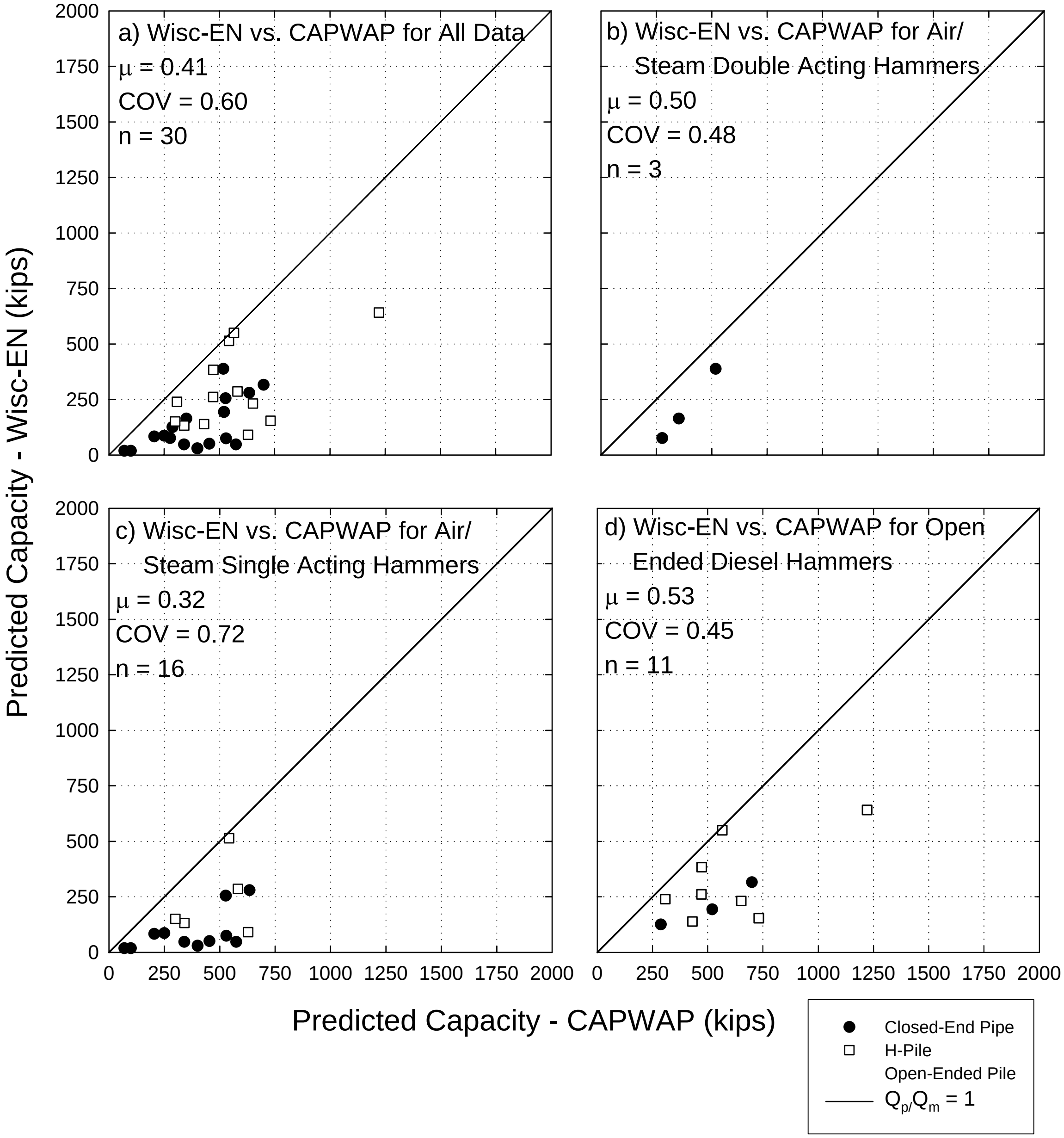


Figure 4.3. Wisc-EN vs CAPWAP Broken Down by Hammer Type

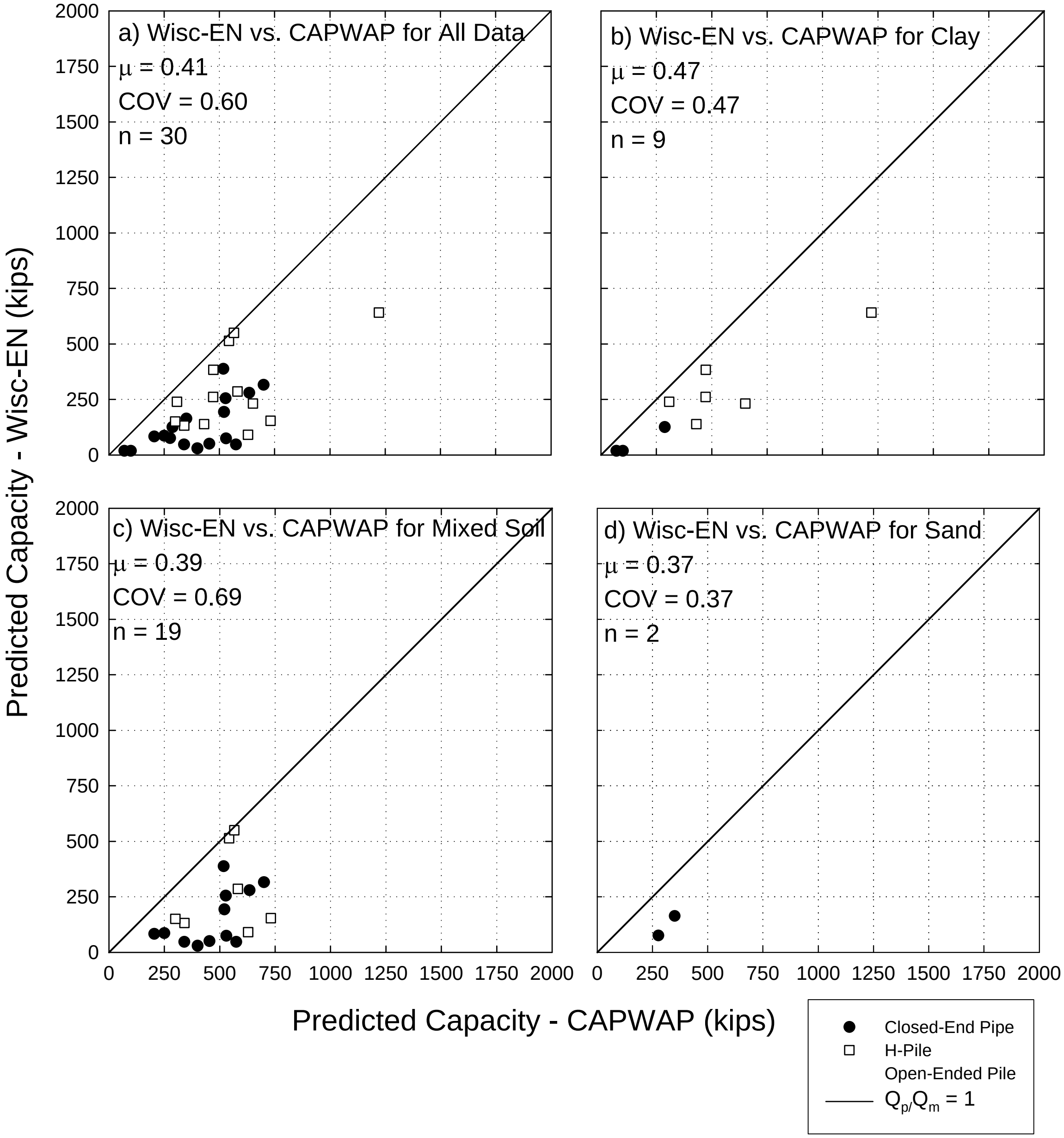


Figure 4.4. Wisc-EN vs CAPWAP Broken Down by Soil Type

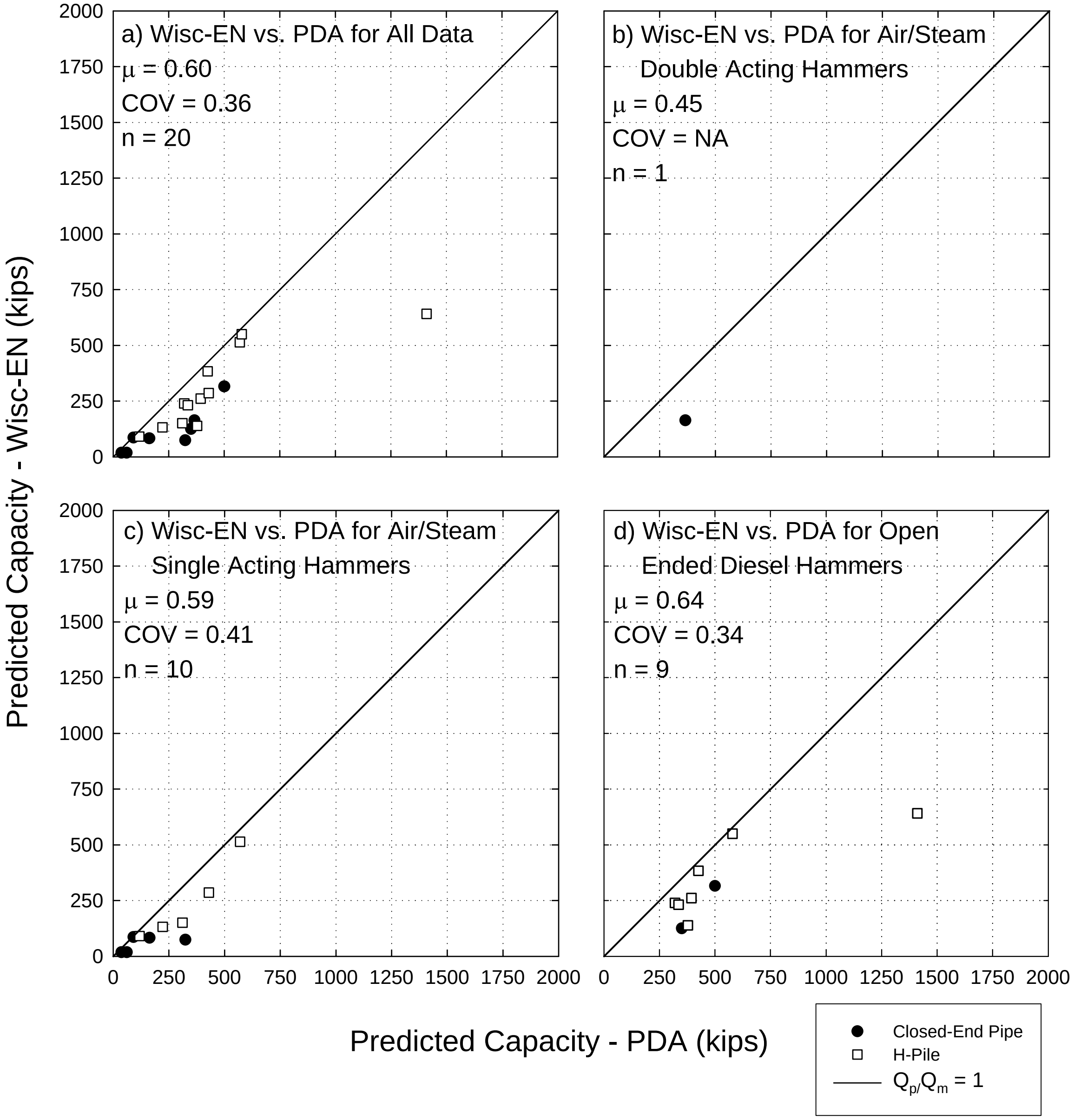


Figure 4.5. Wisc-EN vs PDA Broken Down by Hammer Type

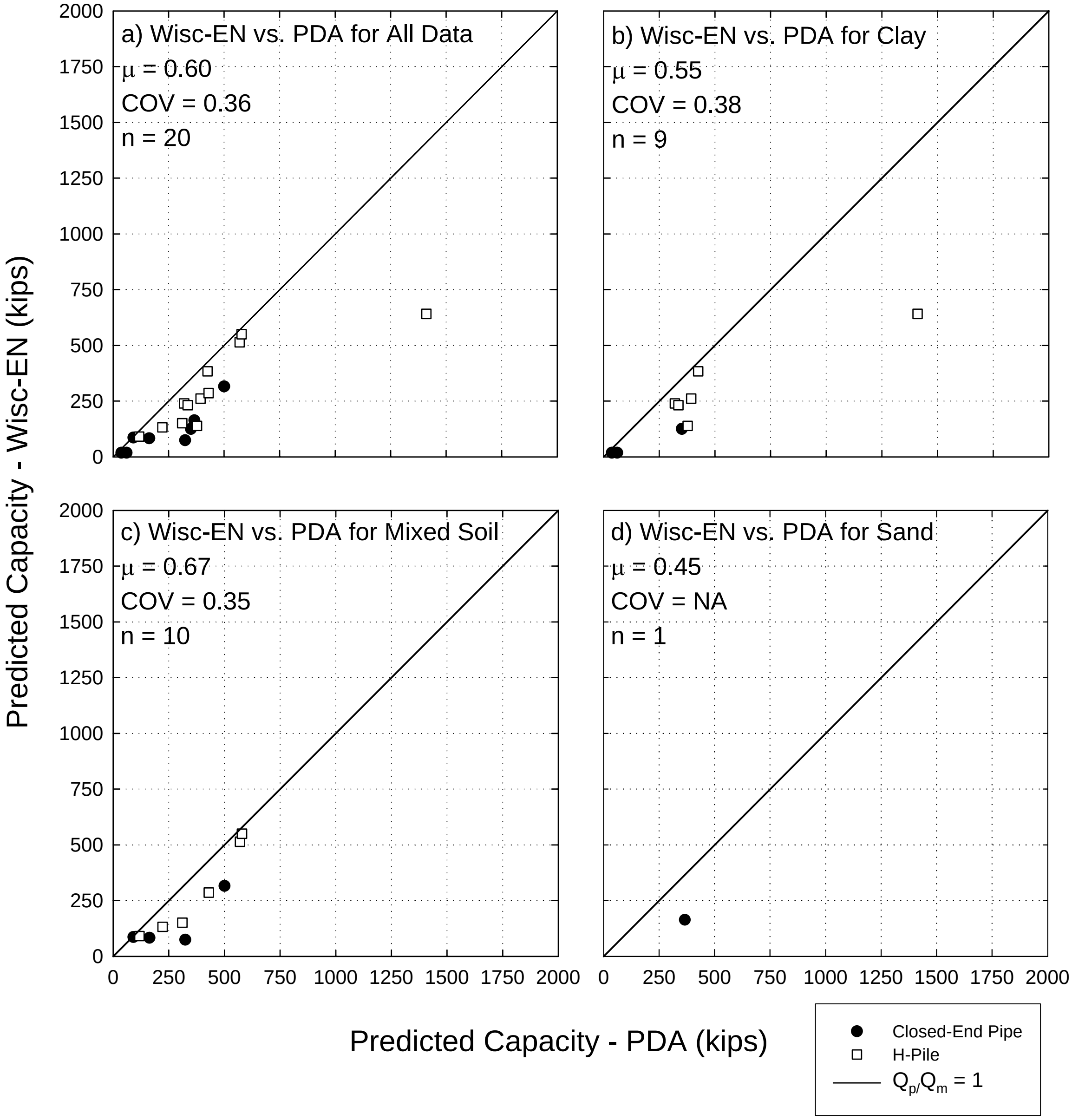


Figure 4.6. Wisc-EN vs PDA Broken Down by Soil Type

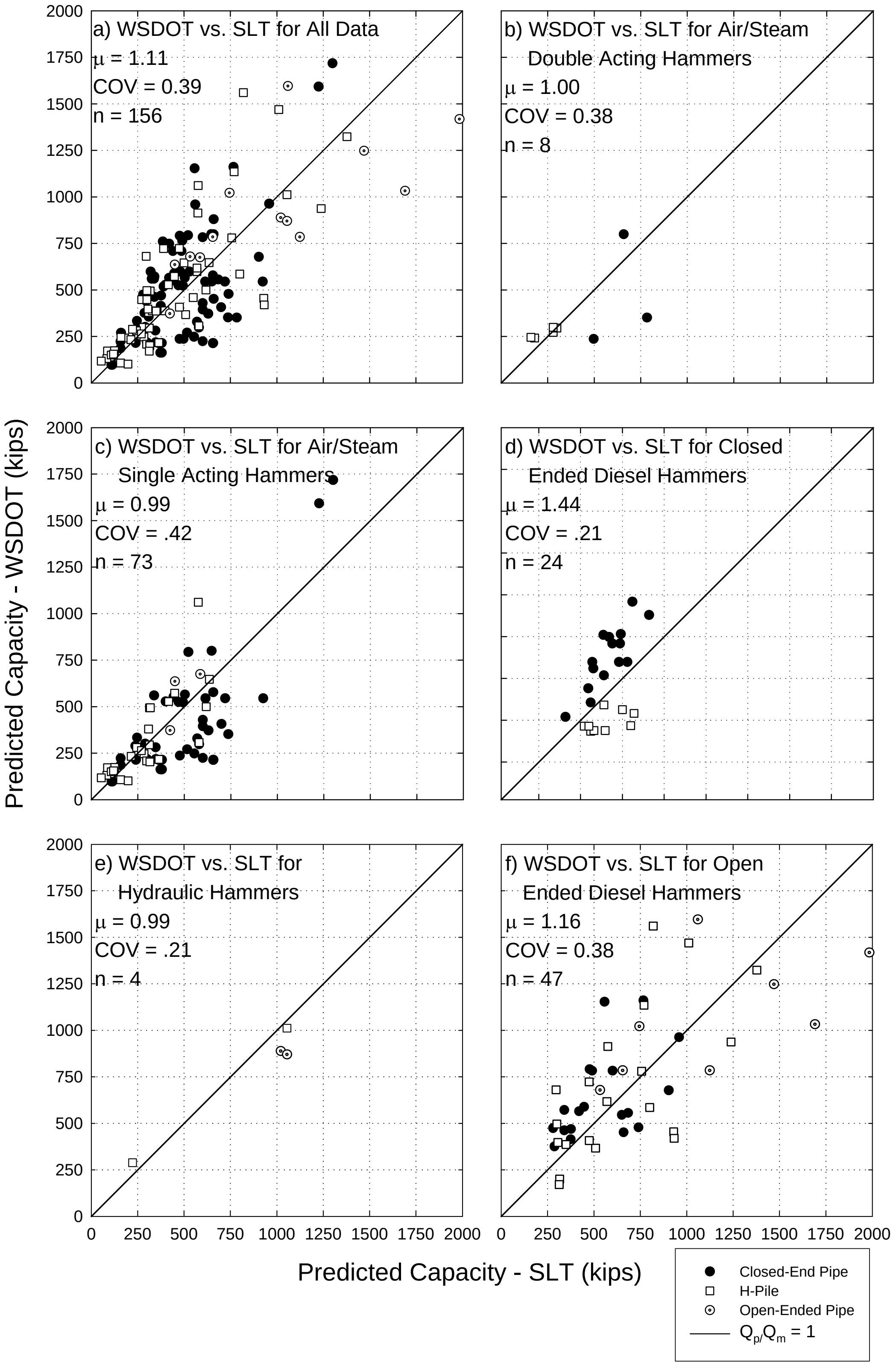


Figure 4.7. WSDOT vs SLT Broken Down by Hammer Type

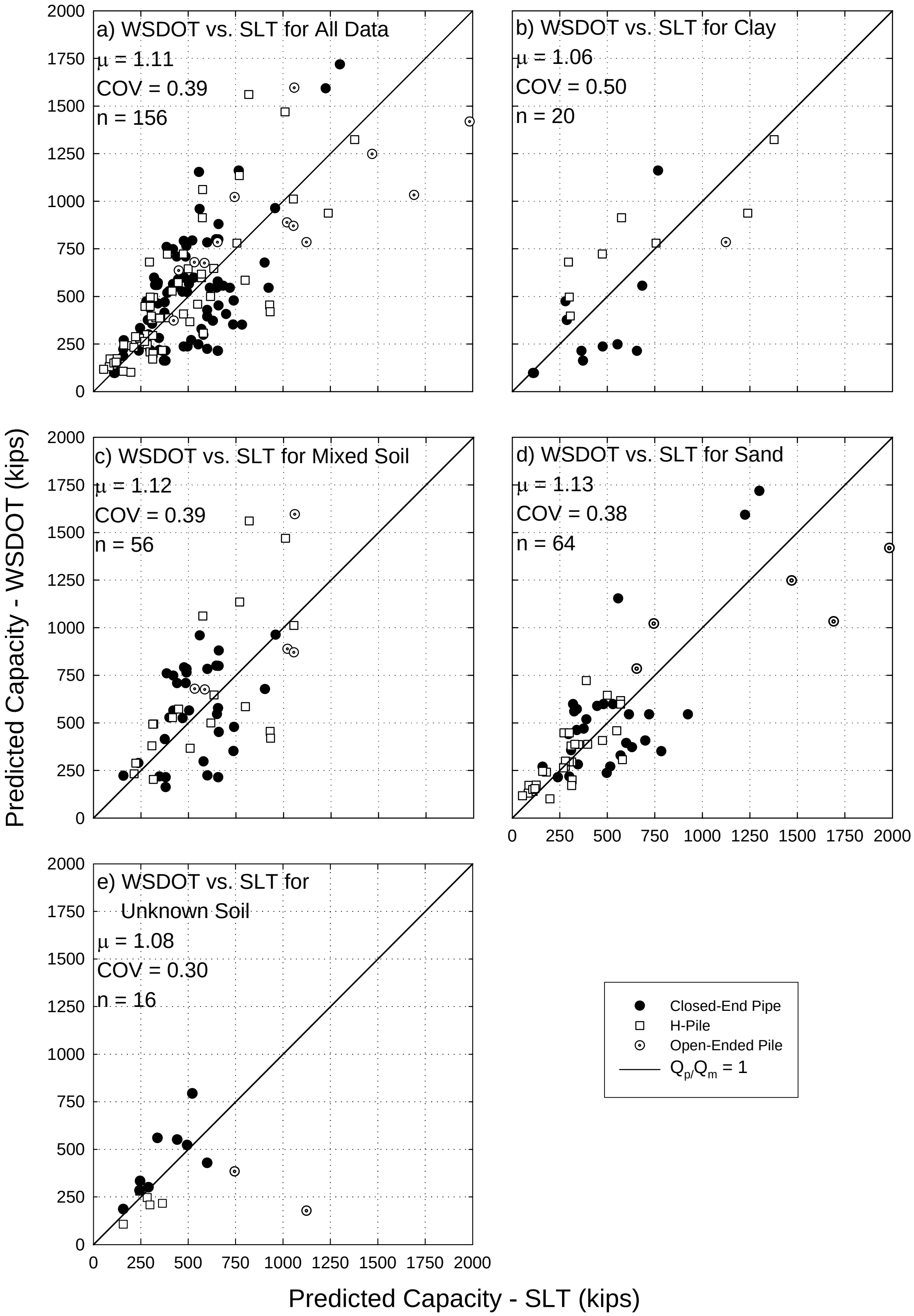


Figure 4.8. WSDOT vs SLT Broken Down by Soil Type

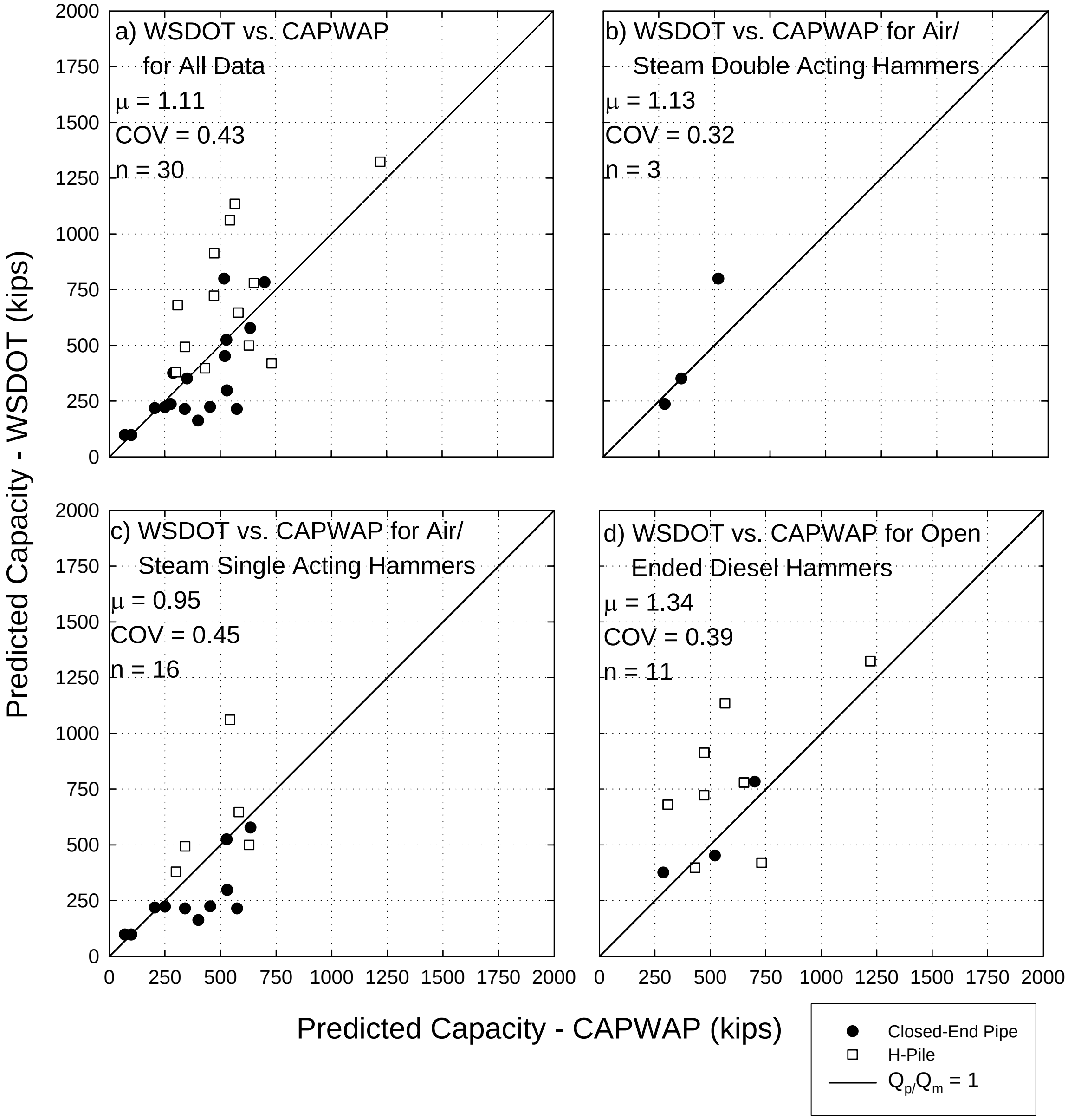


Figure 4.9. WSDOT vs CAPWAP Broken Down by Hammer Type

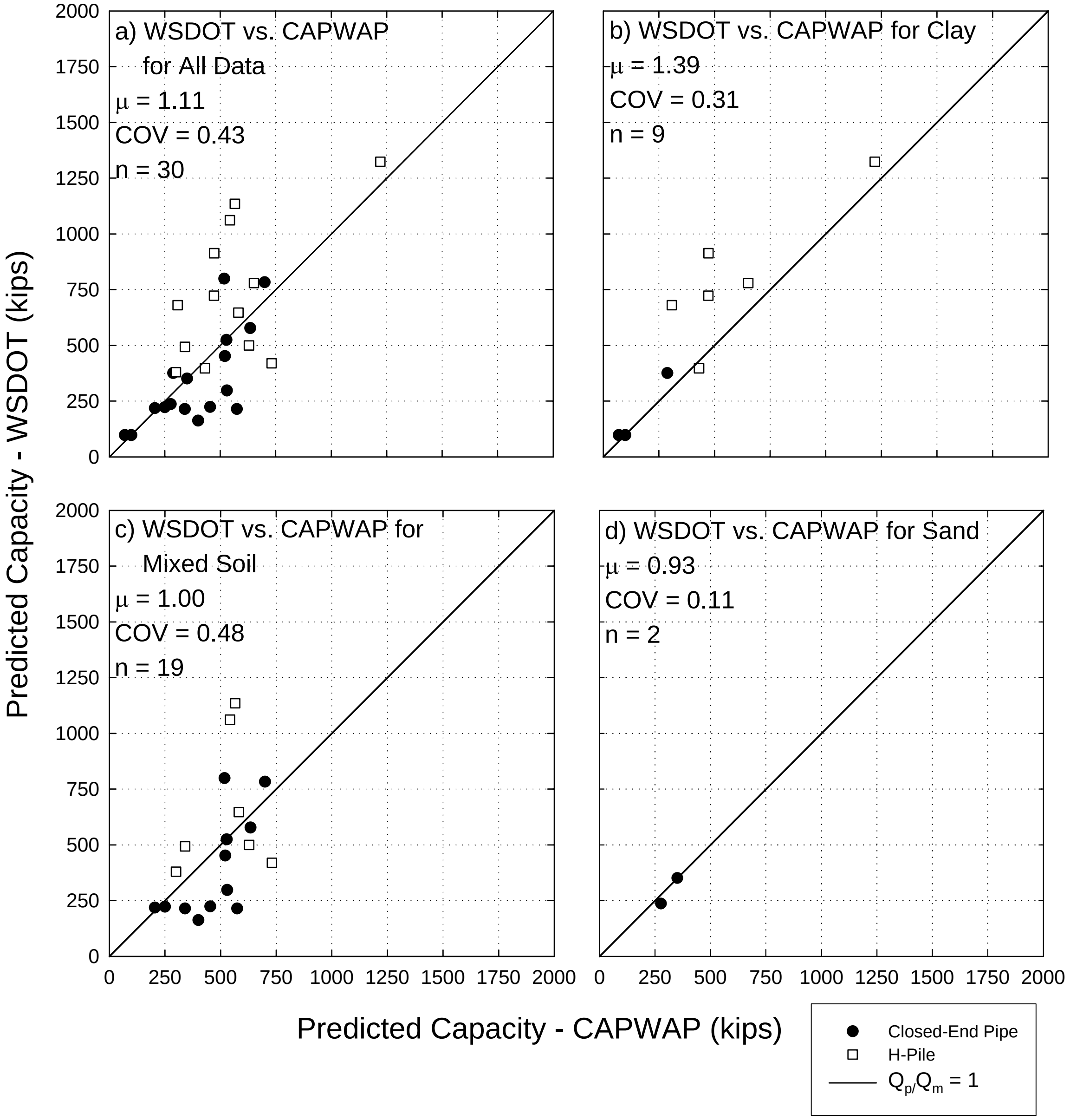


Figure 4.10. WSDOT vs CAPWAP Broken Down by Soil Type

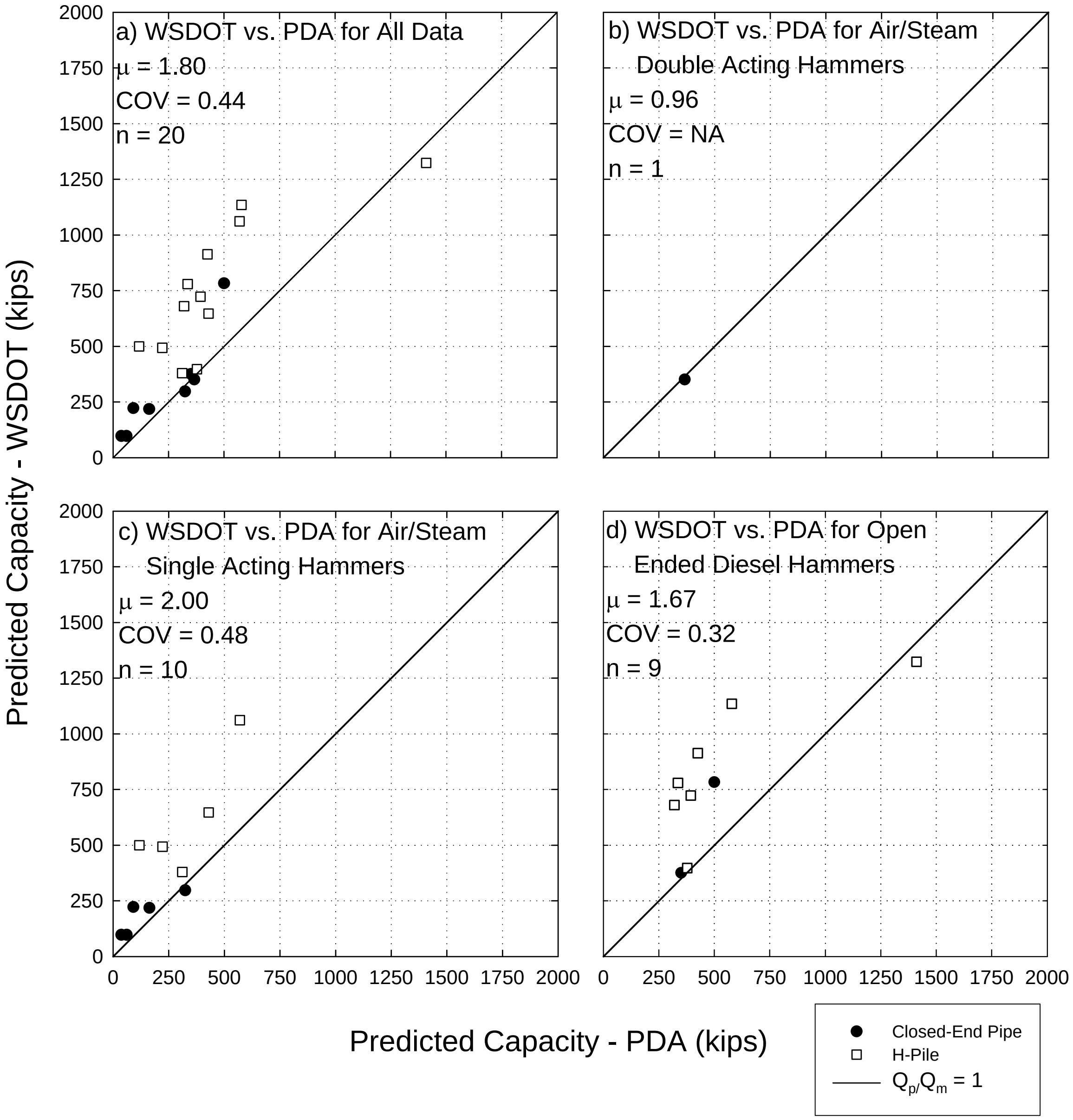


Figure 4.11. WSDOT vs PDA Broken Down by Hammer Type

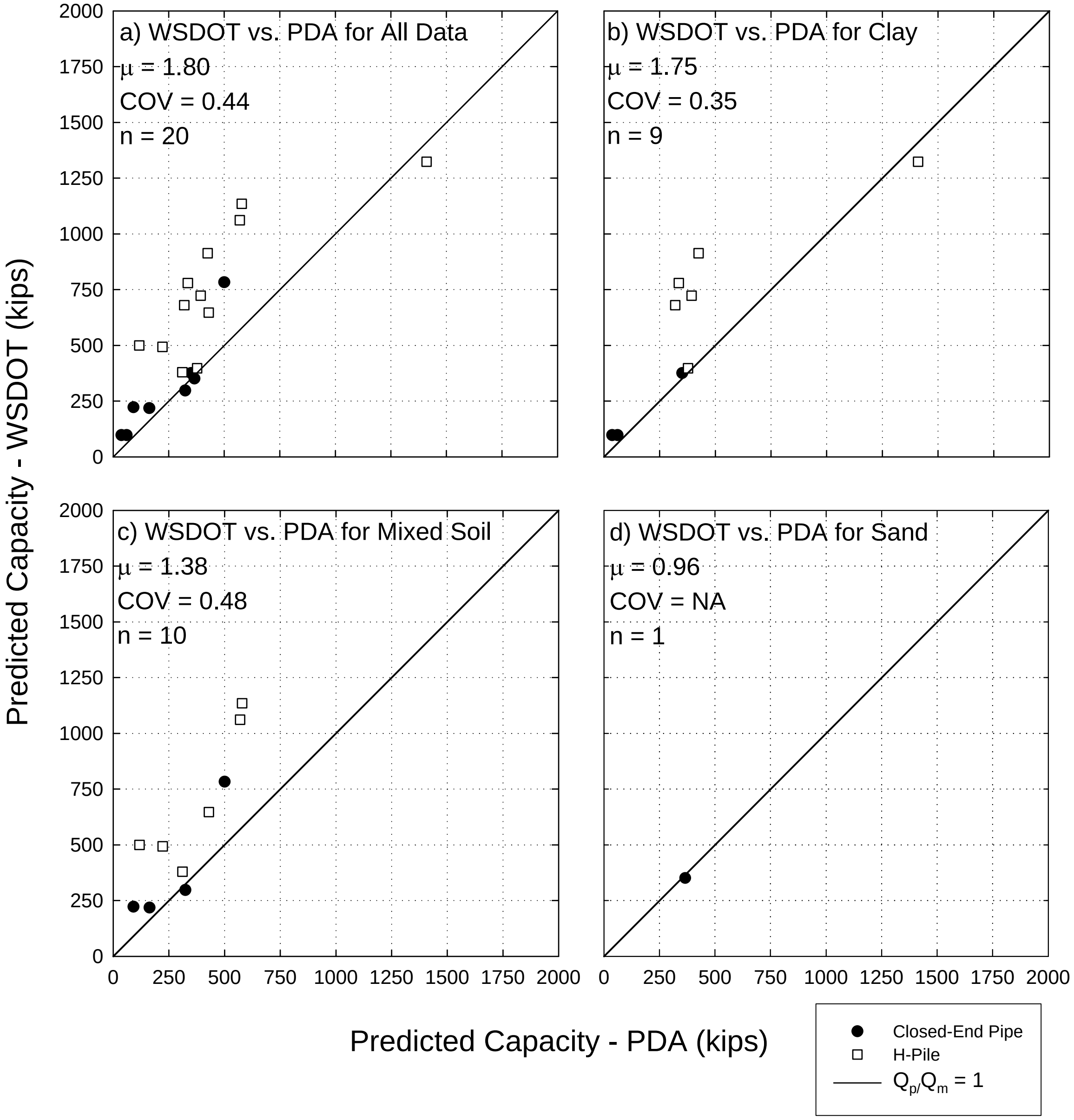


Figure 4.12. WSDOT vs PDA Broken Down by Soil Type

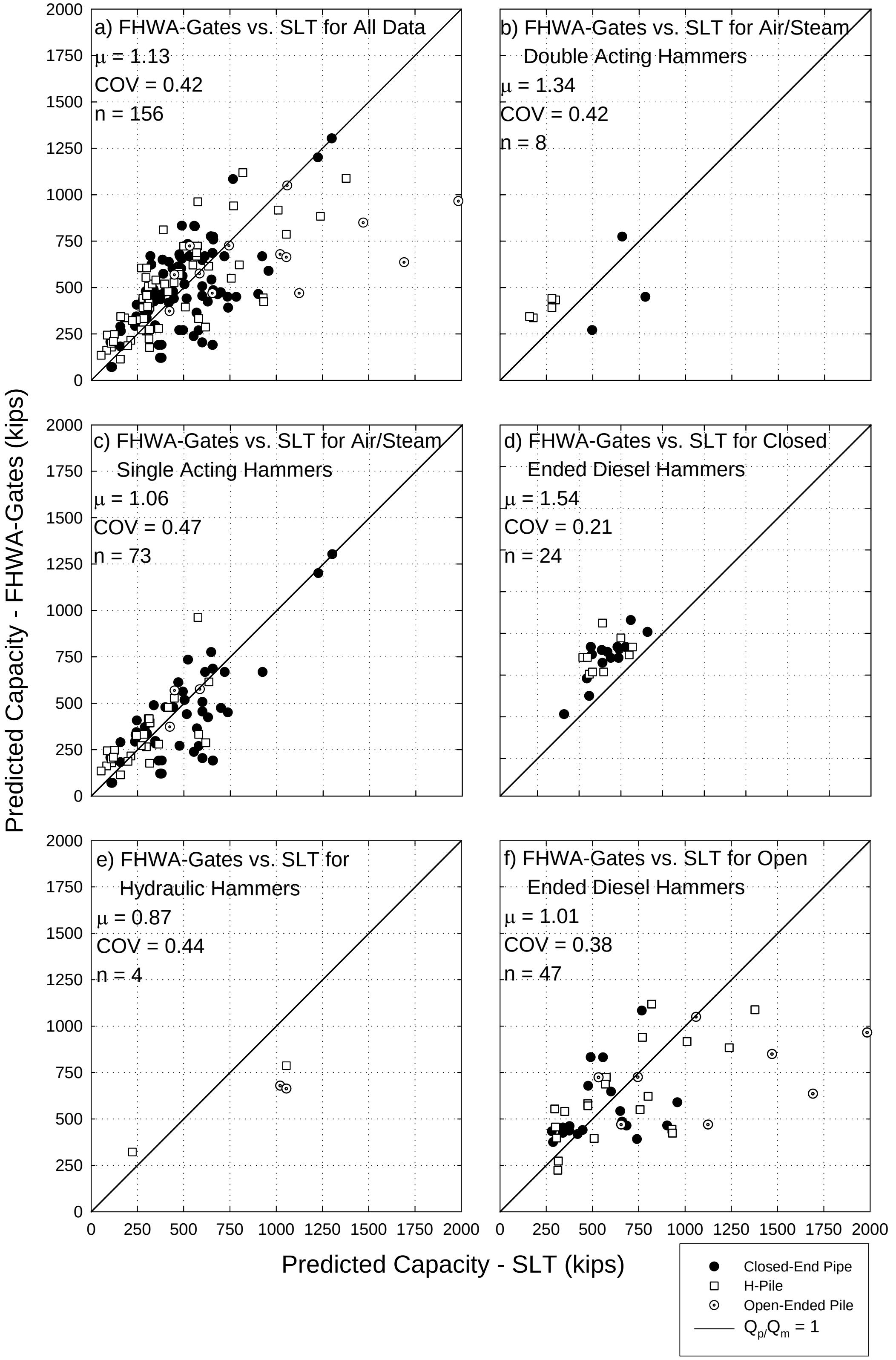


Figure 4.13. FHWA-Gates vs SLT Broken Down by Hammer Type

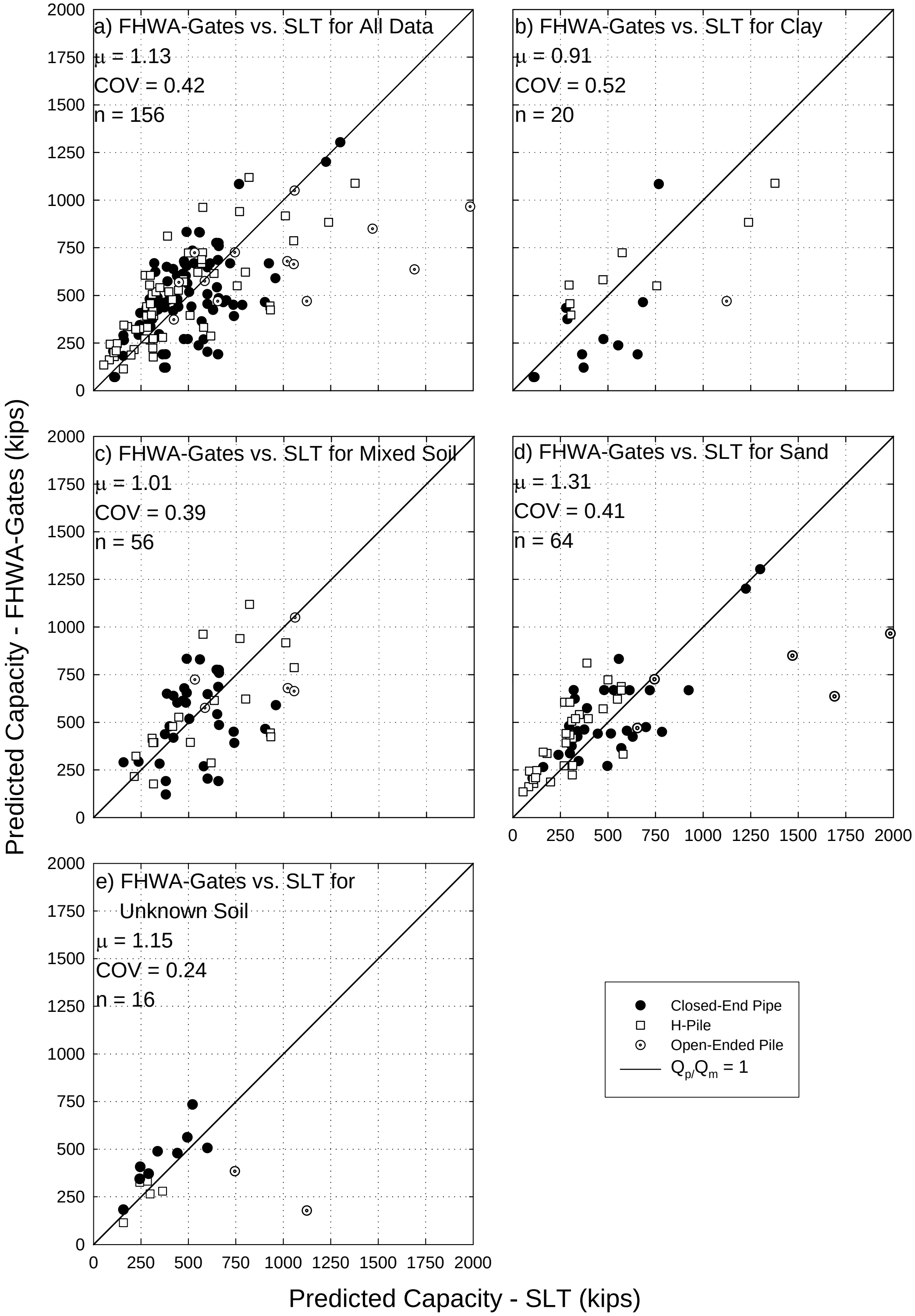


Figure 4.14. FHWA-Gates vs SLT Broken Down by Soil Type

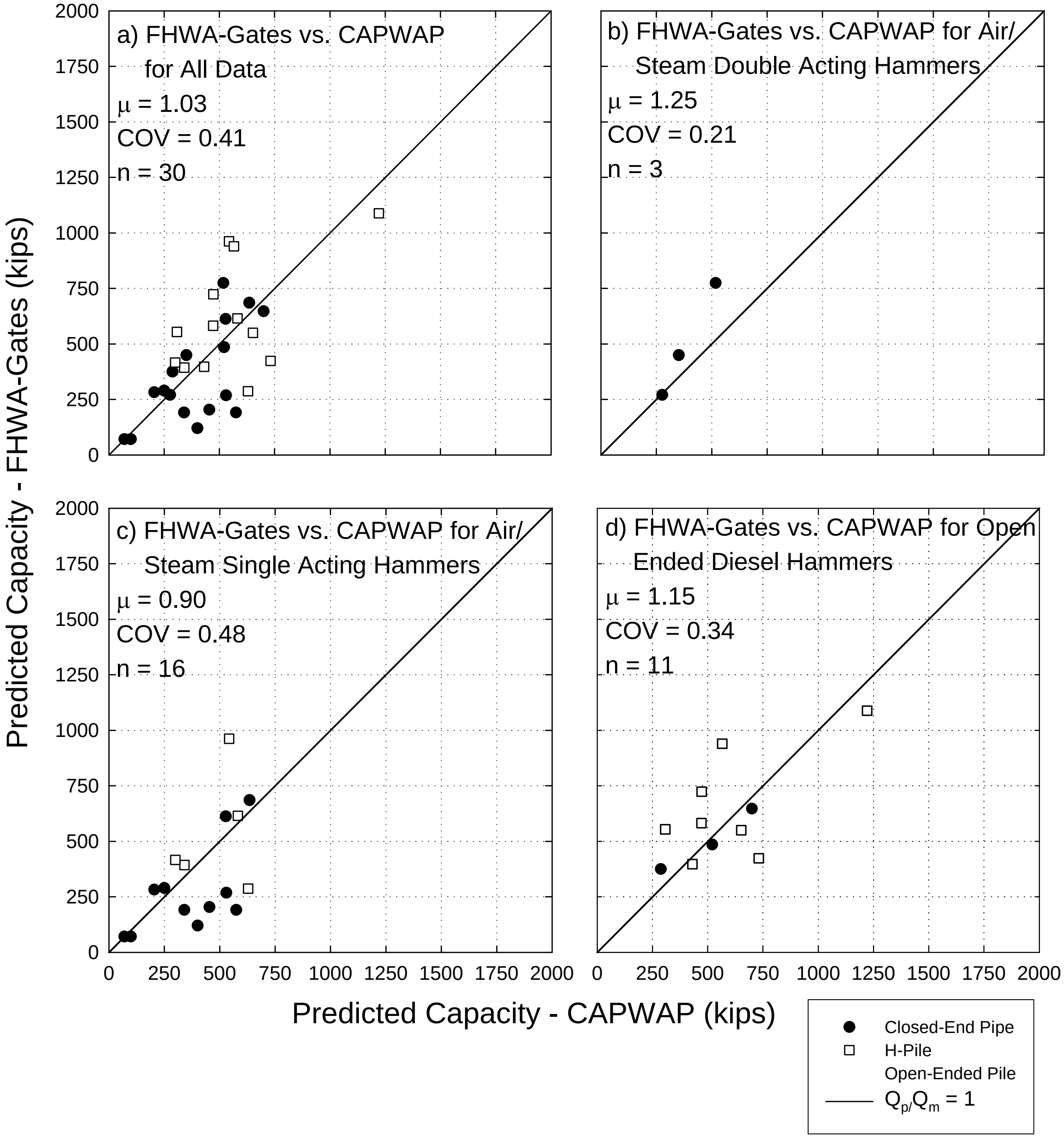


Figure 4.15. FHWA-Gates vs CAPWAP Broken Down by Hammer Type

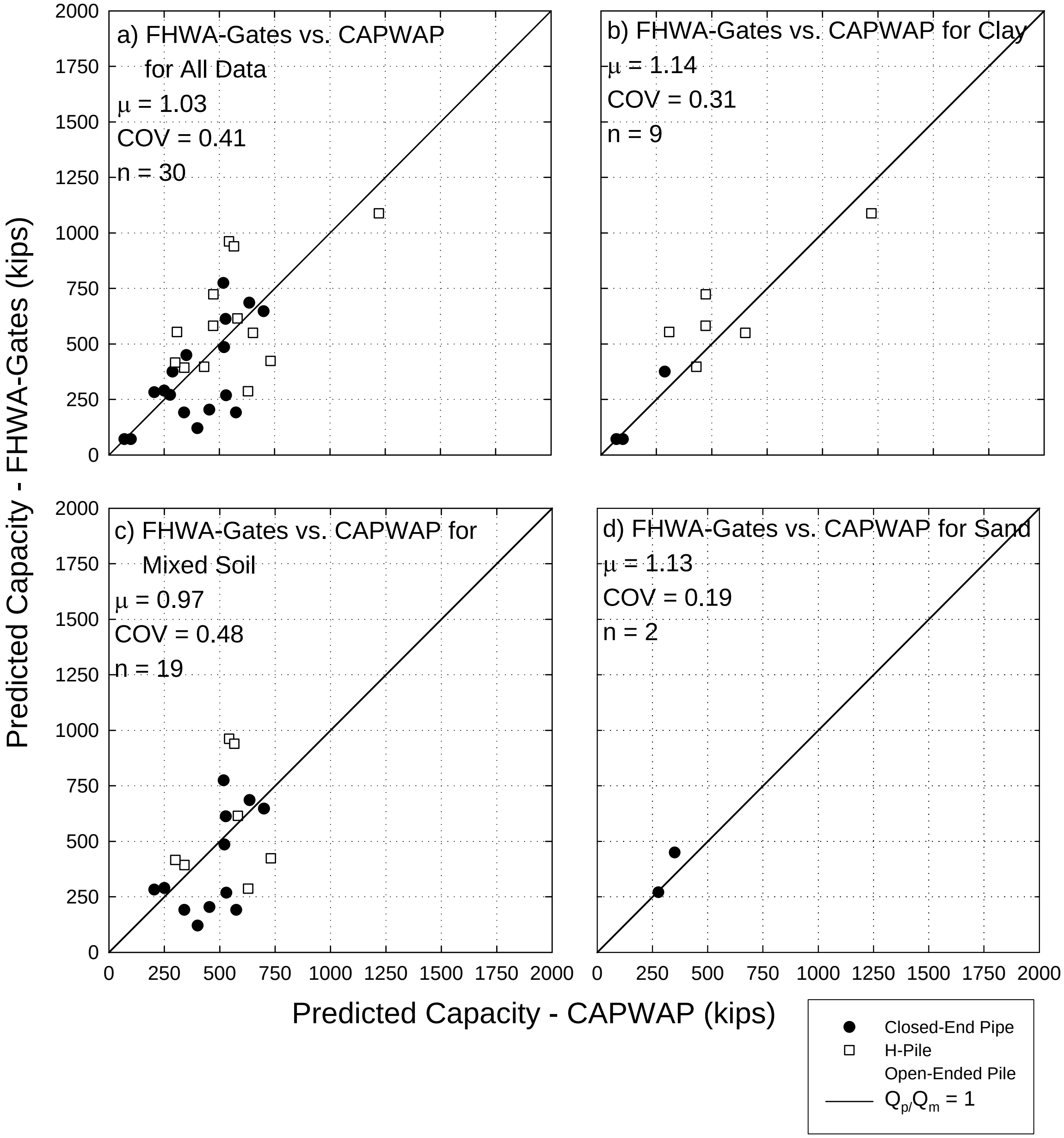


Figure 4.16. FHWA-Gates vs CAPWAP Broken Down by Soil Type

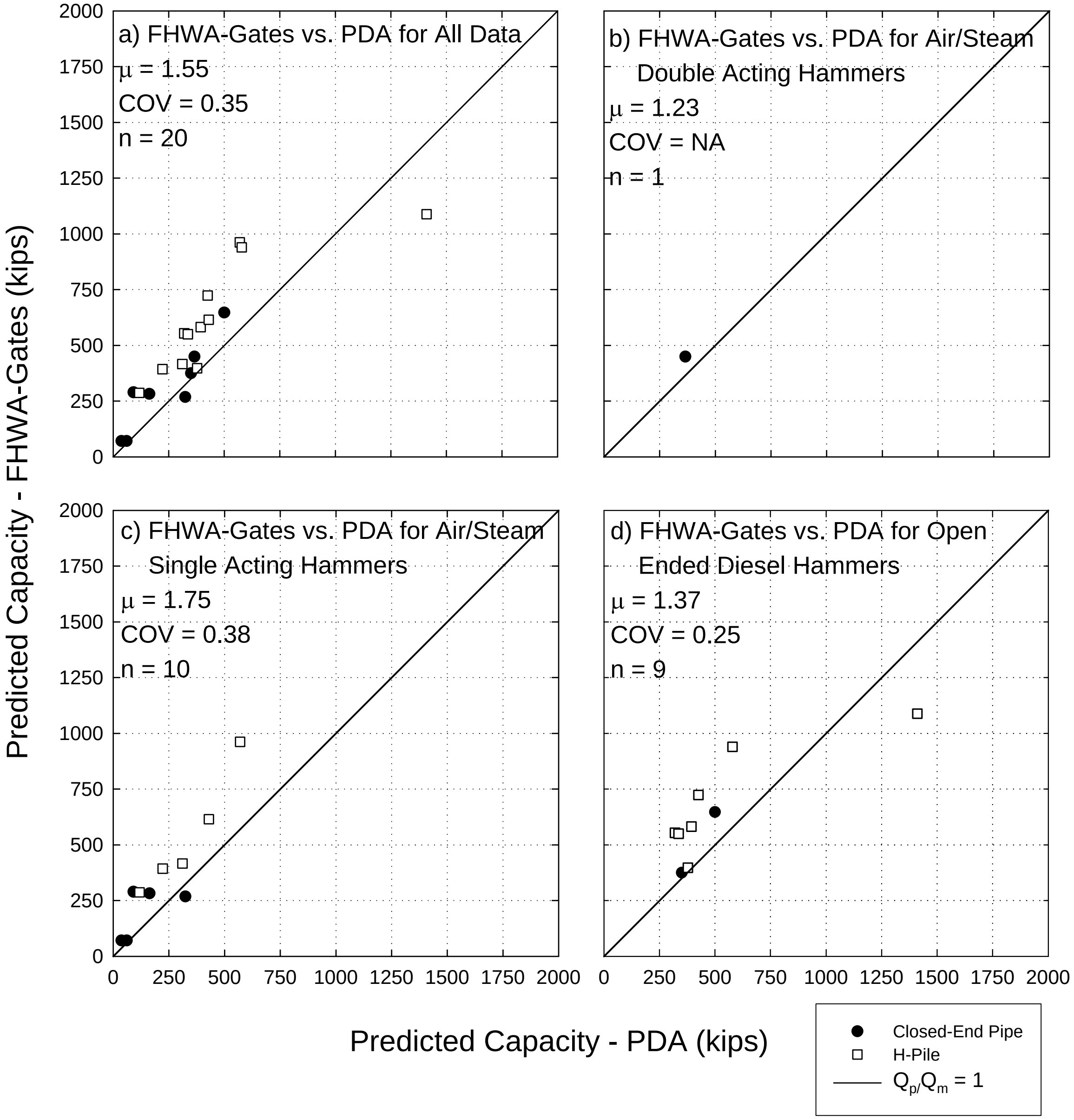


Figure 4.17. FHWA-Gates vs PDA Broken Down by Hammer Type

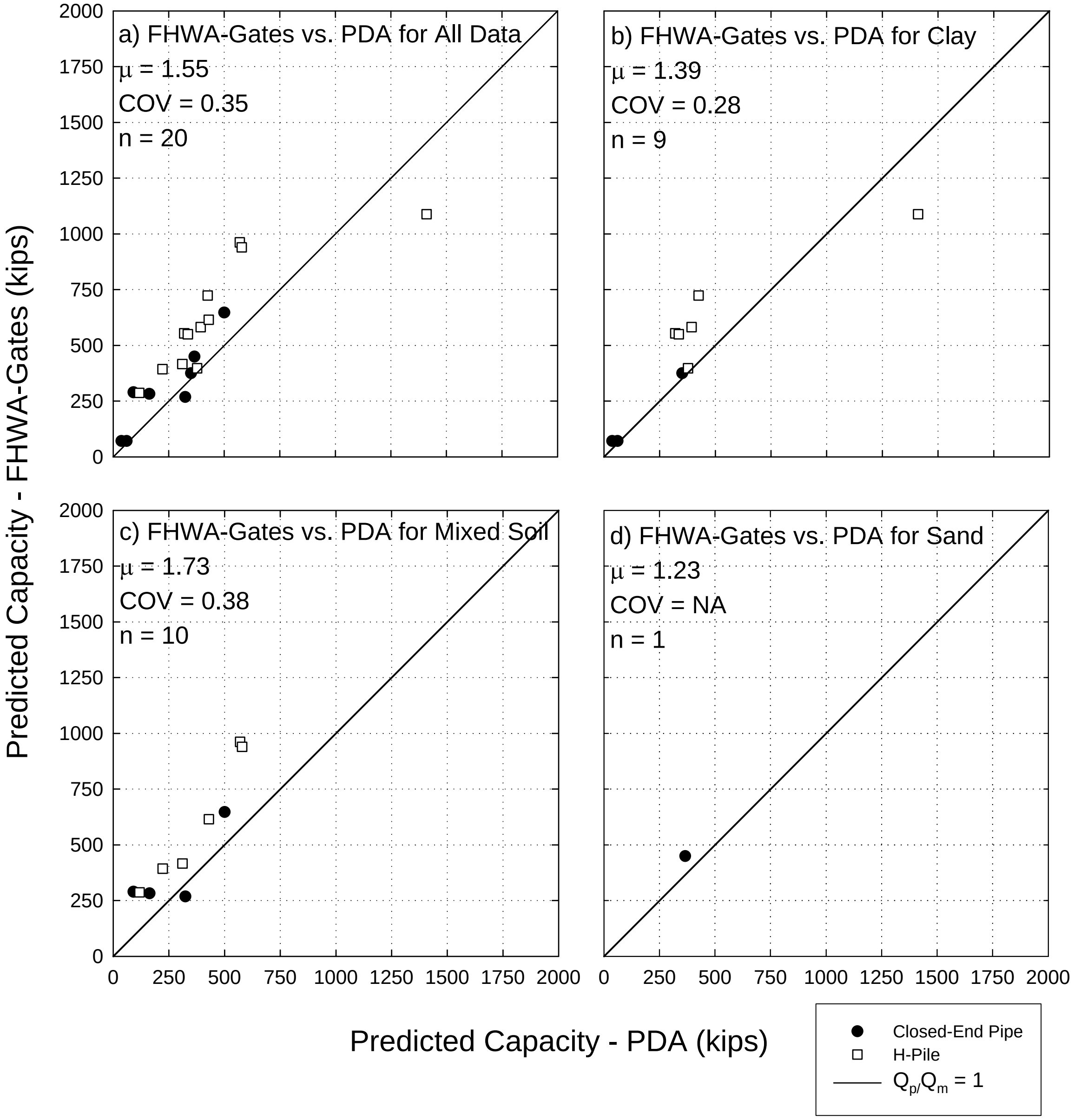


Figure 4.18. FHWA-Gates vs PDA Broken Down by Soil Type

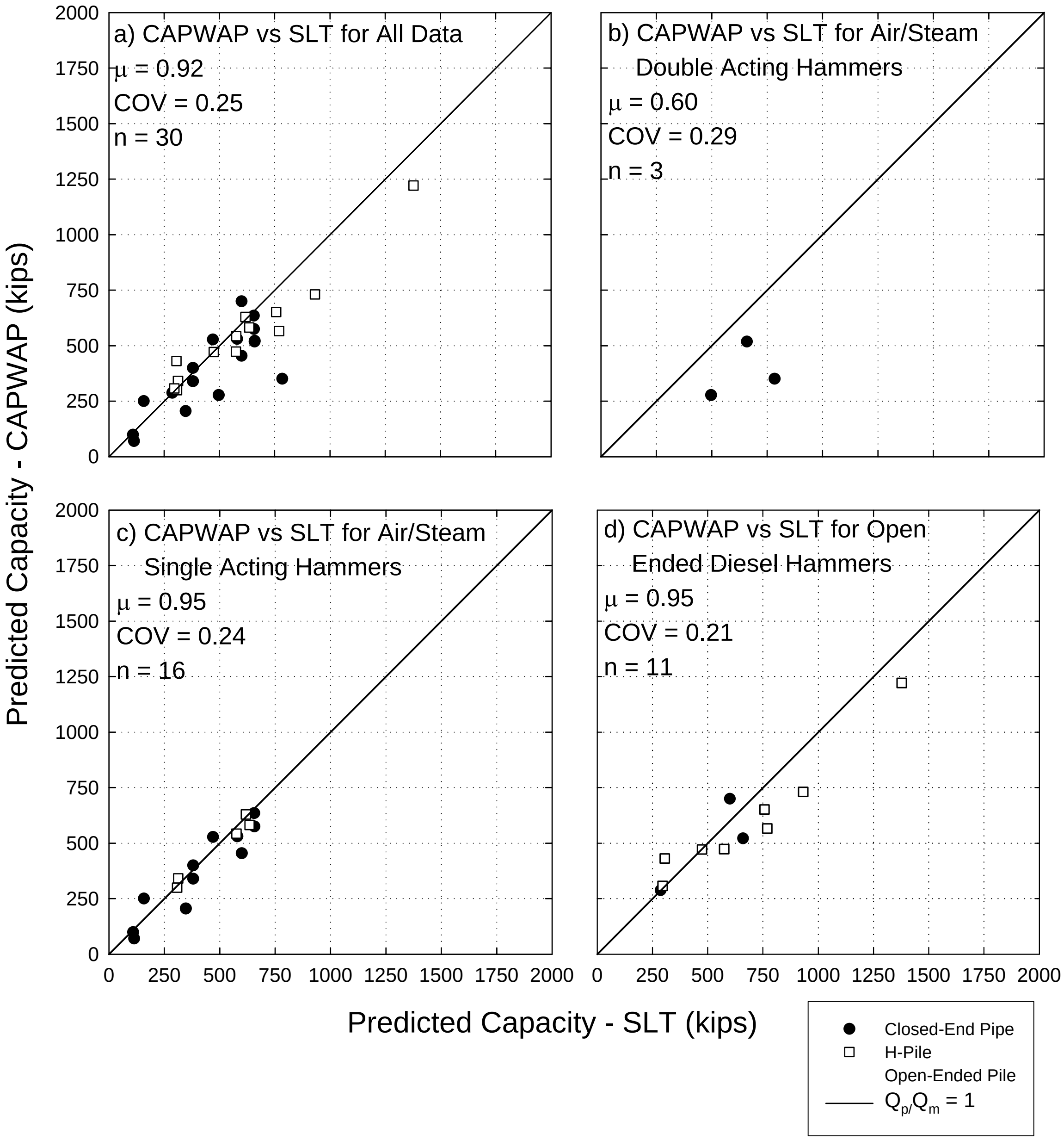


Figure 4.19. CAPWAP vs SLT Broken Down by Hammer Type

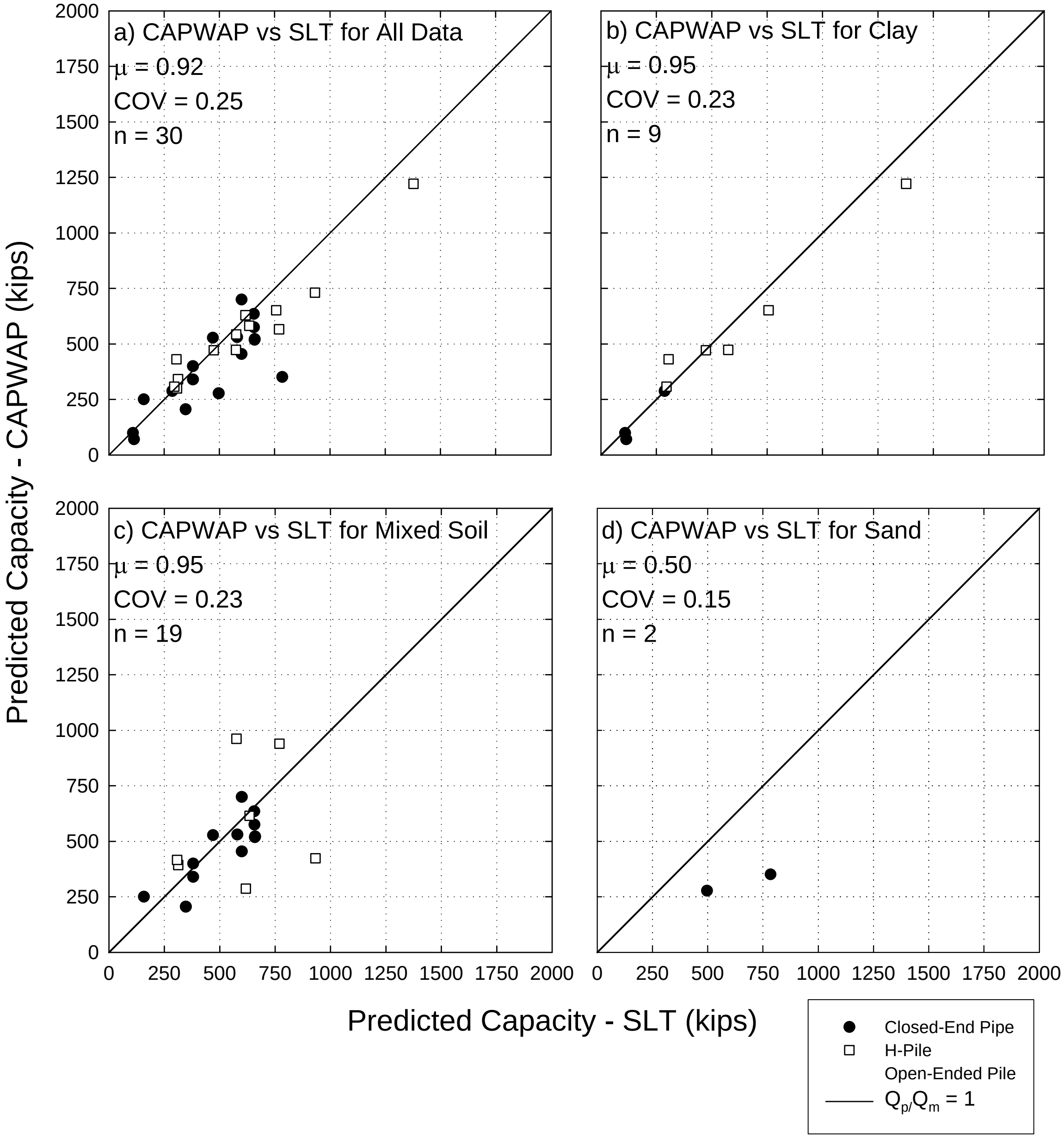


Figure 4.20. CAPWAP vs SLT Broken Down by Soil Type

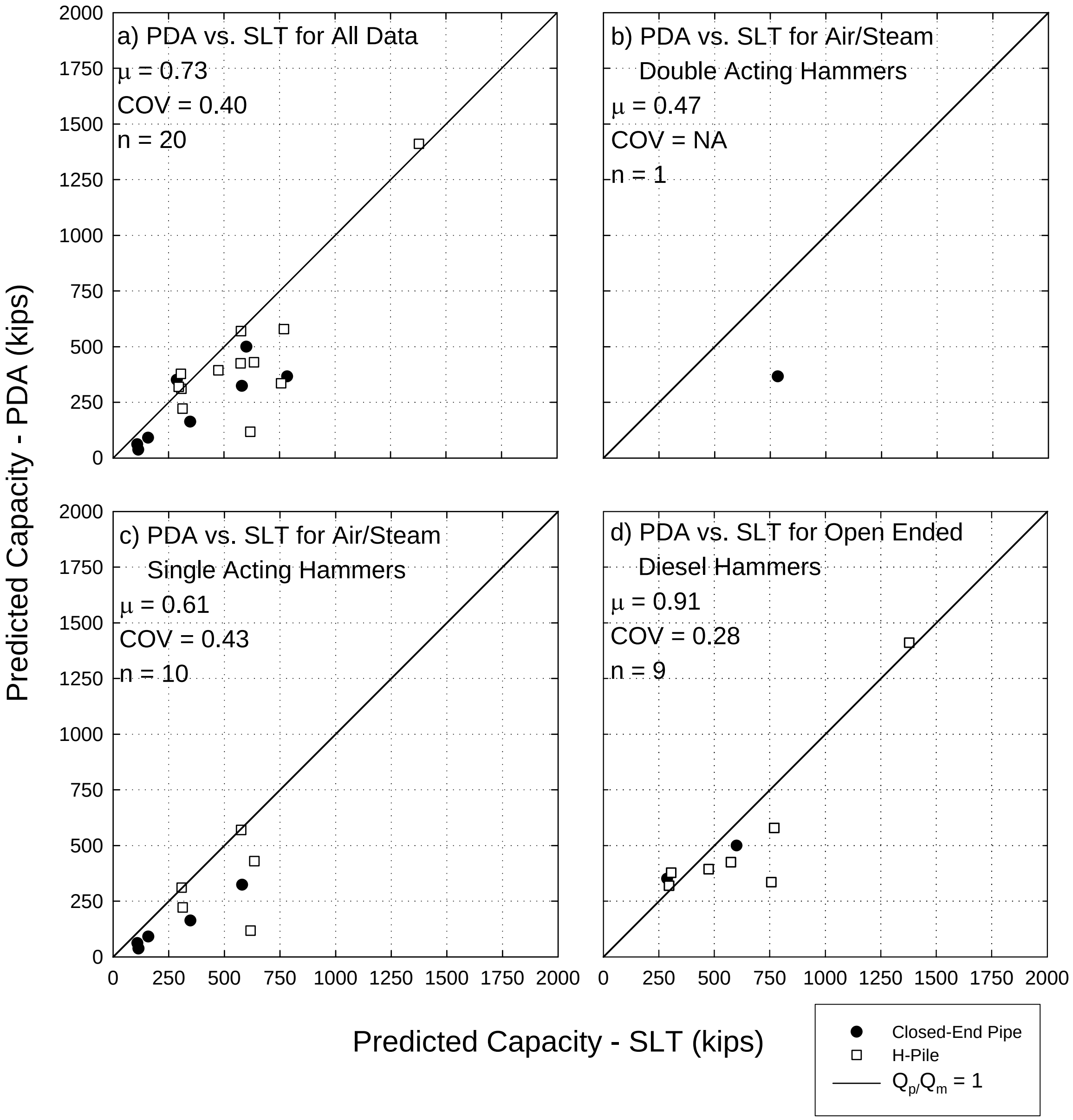


Figure 4.21. PDA vs. SLT Broken Down by Hammer Type

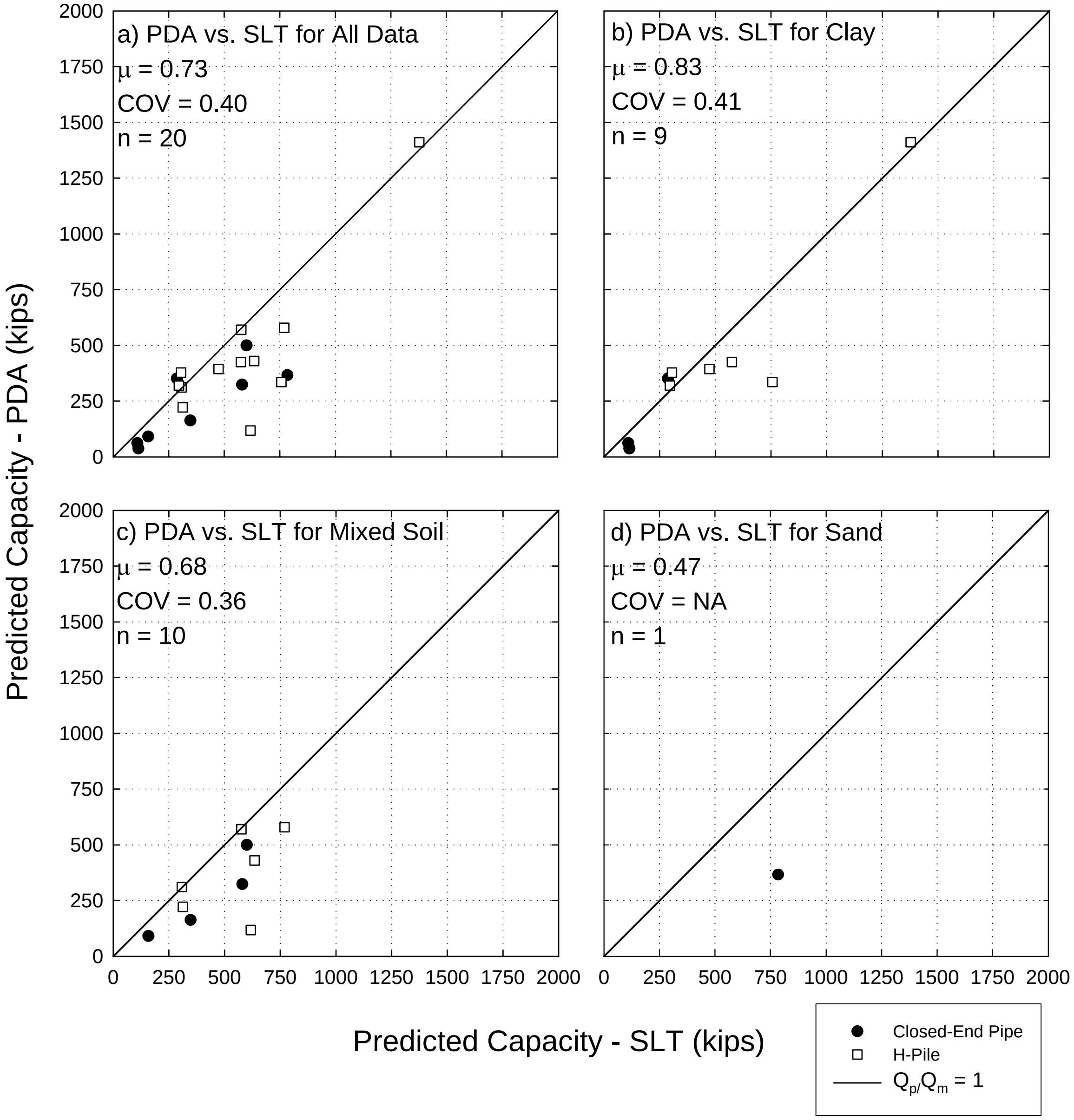


Figure 4.22. PDA vs. SLT Broken Down by Soil Type

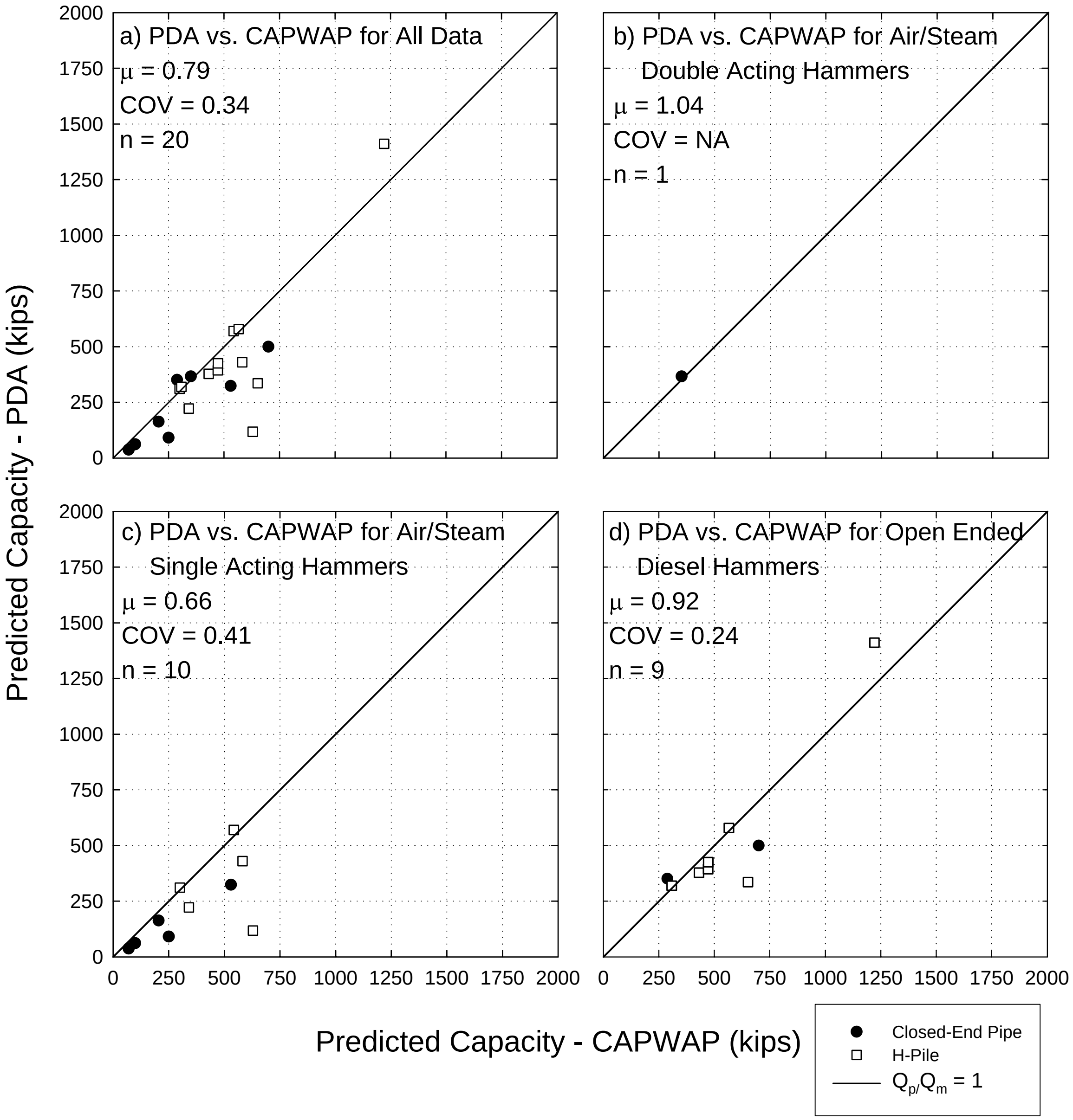


Figure 4.23. PDA vs. CAPWAP broken Down by Hammer Type

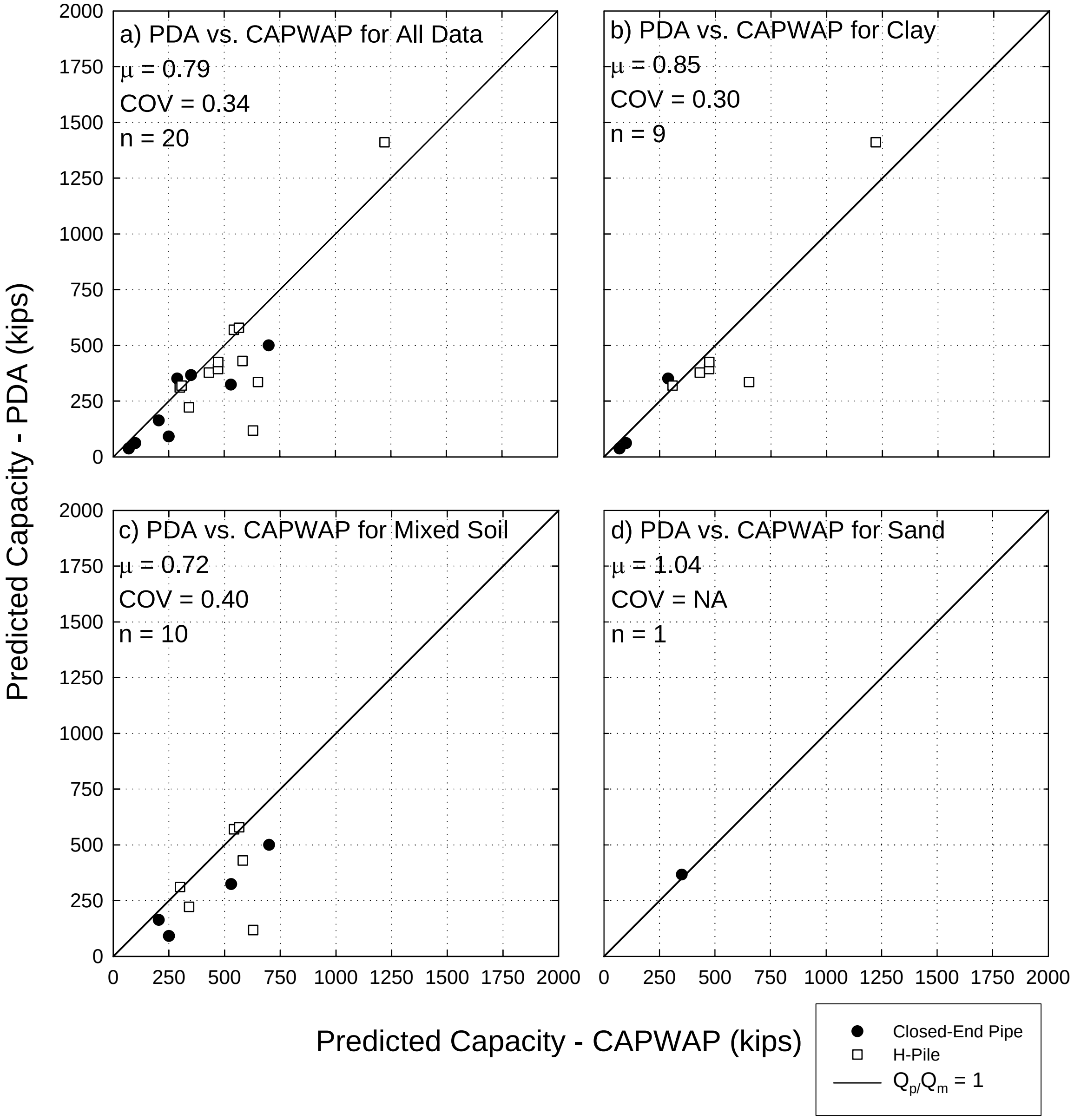


Figure 4.24. PDA vs. CAPWAP broken Down by Soil Type

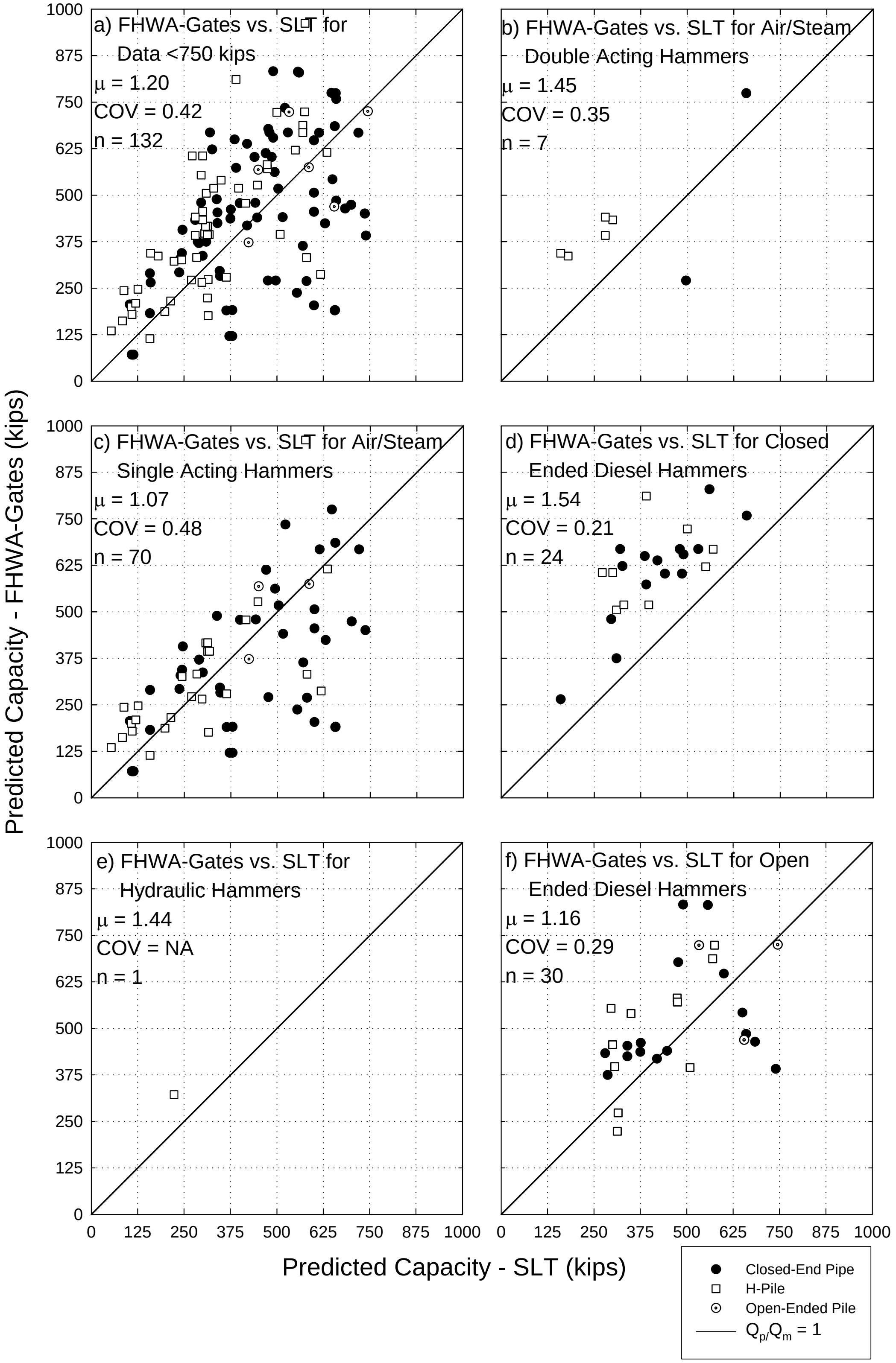


Figure 4.25. FHWA-Gates (<750) vs SLT Broken Down by Hammer Type

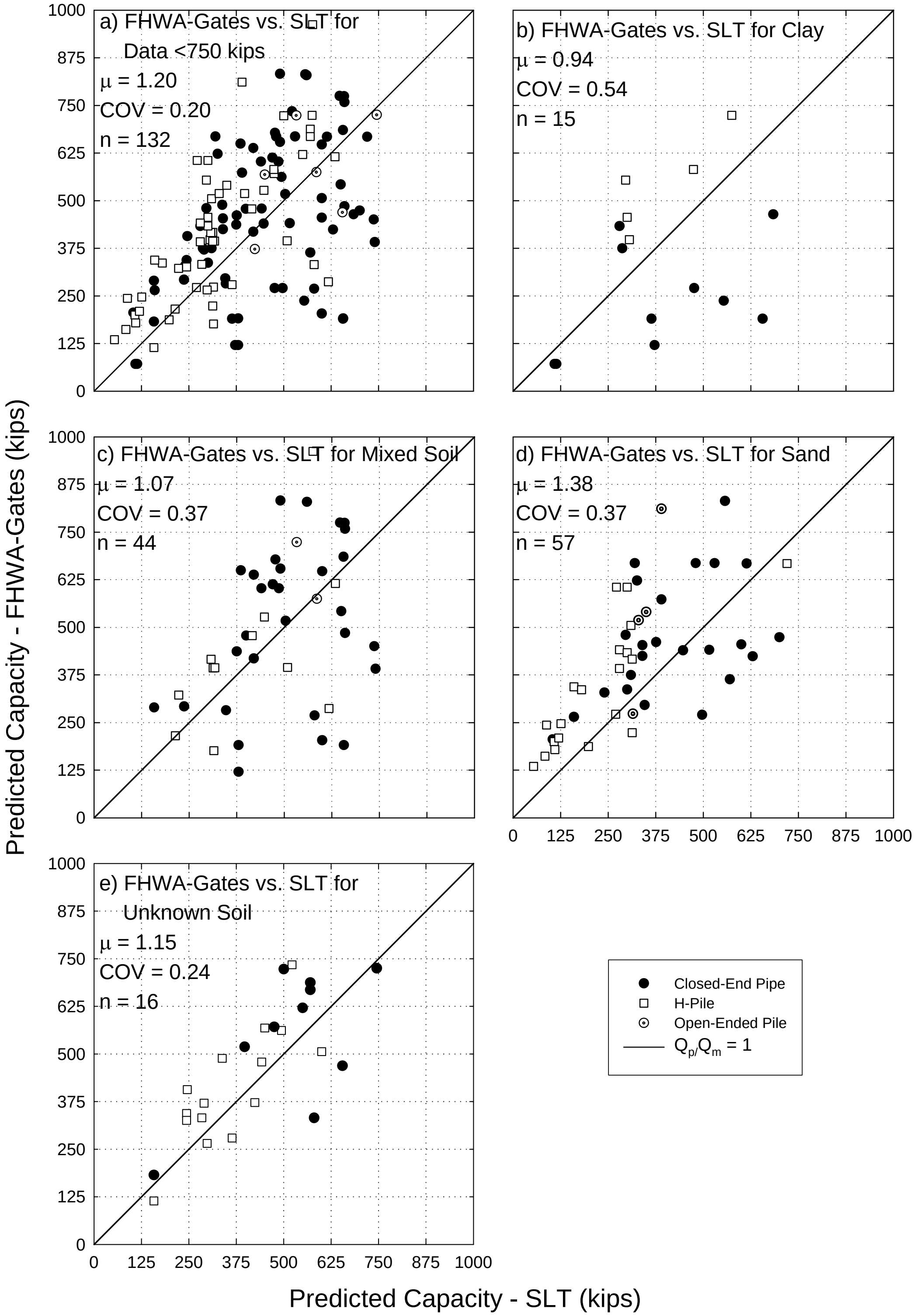


Figure 4.26. FHWA-Gates (<750) vs SLT Broken Down by Soil Type

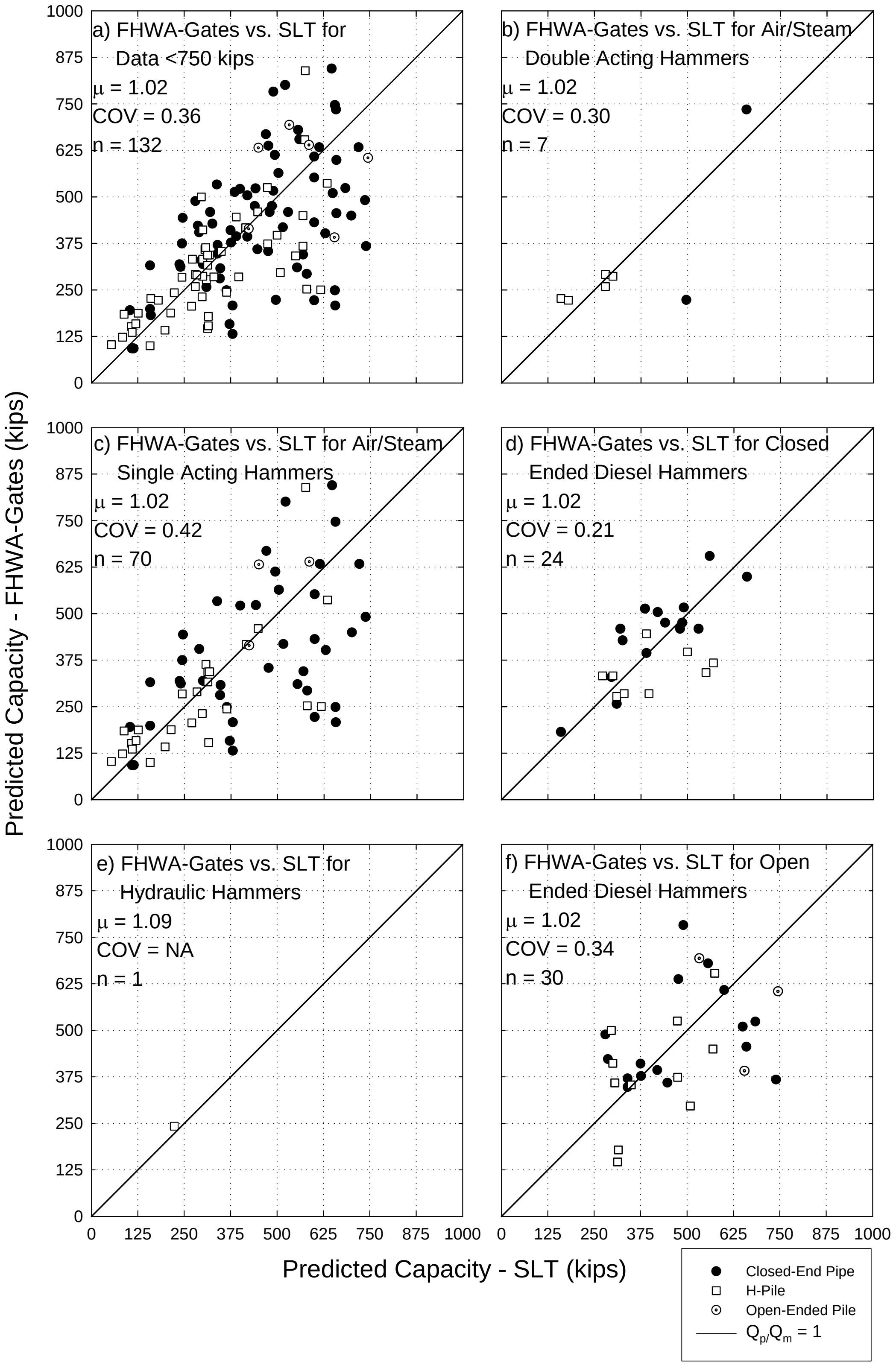


Figure 4.27. FHWA-Gates (corr <750) vs SLT Broken Down by Hammer Type

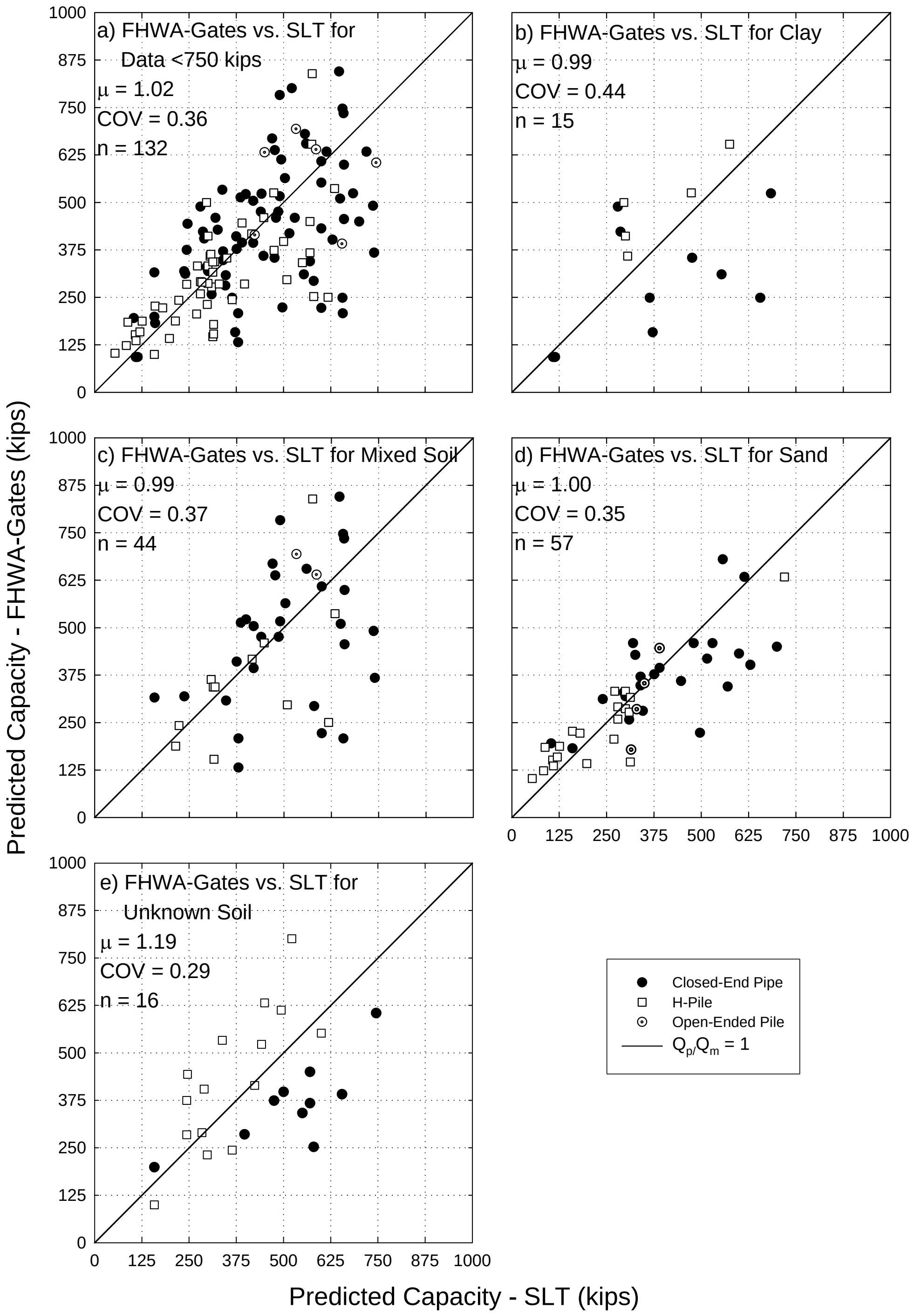


Figure 4.28. FHWA-Gates (corr <750) vs SLT Broken Down by Soil Type

Chapter 5

5.0 PREDICTED VERSUS MEASURED CAPACITY USING THE DATABASE COLLECTED FROM WISCONSIN DOT

5.1 INTRODUCTION

Two databases are used in this report to assess the accuracy with which pile capacities can be determined from driving behavior. The previous chapter focused on the first database which contains static load tests for each pile. The second database contains records for 316 piles driven only in Wisconsin. Data for each pile in this database allows for determining the pile capacity using simple dynamic formulae and PDA (EOD). In some cases, CAPWAP(BOR) predictions are available, and in a few cases, static load tests were conducted.

As presented in Chapter 4, the ratio of predicted capacity (Q_P) to measured capacity (Q_M) is the metric used to quantify how well or poorly a predictive method performs. Statistics for each of the predictive methods are used to quantify the accuracy and precision for several pile driving formulas. Since there are so few static load tests conducted, predictions are compared with PDA and CAPWAP results.

5.2 DESCRIPTION OF DATA

The data analyzed in this report comes from several locations within the State of Wisconsin. Results from a total of 316 piles were collected from the Marquette Interchange, the Sixth Street Viaduct, Arrowhead Bridge, Bridgeport, Prescott Bridge, the Clairemont Avenue Bridge, the Fort Atkinson Bypass, the Trempeauleau River Bridge, the Wisconsin River Bridge, the Chippewa River Bridge, La Crosse, and the South Beltline in Madison. The data used in this report was provided by the Wisconsin Department of Transportation.

The data encompass several different soil types and are classified as sand, clay, or a mixture of the two. Soil that behaves in a drained manner is categorized as sand. Soil that behaves in an undrained manner is identified as clay. The soil type for each pile is classified according to the soil along the sides of the pile and the soil at the tip of the pile. Based on this classification, the soil type along the piles can be divided into five major groups. These groups are:

1) Sand at the Sides and Sand at the Tip
2) Clay at the Sides and Clay at the Tip
3) Mixture at the Sides and Sand at the Tip
4) Mixture at the Sides and Clay at the Tip
5) Mixture at the Sides and Mixture at the Tip.

Other combinations were either absent from the dataset or of insufficient number from which to draw conclusions. All data, regardless of the soil conditions at the tip and sides of the pile, is also analyzed as one dataset.

There are thirty piles included in the analysis of all of the data that did not fall into one of the five major groups. The soil conditions for the majority of these piles could not be classified due to a lack of information about the soil present at the tip of the pile. For the purposes of the analysis, the soil along the sides of a pile is called mixed if neither sand nor clay makes up a 70% majority of the soil present. Soil at the tip of a pile is called mixed if it could not be determined whether the soil is drained or undrained. For example, a silty sand at the tip of a pile would be classified as mixed.

The piles included in this report are closed-end pipe piles, open-ended pipe piles, and H-Piles. A summary of the data is presented in Table 5.1, while a summary of the character of the data is given in Table 5.2. The closed-end pipe piles range in diameter from 10.75” to 16”. The sizes are fairly evenly distributed throughout this range. All of the open-ended pipe piles have a diameter of 9.5”. Forty-two piles are HP 12x53 and three are HP 14x73. The average length of a pile is about 97 feet. However, lengths vary from 32.7 to 266 feet. The majority of the piles were driven with diesel hammers;

however, 27 of the 316 piles were driven using air/steam hammers, and three were driven with a hydraulic hammer.

The capacity of seven of the 316 piles could not be determined using dynamic formulae. Because the piles' set or the hammer stroke at the end of driving could not be determined. Three of these seven piles were driven using a hydraulic hammer, and blow frequency was reported, but not hammer stroke. A correlation between blow frequency and hammer stroke could not be determined reliably, so this data was insufficient to determine capacity with a dynamic formula. Static load tests were performed on the three piles driven with a hydraulic hammer, and the results of the static load tests are included in the database.

5.3 WISC-EN AND FHWA-GATES COMPARED WITH PDA-EOD

The predicted capacity for all of the piles in the database was determined using the Wisc-EN formula and the FHWA-Gates formula. It should be noted that the Wisc-EN Formula includes a built-in factor of safety of six. The predicted capacity is therefore an allowable capacity. The FHWA-Gates formula does not have a built-in factor of safety, and its prediction is an ultimate capacity. Also, the predicted ultimate capacity of each pile as determined by PDA measurements at the end-of-driving was recorded in the database.

The Wisc-EN capacity vs. the PDA-EOD capacity is plotted in Figure 5.1. The relationship is shown for all data, as well as for the five major soil groups. The value of the average Wisc-EN/PDA-EOD capacity ratio is 0.72. This means the Wisc-EN formula predicts an allowable capacity less than the PDA-EOD ultimate capacity, as would be expected. The COV for the data is 0.44. On each graph, a solid line is drawn at a slope of 1:1 to illustrate perfect agreement between the methods. A data point below this line indicates the Wisc-EN formula allowable capacity is less than the PDA-EOD ultimate capacity and a point above the line indicates the Wisc-EN allowable capacity is greater than the PDA-EOD ultimate capacity. The mean, COV and number of data points for each graph are reported in Table 5.3.

A plot of capacity predicted by the FHWA-Gates formula vs. the PDA-EOD capacity is shown in Figure 5.2. The value of the average FHWA-Gates/PDA-EOD capacity ratio is 1.79. This means the FHWA-Gates method tends to predict a higher capacity than the PDA-EOD. The COV of the data is 0.46. As in Figure 5.1, a line showing perfect agreement between the two methods is shown. The mean, COV, and number of data points for each graph are reported in Table 5.4.

The average FHWA-Gates/PDA-EOD capacity ratio is greater than unity, while the average Wisc-EN/PDA-EOD capacity ratio is less than unity. The latter is expected, as the Wisc-EN Formula predicts an allowable capacity, which should always be less than the ultimate capacity. Both datasets have similar amounts of scatter (COV). In sands, when the pile capacity is small (less then 250 kips), the Wisc-EN allowable capacity, with a factor of safety of 6, is similar to the ultimate PDA-EOD capacity. The value of the Wisc-EN/PDA-EOD capacity ratio becomes less than unity as predicted capacity increases. For piles driven through a mixture of soils into sand, the Wisc-EN/PDA-EOD capacity ratio is less than 1, but there is a small amount of scatter within the data. The FHWA-Gates Formula, when used for piles driven through a mixed soil profile into sand, appears to agree fairly well with the PDA-EOD predictions at capacities above 250 kips.

Based purely upon comparing the Wisc-EN Formula and FHWA-Gates Formula to PDA-EOD predicted capacity, the FHWA-Gates Formula appears to offer no real improvement in accurately predicting capacity. The amount of scatter between the two dynamic formulae is almost identical, and the bias of the FHWA-Gates Formula is larger than that of the Wisc-EN Formula.

5.4 WISC-EN AND FHWA-GATES COMPARED TO PDA-BOR

The ultimate capacity of a pile is time-dependent. Typically, the capacity of a pile will increase with time (pile setup). Dynamic formulae, such as Wisc-EN and FHWA-Gates, empirically consider time effects because they have relied on static load tests to develop their formulations. The PDA predicts the capacity at the time of driving, and therefore does not consider time effects. One method to consider time effects is to drive the pile, and then redrive the pile several days (to weeks) later. PDA measurements conducted during the beginning of restrike (BOR) provide improved estimates of static pile capacity because they include effects of setup. Accordingly, it is worthwhile to investigate how well the dynamic formulae (and PDA-EOD) agree with capacities predicted from restrike behavior.

Pile restrikes were performed on 93 of the piles in the database an average of 24 days after the end of driving. All but one of these tests was performed at the Marquette Interchange; the other one is from Arrowhead Bridge. PDA measurements were taken at both the end-of-driving and the beginning-of-restrike. The PDA-EOD capacity vs. PDA-BOR capacity is plotted in Figures 5.3 to 5.5. All but two of the piles gained capacity between the end-of-driving and the beginning-of-restrike. PDA predicted a significant loss of capacity between the end-of-driving and beginning-of-restrike for only one pile, Pile IPS-03-12 (Figure 5.3). No definitive reason for this observation was offered. CAPWAP predicted an increase in capacity of the same pile, and thus, the PDA-BOR results are considered herein to be an anomaly.

The average PDA-EOD/PDA-BOR capacity ratio is 0.60 (Table 5.5). This means that at the time of restrike, a pile had, on the average, gained 67% more capacity. The restruck piles can be divided into two categories, those restruck a short time after the end-of-driving (a few days), and those restruck after a longer time lapse (about six weeks).

The first category includes 40 piles that were restruck an average of 2.5 days after the end-of-driving. The average PDA-EOD/PDA-BOR capacity ratio for these piles is 0.72. Between the end-of-driving and beginning-of-restrike, the piles had gained an average of 39% more capacity.

The 53 piles in the second category were restruck an average of 41 days after the end-of-driving. The average PDA-EOD/PDA-BOR capacity ratio is 0.46. This means the piles gained an average of 117% more capacity.

The discussion below is based on the average time after end-of-driving and average increase in capacity for all piles analyzed. From the above discussion, pile capacity can increase for some time after the end-of-driving, so the values in the following analysis are likely conservative.

Based on the PDA-EOD/PDA-BOR results, comparing either the Wisc-EN or the FHWA-Gates formula to the PDA-EOD capacity may not be a good indicator of either formula's accuracy. The two dynamic formulae can be compared to the PDA-BOR predicted capacity instead.

5.4.1 Wisc-EN

The Wisc-EN allowable capacity vs. PDA-BOR ultimate capacity data is plotted in Figures 5.6 to 5.8. A summary of the statistics is in Table 5.6. The average Wisc-EN/PDA-BOR capacity ratio is 0.47, with a COV of 0.59. The average Wisc-EN/PDA-EOD capacity ratio is 0.72, with a COV of 0.44. Generally, as the PDA-BOR predicted capacity increases, the disagreement between the two methods increases. Of the 93 piles driven, the Wisc-EN Formula predicted a capacity greater than that predicted by the PDA-BOR only three times, and each time the overprediction was small.

5.4.2 FHWA-Gates

The FHWA-Gates capacity vs. the PDA-BOR capacity can be seen in Figures 5.9 to 5.11. A summary of the statistics can be seen in Table 5.7. The average FHWA-Gates/PDA-BOR capacity ratio is 0.81, with a COV of 0.49. The average FHWA-Gates/PDA-EOD capacity ratio is 1.79 with a COV of 0.46. As with the Wisc-EN Formula, the ratio of the FHWA-Gates Formula to the PDA-BOR capacity becomes progressively less than unity as the predicted capacity increases. About one-quarter of the time, the FHWA-Gates Formula predicted a capacity higher than that predicted by the PDA-BOR.

When the two dynamic formulae are compared to the capacity predicted by PDA-BOR, the FHWA-Gates formula appears to more accurately predict capacity. The average Wisc-EN/PDA-EOD capacity ratio is 0.72. The average Wisc-EN/PDA-BOR capacity ratio is 0.47. The average FHWA-Gates/PDA-EOD capacity ratio is 1.79, while the average FHWA-Gates/PDA-BOR capacity ratio is 0.81. Both dynamic formulae had almost the same COV when compared to the PDA-EOD method. When the PDA-BOR method is used for comparison, the scatter (COV) for the FHWA-Gates formula becomes 0.10 smaller than the scatter for the Wisc-EN formula. It should also be noted that the Wisc-EN capacity is an allowable capacity with a FS=6, while the FHWA-Gates capacity is an ultimate capacity with no factor of safety.

5.5 STATIC LOAD TEST RESULTS

A static load test was performed on 12 of the 316 piles in the database. The static load test can be considered the most accurate predictor of pile capacity, and comparing the different methods examined previously to the static load test results can give a good indication of the relative accuracy of the different predictive methods. The capacities determined from the predictive methods vs. the static load test capacity can be seen plotted in Figures 5.12 to 5.14. An arrow on a data point indicates that the static load test was not conducted to failure, and the actual pile capacity is higher, although it cannot be determined how much higher. Table 5.8 summarizes the statistics of the Predictive Method/SLT capacity ratios.

A static load test was run on Pile B-14-3S forty-seven days after the end-of-driving, and its capacity was determined to be 600 kips. A PDA-BOR analysis was run on the same pile 84 days after the end-of-driving, and its capacity was determined to be 1763 kips. This data is plotted in Figure 5.13. This large difference in capacity is not reflected in the CAPWAP analysis, which was also run 84 days after the end-of-driving and predicted a capacity of 551 kips. No explanation is offered for this large discrepancy, and the PDA-BOR result is considered to be an anomaly.

Before any conclusions can be drawn about the mean and the cov of the PDA-BOR/SLT capacity ratios and CAPWAP-BOR/SLT capacity ratios, the time difference between when a static load test and when the PDA or CAPWAP analyses were run must be considered. Because of the time difference between when the analyses were run, and the potential for pile setup in that time, the agreement between the two methods can be difficult to determine. Methods that utilize data from the beginning-of-restrike (PDA-BOR and CAPWAP-BOR) tend to predict a capacity similar to that predicted by a static load test; however, the BOR results may predict loads greater than the static load test if the BOR values were measured at times greater than the time at which a load test was conducted. Methods based on end-of-driving data (the dynamic formulae and PDA-EOD) tend to predict a capacity less than that predicted by a static load test. The statistical values for different predictive methods and static load tests can be seen in Table 5.8. Though there is a small dataset from which to draw conclusions, the PDA-EOD method exhibits the smallest values and has a relatively small scatter. The Wisc-EN method smallest mean and exhibits the least amount of scatter. The PDA-BOR method over-predicts capacity, on the average, and exhibits the most scatter of any of the predictive methods. However, due to the small dataset, it is difficult to make any firm conclusions.

5.6 FHWA-GATES COMPARED TO WISC-EN

The agreement between the Wisc-EN Formula and other predictive methods has been examined, as well as the agreement between the FHWA-Gates formula and other predictive methods. The agreement between the Wisc-EN Formula and the FHWA-Gates Formula at the end-of-driving is also of interest. The average FHWA-Gates/Wisc-EN capacity ratio is 2.55, with a COV of 0.23. The statistics can be seen in Table 5.9. This means the FHWA-Gates Formula predicts a capacity about 2.5 times that predicted by the Wisc-EN Formula. This is expected, as the Wisc-EN Formula predicts an allowable capacity with a FS=6, while the FHWA-Gates Formula predicts an ultimate capacity. When looking at individual soil categories, the value of the average capacity ratio ranges from 1.82 to 2.88. The COV is similar across the soil categories. The large difference in average ratio values seems to imply that soil type can have an impact on the agreement of the formulas. Within any soil category, the scatter between the two formulas is small.

5.7 EFFECT OF HAMMER TYPE

Of the 316 piles in the Wisconsin Database, 286 were driven with an open-ended diesel hammer, 27 were driven with a single-acting air/steam hammer, and 3 were driven with a hydraulic hammer. For the hydraulic hammers in this study, the stroke could not be reliably determined, and it was not possible to determine the capacity of piles driven with these hammers using dynamic formulae. When looking at the effect of hammer type on predicted capacity using dynamic formulae, only piles driven with a diesel or air/steam hammer can be compared.

5.7.1 Wisc-EN

The Wisc-EN capacity vs. Static Load Test capacity broken down by hammer type is plotted in Figure 5.15. The statistics are provided in Table 5.10. Whether the hammer used to drive the pile was diesel or air/steam had little effect on the scatter within the data. For either hammer type, the Wisc-EN allowable capacity is less than half of the pile capacity determined using a static load test. For air/steam hammers the bias of the data, 0.55, is a better prediction than for all data, which had a bias of 0.48. The average capacity ratio for diesel hammers was lower, at 0.39. While there are few data points from which to draw conclusions, at higher pile capacities, the Wisc-EN formula tends to underpredict capacity by larger amounts.

5.7.2 FHWA-Gates

The FHWA-Gates capacity vs. SLT capacity broken down by hammer type is plotted in Figure 5.16, and the statistics for the data are presented in Table 5.11. When a pile was driven using an air/steam hammer, the FHWA-Gates formula tended to overpredict capacity, with an average FHWA-Gates/SLT capacity ratio of 1.24. For diesel hammers, the average capacity ratio was 0.81, an underprediction of capacity. Both hammer types predicted capacity with similar amounts of scatter. When the pile was driven with a diesel hammer, the FHWA-Gates formula tended to underpredict capacity as the pile capacity increased, a trend which also occurred with the Wisc-EN formula. The SLT capacity for piles driven with an air/steam hammer falls into a narrow range, and it cannot be determined if there is any trend to overpredict or underpredict capacity as pile capacity increases.

5.7.3 PDA-EOD

Figure 5.17 plots the PDA-EOD capacity vs. SLT capacity for the piles in the Wisconsin Database. The statistics for these graphs are presented in Table 5.12. For hydraulic hammers, the average PDA-EOD/SLT capacity ratio is slightly higher than the average capacity for all data, 0.77. However, there are only three data points from which to draw conclusions. Diesel hammers have a slightly higher average capacity ratio than the ratio for all data. The average capacity ratio for air/steam hammers is 0.68, which is a greater underprediction than for all data. The scatter (COV) for diesel and hydraulic hammers is comparable to that of all data, while the scatter for air/steam hammers is higher. As was the trend for the Wisc-EN and FHWA-Gates formulae, the PDA-EOD method displays more bias at higher pile capacities.

5.8 Wisc-EN, FHWA-Gates, PDA-EOD compared to CAPWAP-BOR

5.8.1 Wisc-EN

If pile dynamic monitoring is conducted during pile driving, CAPWAP can be used to predict pile capacity. The Wisc-EN capacity vs. CAPWAP-BOR capacity is shown in Figure 5.18. The statistics for the graphs are presented in Table 5.13. All piles for which a CAPWAP analysis was run were driven with diesel hammers. The average Wisc-EN/CAPWAP-BOR predicted capacity is 0.45, with a COV of 0.49. As the CAPWAP-BOR predicted capacity becomes larger, the bias of the Wisc-EN Formula increases. For all 92 piles, the Wisc-EN Formula predicted a lower capacity than CAPWAP-BOR, as would be expected, due to the allowable capacity that the Wisc-EN Formula predicts.

5.8.2 FHWA-Gates

Figure 5.19 plots the FHWA-Gates capacity vs. the CAPWAP-BOR capacity. The statistics are reported in Table 5.13. The average FHWA-Gates/CAPWAP-BOR capacity is 0.79 with a scatter of 0.37. There is a smaller tendency by the FHWA-Gates formula to underpredict capacity at large pile capacities. The tendency to underpredict capacity compared to the CAPWAP-BOR capacity begins to manifest in the capacity range of 750 to 1000 kips.

5.8.3 PDA-EOD

The PDA-EOD capacity vs. CAPWAP-BOR capacity broken down by hammer type is shown in Figure 5.20. The statistics from the graphs are presented in Table 5.14. Regardless of hammer type, PDA-EOD always predicted a capacity lower than that predicted by CAPWAP-BOR. The average PDA-EOD/CAPWAP-BOR capacity ratio for diesel hammers is 0.58, while it is 0.75 for hydraulic hammers. However, only three piles were driven with a hydraulic hammer, so no firm trends can be determined. Both hammer types have similar amounts of scatter.

The average Wisc-EN, FHWA-Gates, and PDA-EOD/CAPWAP-BOR capacity ratios were all less than one, meaning an underprediction of capacity. While it can be informative to compare these predictive methods to CAPWAP-BOR, care must used in drawing conclusions from the data. It is important to note the time difference between when the data for predicting capacity was gathered for the different predictive methods. The capacities predicted by the Wisc-EN formula, the FHWA-Gates formula, and PDA-EOD are based on measurements taken at the end-of-driving. The CAPWAP-BOR capacity is based on measurements taken at the beginning-of-restrike, which occurred an average of 25 days after the end-of-driving. As discussed previously, the piles in this database tended to gain capacity with time after the end-of-driving. So, the tendency of the three predictive methods to underpredict capacity compared to CAPWAP-BOR is consistent with earlier findings.

The average Wisc-EN/PDA-EOD capacity ratio does not change significantly with hammer type. The average capacity ratio is 0.73 for diesel hammers and 0.68 for air/steam hammers. The average FHWA-Gates/PDA-EOD capacity ratio is more sensitive to hammer type. For all data, the average capacity ratio is 1.79. Diesel hammers have a similar average capacity ratio of 1.77. The average capacity ratio is 2.05 for air/steam hammers. Of the 309 piles for which there are Wisc-EN and FHWA-Gates predicted capacities, 283 of them were driven with a diesel hammer. These piles dominate the data, and the average capacity ratio was very similar to the average for all data for those piles driven with a diesel hammer.

When comparing the Wisc-EN and FHWA-Gates capacities to static load test capacities, the trend appears to be that air/steam hammers will lead to higher predicted capacities than the average for all data, while diesel hammers tend to predict a lower capacity than the average for all data. The opposite trend emerged for the average PDA-EOD/SLT capacity ratio, diesel hammers tended to predict a higher capacity than the average while air/steam hammers tended to predict a capacity lower than the average.

5.9 WSDOT Formula

Another dynamic formula for predicting pile capacity is the WSDOT formula. It originated as a modification of the FHWA-Gates formula. One significant difference between the two formulae is that the WSDOT formula includes a term that is based on hammer and pile type.

5.9.1 PDA-EOD

The WSDOT capacity vs. PDA-EOD capacity is shown in Figure 5.21. The statistics for the graphs are shown in Table 5.15. The average WSDOT/PDA-EOD capacity ratio is 1.93, with a COV of 0.38. This is a slightly higher capacity ratio with a smaller scatter than the average FHWA-Gates/PDA-EOD capacity ratio, which is 1.79, with a scatter of 0.46. The Wisc-EN/PDA-EOD capacity ratio is 0.72 with a scatter of 0.44, although this is an allowable capacity. Of the three dynamic formulae evaluated, the average WSDOT/PDA-EOD capacity ratio has the greatest bias. The average WSDOT/PDA-EOD capacity ratio has the smallest amount of scatter. While the WSDOT formula attempts to take hammer type into account, there is a trend in the data where air/steam hammers have a higher average capacity ratio than diesel hammers. This same trend was observed for the FHWA-Gates/PDA-EOD capacity ratio.

5.9.2 SLT

Figure 5.22 plots the WSDOT capacity vs. SLT capacity broken down by hammer type. The statistics for the graphs are displayed in Table 5.16. The average WSDOT/SLT capacity ratio is 1.25 with a scatter of 0.27. The average Wisc-EN/SLT capacity ratio is 0.48 and the FHWA-Gates/SLT capacity ratio is 1.05. All three average capacity ratios have similar amounts of scatter. When examined by hammer type, the WSDOT/SLT capacity ratio is 1.04 for diesel hammers and 1.43 for air/steam hammers. When compared to static load tests, the three dynamic formulae all tend to have higher average capacity ratios with air/steam hammers than with diesel hammers. For diesel hammers, the Wisc-EN and FHWA-Gates formulae show a tendency to more greatly underpredict pile capacity when the pile capacity is above 750 kips. There is not enough data to determine whether this same trend appears for WSDOT vs. SLT capacities. There is a limited amount of static load tests from which to draw conclusions for any of the dynamic formulae. The tendency to more greatly underpredict pile capacity at pile capacities greater than 750 kips was not observed with air/steam hammers. For both the FHWA-Gates and WSDOT formulae, when using an air/steam hammer, a tendency to overpredict pile capacity at pile capacities greater than about 750 kips was observed.

5.9.3 CAPWAP-BOR

The WSDOT capacity vs. CAPWAP-BOR capacity is shown in Figure 5.23. A summary of the statistics of the data is presented in Table 5.17. The average WSDOT/CAPWAP-BOR capacity ratio is 1.11. This compares to average Wisc-EN, FHWA-Gates, and PDA-EOD/CAPWAP-BOR capacity ratios of 0.45, 0.79 and 0.59, respectively. The average WSDOT/CAPWAP-BOR capacity ratio displays the least bias of the four average capacity ratios. The smallest scatter for average capacity ratios is 0.3, from the PDA-EOD capacity. The scatter (COV) for the average WSDOT/CAPWAP-BOR capacity ratio is 0.41. There does not appear to be any trend to either overpredict or underpredict capacity as the CAPWAP-BOR capacity increases.

5.10 CORRECTED FHWA-GATES FORMULA

5.10.1 PDA-EOD

The Corrected FHWA-Gates capacity vs. PDA-EOD capacity is shown in Figure 5.24. Statistics for the corrected FHWA-Gates formula are shown in Tables 5.18 and 5.19. Table 5.18 presents the statistics for all piles, while Table 5.19 presents the statistics for piles where the predicted capacity is less than 750 kips.

For all piles, the average capacity ratio is 1.52, with a COV of 0.44. While this is an overprediction of capacity, it was determined that piles in the database gained, on average, an additional 67% capacity due to pile set-up. The FHWA-Gates formula empirically accounts for this while PDA-EOD does not. The uncorrected FHWA-Gates/PDA-EOD capacity ratio is 1.79 with a COV of 0.46. The correlation between the corrected and uncorrected FHWA-Gates formula and a PDA-EOD analysis is similar, however the Corrected FHWA-Gates formula does not overpredict capacity relative to PDA-EOD to as great an extent as the uncorrected FHWA-Gates formula.

When only examining piles with a PDA-EOD predicted capacity less than 750 kips, the average capacity ratio is 1.53 with a COV of 0.44. These statistics are very similar to those for all piles. It should be noted that there are 300 piles with predicted capacities less than 750 kips, while there are only 309 total piles. Because the data is dominated by piles with capacities less than 750 kips, it is difficult to draw any conclusions about the corrected FHWA-Gates formula at capacities greater than 750 kips.

5.10.2 SLT

Figure 5.24 plots the corrected FHWA-Gates capacity vs. static load test results. Statistics for this data are presented in Tables 5.18 and 5.19. For all piles, the average Corrected FHWA-Gates/SLT capacity ratio is 1.06 with a COV of 0.37. While there are only six data points from which to draw conclusions, the Corrected FHWA-Gates formula appears to predict capacities that are in fair agreement with those determined from static load tests.

When examining only piles with capacities of less than 750 kips, the average Corrected FHWA-Gates/SLT capacity ratio is 1.13 with a COV of 0.36. This is a slightly higher average capacity ratio than for all piles, but the statistics are fairly similar between all piles and for piles with measured capacities less than 750 kips. Firm conclusions about the tendencies of the Corrected FHWA-Gates formula at capacities greater than 750 kips are difficult to determine because of the limited data available.

5.10.3 CAPWAP-BOR

The Corrected FHWA-Gates capacity vs. CAPWAP-BOR capacity is shown in Figure 5.24. Tables 5.18 and 5.19 present the statistics for this data.

When all piles are included in the analysis, the average Corrected FHWA-Gates/CAPWAP-BOR capacity ratio is 0.75 with a COV of 0.37. Of the 92 piles with CAPWAP-BOR capacity predictions, 80 of the piles (87%) have predicted capacities greater than 750 kips. From Figure 5.24, the Corrected FHWA-Gates formula begins to progressively underpredict capacity with respect to CAPWAP-BOR at higher pile capacities.

When limiting the data to piles with a capacity less than 750 kips, the tendency to progressively underpredict capacity does not seem to manifest itself. The average Corrected FHWA-Gates/CAPWAP-BOR capacity ratio is 0.99 with a COV of 0.26. These statistics indicate a strong agreement between the Corrected FHWA-Gates formula and CAPWAP-BOR at lower capacities. Of the predictive methods to which the Corrected FHWA-Gates formula has been compared (static load tests, PDA-EOD, and CAPWAP-BOR), 0.99 is the average capacity ratio closest to unity. The COV of 0.26 associated with the data is also the strongest correlation present in the various capacity ratios.

5.11 CONCLUSIONS

5.11.1 PDA-EOD

For every pile in the database, a PDA analysis at the end-of-driving was conducted. Other tests such as PDA-BOR, CAPWAP-BOR, and static load tests were only run on a limited number of piles. The PDA-EOD capacity was used early in this chapter to compare the Wisc-EN formula and the FHWA-Gates formula. However, the validity of doing this can be called into question by examining the accuracy of the PDA-EOD capacity.

The average PDA-EOD/SLT capacity ratio is 0.77 with a COV of 0.33. By comparing the predicted capacity of a dynamic formula to the PDA-EOD capacity, already some amount of error is introduced. Another problem with using the PDA-EOD method to compare dynamic formulae is the fact that the average FHWA-Gates and WSDOT/SLT capacity ratios are 0.76 and 1.25, respectively. The bias and COV or the FHWA-Gates and WSDOT formulae are similar to that of the PDA-EOD method.

The effect of soil type on the average Wisc-EN/PDA-EOD capacity ratio is not very large. The range in bias for the different soil categories (Table 5.3) is 0.19. The range in average FHWA-Gates/PDA-EOD capacity ratio is 0.66 (Table 5.4). Some of this difference could be attributed to the effect of soil on PDA-EOD. The range of the average FHWA-Gates/PDA-BOR capacities across the different soil categories is 0.28. The reaction of soil to the dynamic loading imposed by pile driving is difficult to fully account for and the reaction of different soil types (sand and clay) are different, leading to a wider range of bias at end-of-driving, as opposed to the beginning-of-restrike when the soil has had time to adjust to the pile driving.

The average Wisc-EN/PDA-EOD capacity ratio is 0.72, with a COV of 0.44. This is a somewhat large amount of scatter. Also, when the FS=6 which is used to determine the allowable Wisc-EN capacity is removed, the average capacity ratio becomes 4.32. Comparing the Wisc-EN and PDA-EOD methods to estimate pile capacity does not seem to yield very accurate or economical results.

5.11.2 Wisc-EN

The average Wisc-EN/PDA-EOD, PDA-BOR, CAPWAP-BOR, and SLT capacity ratios are all less than 1, sometimes significantly so. This is to be expected, as the Wisc-EN capacity is an allowable one, as compared to the ultimate capacity predicted by the other methods. When compared to CAPWAP-BOR and static load tests, the Wisc-EN formula always predicted a lower capacity. The Wisc-EN formula predicted a higher capacity than PDA-BOR for only 3 of 93 piles. While the Wisc-EN formula provides a conservative estimate of pile capacity, the large COV and bias associated with its use suggest it is not very economical to rely on the formula. When examining the Wisc-EN allowable capacity vs. CAPWAP-BOR capacity (Figure 5.18), there is a trend of greater bias at higher capacities.

The average Wisc-EN/PDA-EOD and PDA-BOR capacity ratios were broken down by soil type. The range in average capacity ratio across soil type was 0.19 for PDA-EOD and 0.31 for PDA-BOR. Referring to Tables 5.3 and 5.6, it appears that the largest deviation from the normal occurs when the pile tip bears on sand. Closed-end pipe piles dominate the data, and it is difficult to judge the effect of pile type on the formula. When looking at the average Wisc-EN/SLT capacity ratios (Table 5.10), diesel hammers tend to predict a greater bias than the average while air/steam hammers tend to predict a smaller bias.

5.11.3 FHWA-Gates

The average FHWA-Gates/PDA-BOR, CAPWAP-BOR and SLT capacity ratios are 0.81, 0.79, and 0.76, respectively (referring to Tables 5.7, 5.8, and 5.13). Each of these average capacity ratios exhibit less bias (by about 0.3) than when the Wisc-EN capacity is in the numerator. The COV is about 0.1 less for the average FHWA-Gates/PDA-BOR and CAPWAP-BOR capacity ratios, and about 0.1 greater for the average FHWA-Gates/SLT capacity ratio, as compared to for the Wisc-EN formula. The FHWA-Gates formula exhibits a considerably smaller bias than the Wisc-EN formula when compared to more sophisticated methods. This significantly smaller bias suggests that it is a more appropriate dynamic formula to utilize than the Wisc-EN formula. However, as with the Wisc-EN formula, the FHWA-Gates capacity vs. CAPWAP-BOR capacity (Figure 5.19) shows a trend of greater bias as predicted capacity increases.

The average FHWA-Gates/PDA-EOD and PDA-BOR capacity ratios were broken down by soil type. There is a range of 0.66 in the average FHWA-Gates/PDA-EOD capacity. The largest departures from the average occur when the pile tip bears on clay. However, the least bias and scatter is present when the pile tip bears on clay, indicating the FHWA-Gates and PDA-EOD methods agree somewhat well for piles bearing on clay. The average FHWA-Gates/PDA-BOR capacity ratio has a smaller range of 0.28. There also appears to be a much smaller effect on capacity due to soil type when BOR measurements are used, suggesting that for long-term capacity of piles there is not as significant an effect due to soil type. As with the Wisc-EN data, closed-end pipe piles dominate the data and it is difficult to determine any effect of pile type on capacity. Hammer type appears to have some effect on predicted capacity. The average capacity ratio exhibits a bias of -0.19 for diesel hammers and +0.24 for air/steam hammers. There is limited data from which to draw conclusions, but diesel hammers lead to an underprediction of capacity with the FHWA-Gates formula, while air/steam hammers lead to an overprediction.

5.11.4 WSDOT Formula

The average WSDOT/PDA-EOD, CAPWAP-BOR, and SLT capacity ratios are 1.93, 1.11, and 1.25, respectively (refer to Tables 5.15, 5.16, and 5.17). When compared to the more sophisticated CAPWAP-BOR and SLT methods, the WSDOT formula has a bias similar than the FHWA-Gates formula, but the WSDOT formula tends to overpredict capacity while the FHWA-Gates formula tends to underpredict it. The COV for the average WSDOT/CAPWAP-BOR and SLT capacity ratios are 0.41 and 0.27, respectively. This amount of scatter is comparable to that exhibited by the FHWA-Gates formula.

While the WSDOT formula attempts to take hammer and pile type into account, there is still an effect on capacity due to hammer type. The average capacity ratio exhibits a bias of -0.21 for diesel hammers and +0.39 for air/steam hammers. The effect due to diesel hammers is very similar for both the FHWA-Gates and WSDOT formulae. While there are only four data points, it should be noted that the average WSDOT/SLT capacity ratio for diesel hammers is 1.04. While there was a trend for the Wisc-EN and FHWA-Gates formulae to exhibit greater bias as CAPWAP-BOR predicted capacity increases, this trend does not appear in the WSDOT capacity vs. CAPWAP-BOR capacity graph (Figure 5.23).

The Wisc-EN, FHWA-Gates, and WSDOT formulae all rely on the same field observations and require about the same computational effort to determine pile capacity. Therefore, a decision on which one is the most appropriate to use depends on the accuracy and precision of the individual formula. The bias exhibited by the Wisc-EN formula is the greatest of the three formulae and it seems to be the least appropriate formula of the three. Based on bias and COV alone, the FHWA-Gates and WSDOT formulae appear to offer comparable results. However, a few factors make the WSDOT formula appear to be a more appropriate choice than the FHWA-Gates formula for the State of Wisconsin. First, the majority of piles in the Wisconsin database were driven with diesel hammers. Assuming that the database is representative of all piles driven for the Wisconsin DOT, the smaller bias and COV exhibited in the average WSDOT/SLT capacity ratio compared to the average FHWA-Gates/SLT capacity ratio for diesel hammers (see Tables 5.8 and 5.16) would recommend the WSDOT formula. Also, the trend for the FHWA-Gates capacity vs. the CAPWAP-BOR capacity was for the bias to increase as pile capacity increases. This trend did not manifest for the WSDOT capacity vs. the CAPWAP-BOR capacity. Overall, the WSDOT formula would appear to be the most appropriate choice of a dynamic formula.

5.11.5 Corrected FHWA-Gates

All correction factors for this method were developed using the nationwide database. In other words, no data from the Wisconsin database were used to develop the method. This database was used exclusively to identify strengths and weaknesses of the correlations developed.

The target capacities for this method are piles with axial capacities less than 750 kips. The overall database only contains 4 static load tests in which the axial capacities were less than 750 kips. For these data, the mean and cov were a respectable 1.13 and 0.36.

The mean value is about 10 percent greater than determined in the prevous database while the cov is the same. This method also predicted capacities well when compared to CAPWAP-BOR which usually provides predictions very similar to static load tests. Accordingly corrected FHWA-Gates method appears to predict capacities well for both databases.

Table 5.1 Distribution of Hammer, Soil, and Pile Details in Wisconsin Database

Pile Types			**Number**
	H-Pile	12x53	3
		14x74	42
	Open-Ended Pipe Pile	9.5" x 0.5"	4
	Closed-End Pipe Pile	12.25"x0.312"	35
		16"x0.219"	1
		16"x0.312"	1
		13.375"x0.375"	1
		10.75"x0.25"	24
		10.75"x0.365"	20
		10.75"x0.219"	25
		Fluted	7
		12"x?	1
		13.5"x?	45
		13.375"x0.48"	18
		12.75"x0.375"	39
		16"x0.5"	24
		16"x0.625"	1
		14"x0.438"	2
		14"x0.5"	16
		14"x0.458"	2
Pile Lengths			
	30' - 60'		55
	60' - 90'		86
	90' - 120'		88
	120' - 150'		65
	150' - 180'		17
	180' - 210'		2
	210+'		3
Soil Conditions			
	Sand, Sand		194
	Clay, Clay		11
	Clay, Sand		3
	Sand, Clay		0
	Mixed, Clay		16
	Mixed, Sand		56
	Clay, Mixed		0
	Sand, Mixed		0
	Mixed, Mixed		9
	Unspecified		27
Hammer Type			
	Open-Ended Diesel		280
	Closed-End Diesel		0
	Hydraulic		3
	Air/Steam		27

Predicted Allowable Capacity (Wisc-EN)			
	0-250 kips		202
	250-500 kips		74
	500-750 kips		28
	750-1000 kips		4
	1000-1250 kips		0
	1250-1500 kips		1
	>1500 kips		0
Hammer Energy (kip-ft)			
	0-20		9
	20-40		99
	40-60		113
	60-80		20
	80-100		38
	100-120		25
	120-140		4
	140+		3

Table 5.2 Character of the data within the Wisconsin Database

		Databases		
		Wisc (other)	Wisc (MI)	Wisc (Total)
Total Number of Piles		220	96	316
Soil	Sand	188	6	194
	Clay	0	11	11
	Mixed	25	59	84
	Unknown	7	20	27
Pile Type	H	45	0	45
	OE Pipe	4	96	100
	CE Pipe	168	0	168
	Unknown	3	0	3
Hammer Type	A/S (SA)	27	0	27
	A/S (DA)	0	0	0
	OED	193	93	286
	CED	0	0	0
	HYD	0	3	3
Predictions	EN-Wisc	216	93	309
	Gates - FHWA	216	93	309
	ALLEN	216	93	309
	PDA	220	96	316
	CAPWAP	0	94	94
	SLT	5	7	12

Table 5.3 Statistics for Wisc-EN Capacity versus PDA-EOD Capacity

	All Data	Sand, Sand	Clay, Clay	Mix, Sand	Mix, Clay	Mix, Mix
Mean:	0.72	0.66	0.72	0.85	0.70	0.72
COV:	0.44	0.45	0.24	0.44	0.25	0.42
n:	309	191	10	54	16	9

Table 5.4. Statistics for FHWA-Gates Capacity vs. PDA-EOD Capacity

	All Data	Sand, Sand	Clay, Clay	Mix, Sand	Mix, Clay	Mix, Mix
Mean:	1.79	1.90	1.30	1.84	1.24	1.38
COV:	0.46	0.46	0.17	0.49	0.13	0.40
n:	309	191	10	54	16	9

Table 5.5. Statistics for PDA-EOD Capacity vs. PDA-BOR Capacity

	All Data	Sand, Sand	Clay, Clay	Mix, Sand	Mix, Clay	Mix, Mix
Mean:	0.60	0.52	0.55	0.59	0.59	0.65
COV:	0.49	0.21	0.31	0.75	0.31	0.25
n:	93	6	10	34	16	6

Table 5.6. Statistics for Wisc-EN Capacity vs. PDA-BOR Capacity

	All Data	Sand, Sand	Clay, Clay	Mix, Sand	Mix, Clay	Mix, Mix
Mean:	0.47	0.66	0.41	0.35	0.43	0.49
COV:	0.59	0.45	0.49	0.76	0.49	0.47
n:	93	6	11	34	16	6

Table 5.7. Statistics for FHWA-Gates Capacity vs. PDA-BOR Capacity

	All Data	Sand, Sand	Clay, Clay	Mix, Sand	Mix, Clay	Mix, Mix
Mean:	0.81	0.94	0.72	0.66	0.75	0.85
COV:	0.49	0.31	0.41	0.70	0.47	0.40
n:	93	6	10	34	16	6

Table 5.8. Statistics for Capacity from Predictive Methods vs. Static Load Test Capacity

	Wisc-EN/SLT	FHWA-Gates/SLT	PDA-EOD/SLT	PDA-BOR/SLT	CAPWAP-BOR/SLT
Mean:	0.48	0.76	0.77	1.50	1.27
COV:	0.27	0.35	0.33	0.60	0.44
n:	9	9	12	5	7

Table 5.9. Statistics for FHWA-Gates Capacity vs. Wisc-EN Capacity

	All Data	Sand, Sand	Clay, Clay	Mix, Sand	Mix, Clay	Mix, Mix
Average:	2.55	2.88	1.84	1.97	2.16	1.82
COV:	0.23	0.14	0.12	0.14	0.18	0.14
n	309	191	10	54	16	9

Table 5.10. Statistics for Wisc-EN Capacity vs. Static Load Test Capacity

	All Data	Diesel Hammer	Air/Steam Hammer
Average:	0.48	0.39	0.55
COV:	0.27	0.20	0.23
n:	9	4	5

Table 5.11. Statistics for FHWA-Gates Capacity vs. Static Load Test Capacity

	All Data	Diesel Hammer	Air/Steam Hammer
Average:	1.05	0.81	1.24
COV:	0.31	0.25	0.24
n:	9	4	5

Table 5.12. Statistics for PDA-EOD Capacity vs. Static Load Test Capacity

	All Data	Diesel Hammer	Air/Steam Hammer	Hydraulic Hammer
Average:	0.77	0.83	0.68	0.79
COV:	0.33	0.32	0.43	0.33
n:	12	4	5	3

Table 5.13. Statistics for Wisc-EN and FHWA-Gates capacity vs. CAPWAP-BOR

	Wisc-EN/CAPWAP-BOR	FHWA-Gates/CAPWAP-BOR
Average:	0.45	0.79
COV:	0.49	0.37
n:	92	92

Table 5.14. Statistics for PDA-EOD Capacity vs. CAPWAP-BOR Capacity

	All Data	Diesel Hammer	Hydraulic Hammers
Average:	0.59	0.58	0.75
COV:	0.3	0.29	0.29
n:	95	92	3

Table 5.15. Statistics for WSDOT capacity vs. PDA-EOD capacity

	All Data	Diesel Hammer	Air / Steam Hammers
Average:	1.93	1.91	2.14
COV:	0.38	0.39	0.24
n:	309	282	27

Table 5.16. Statistics for WSDOT capacity vs. SLT capacity

	All Data	Diesel Hammer	Air / Steam Hammers
Average:	1.25	1.04	1.43
COV:	0.27	0.28	0.28
n:	9	4	5

Table 5.17. Statistics for WSDOT capacity vs. CAPWAP-BOR capacity

	All Data	Diesel Hammer
Average:	1.11	1.11
COV:	0.41	0.41
n:	92	92

Table 5.18. Statistics for Corrected FHWA-Gates

	All Data		
	FHWA-Gates Corrected / PDA-EOD	FHWA-Gates Corrected / SLT	FHWA-Gates Corrected / CAPWAP-BOR
Average:	1.52	1.06	0.75
Std. Dev:	0.67	0.39	0.28
COV:	0.44	0.37	0.37
n:	309	6	92

Table 5.19. Statistics for Corrected FHWA-Gates, limited to capacities less than 750 kips.

	Capacity < 750 kips		
	FHWA-Gates Corrected / PDA-EOD	**FHWA-Gates Corrected / SLT**	**FHWA-Gates Corrected / CAPWAP-BOR**
Average:	1.53	1.13	0.99
Std. Dev:	0.68	0.40	0.25
COV:	0.44	0.36	0.26
n:	300	4	12

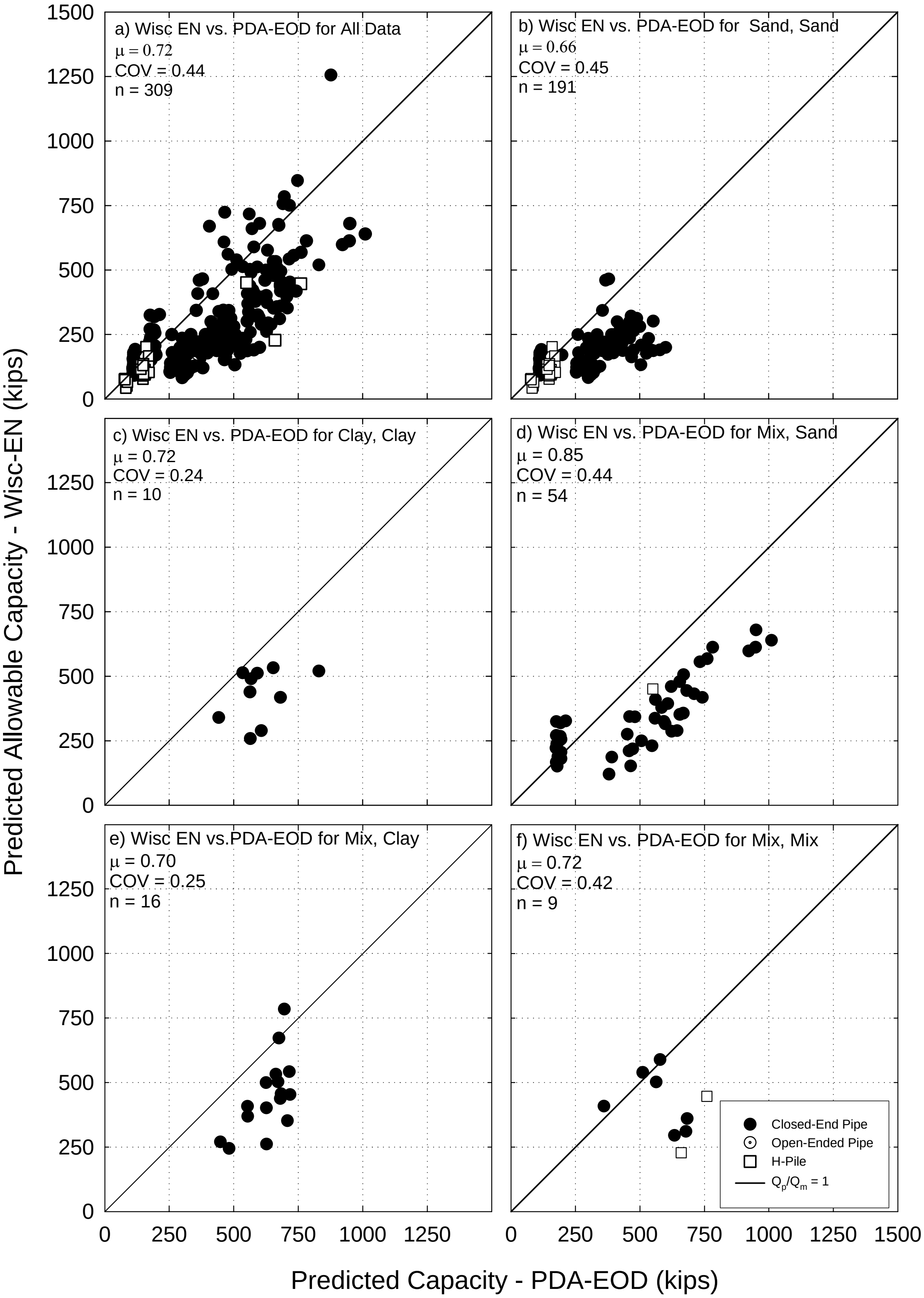


Figure 5.1. Wisc-EN vs. PDA-EOD

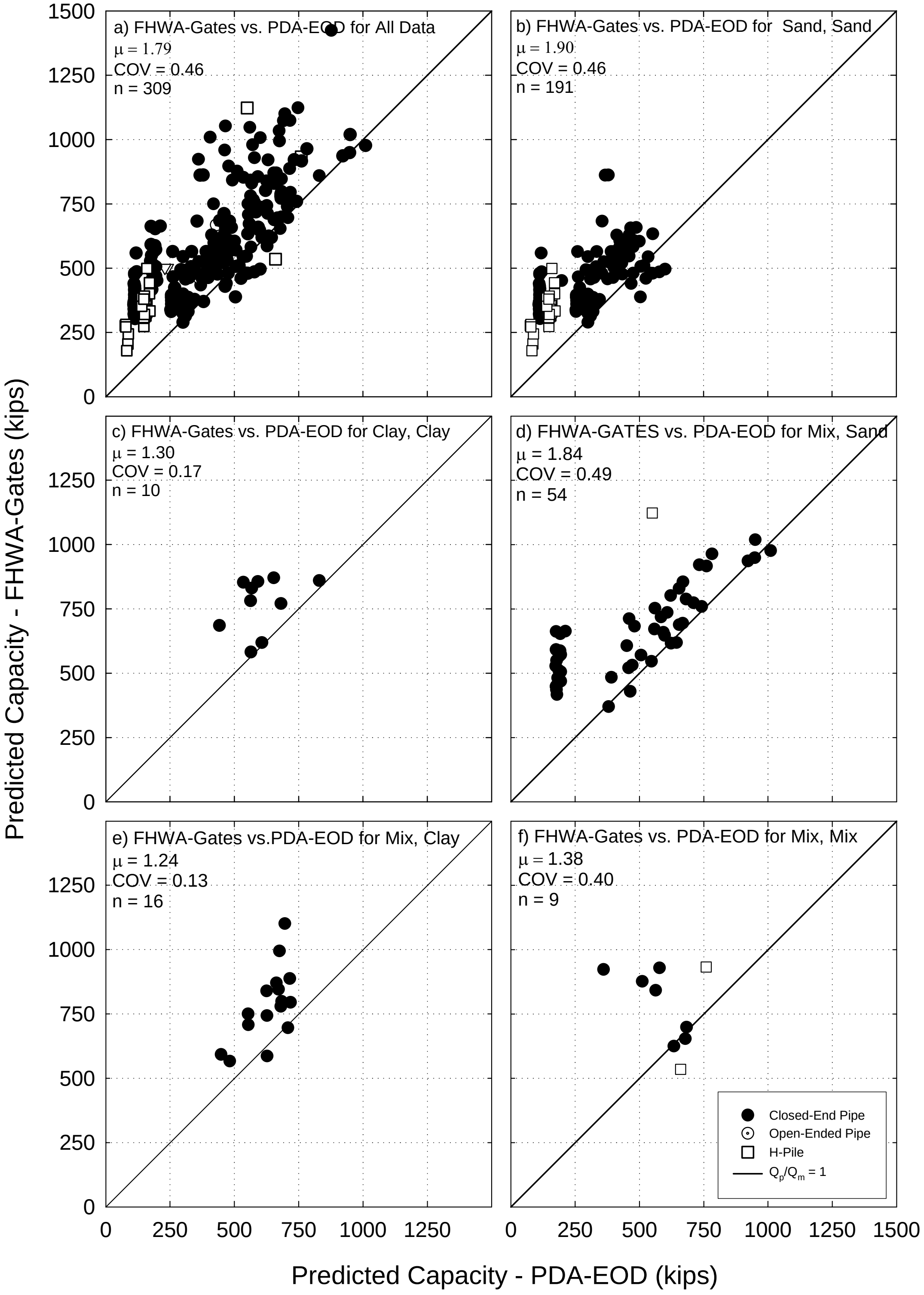


Figure 5.2. FHWA-Gates vs. PDA-EOD

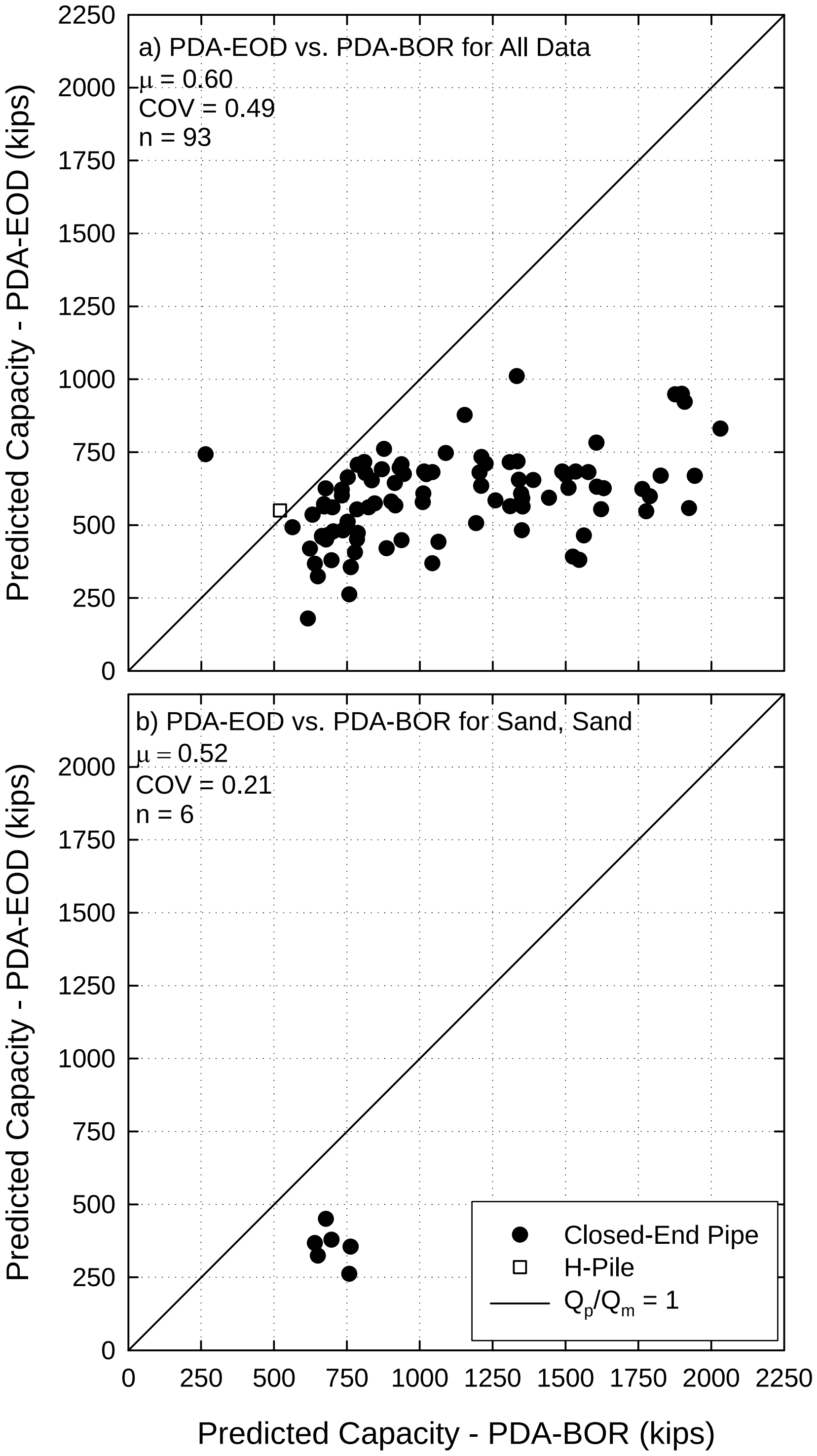


Figure 5.3. PDA-EOD vs. PDA-BOR for All Data, and Sand, Sand

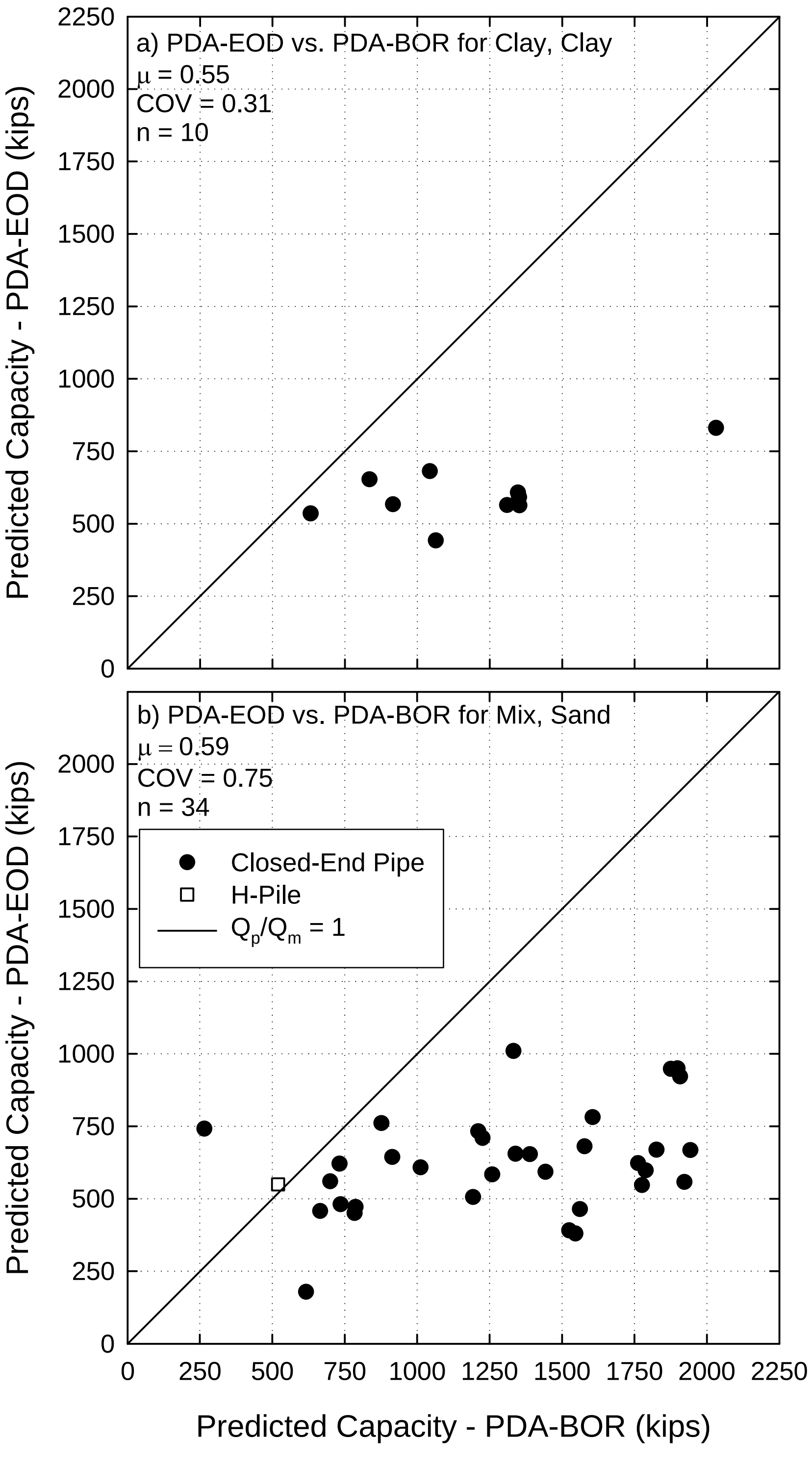


Figure 5.4. PDA-EOD vs. PDA-BOR for Clay, Clay and Mix, Sand

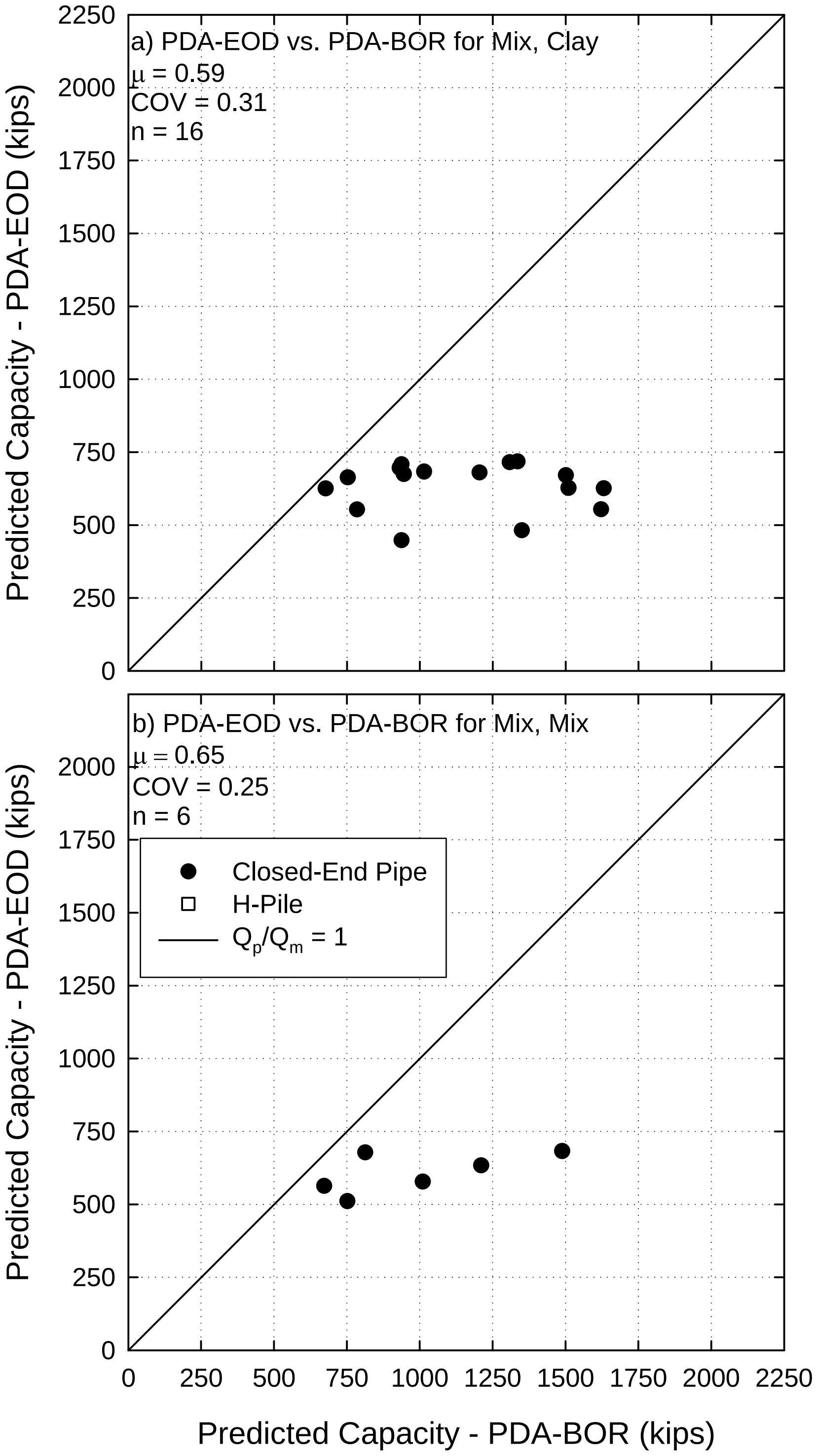


Figure 5.5. PDA-EOD vs. PDA-BOR for Mix, Clay and Mix, Mix

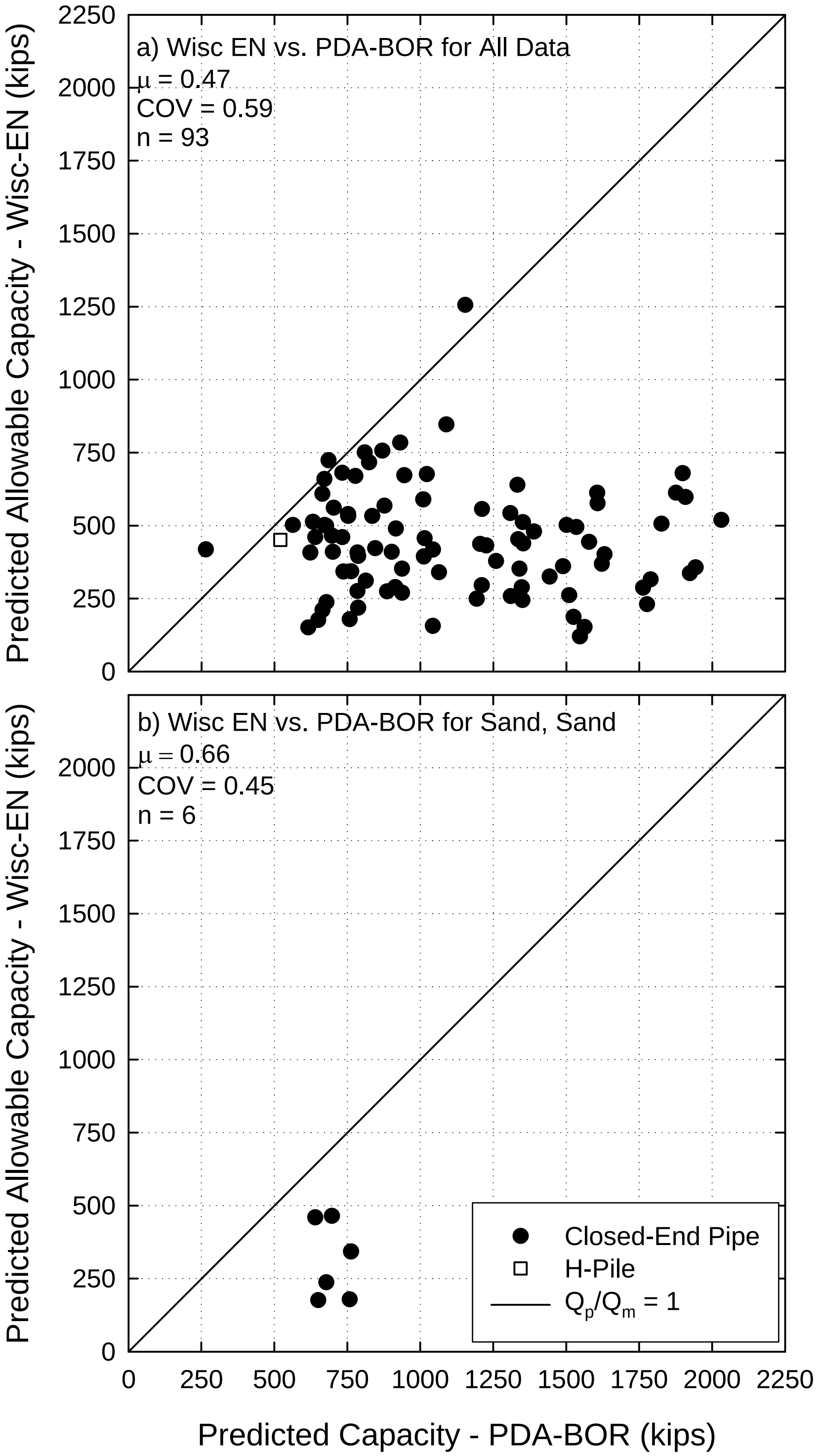


Figure 5.6. Wisc-EN vs. PDA-BOR for All Data and Sand, Sand

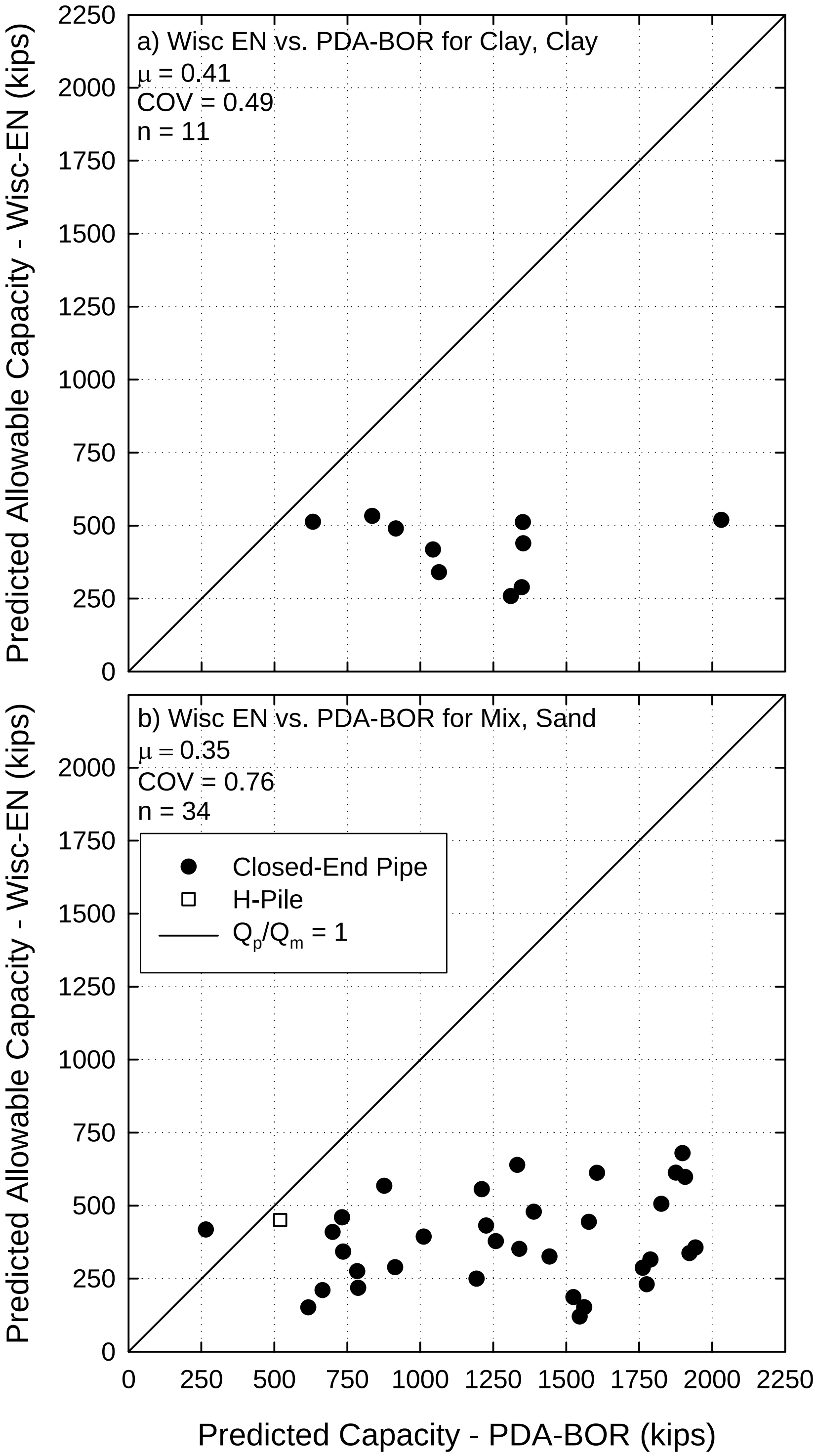


Figure 5.7. Wisc-EN vs. PDA-BOR for Clay, Clay and Mix, Sand

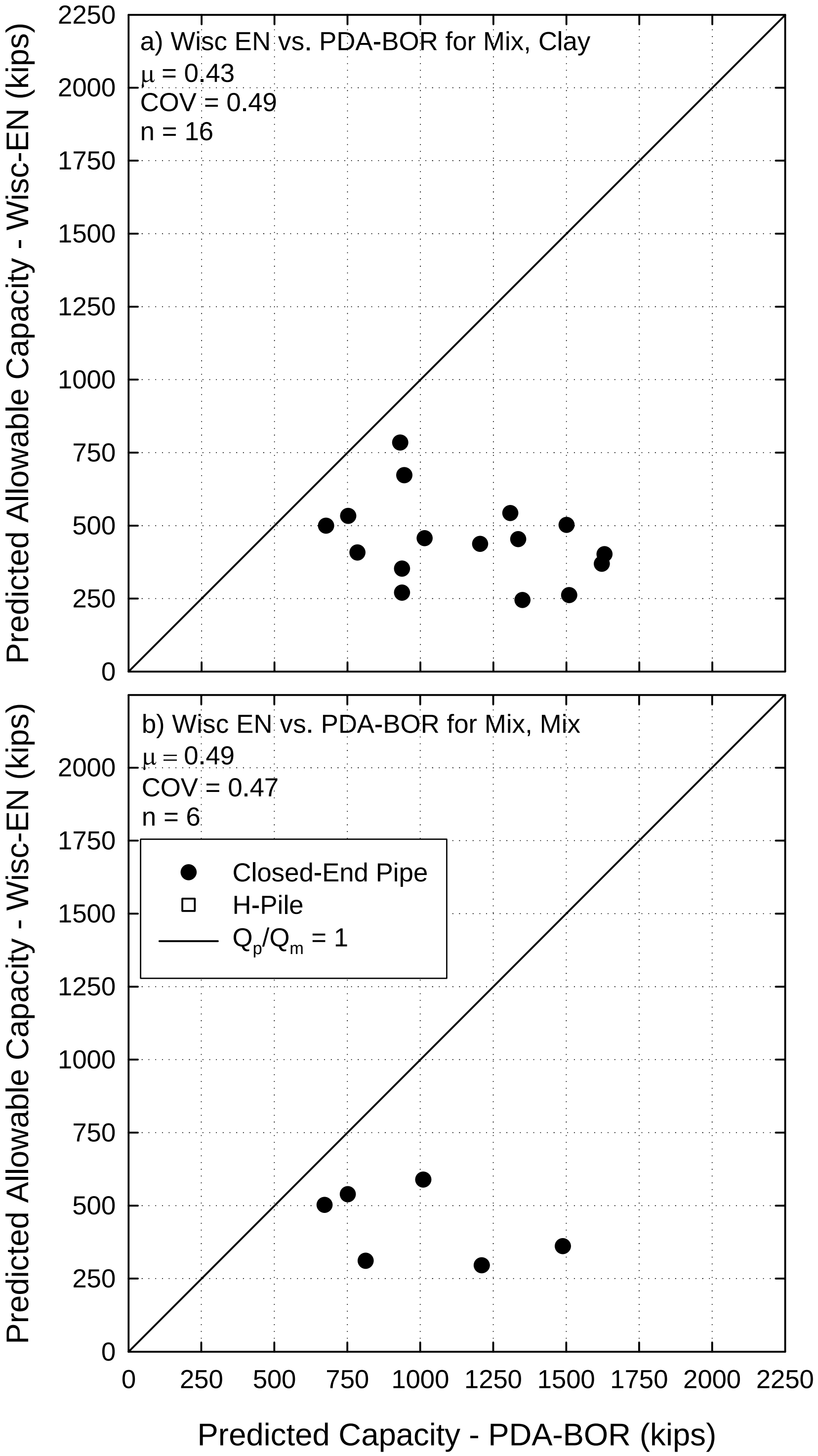


Figure 5.8. Wisc-EN vs. PDA-BOR for Mix, Clay and Mix, Mix

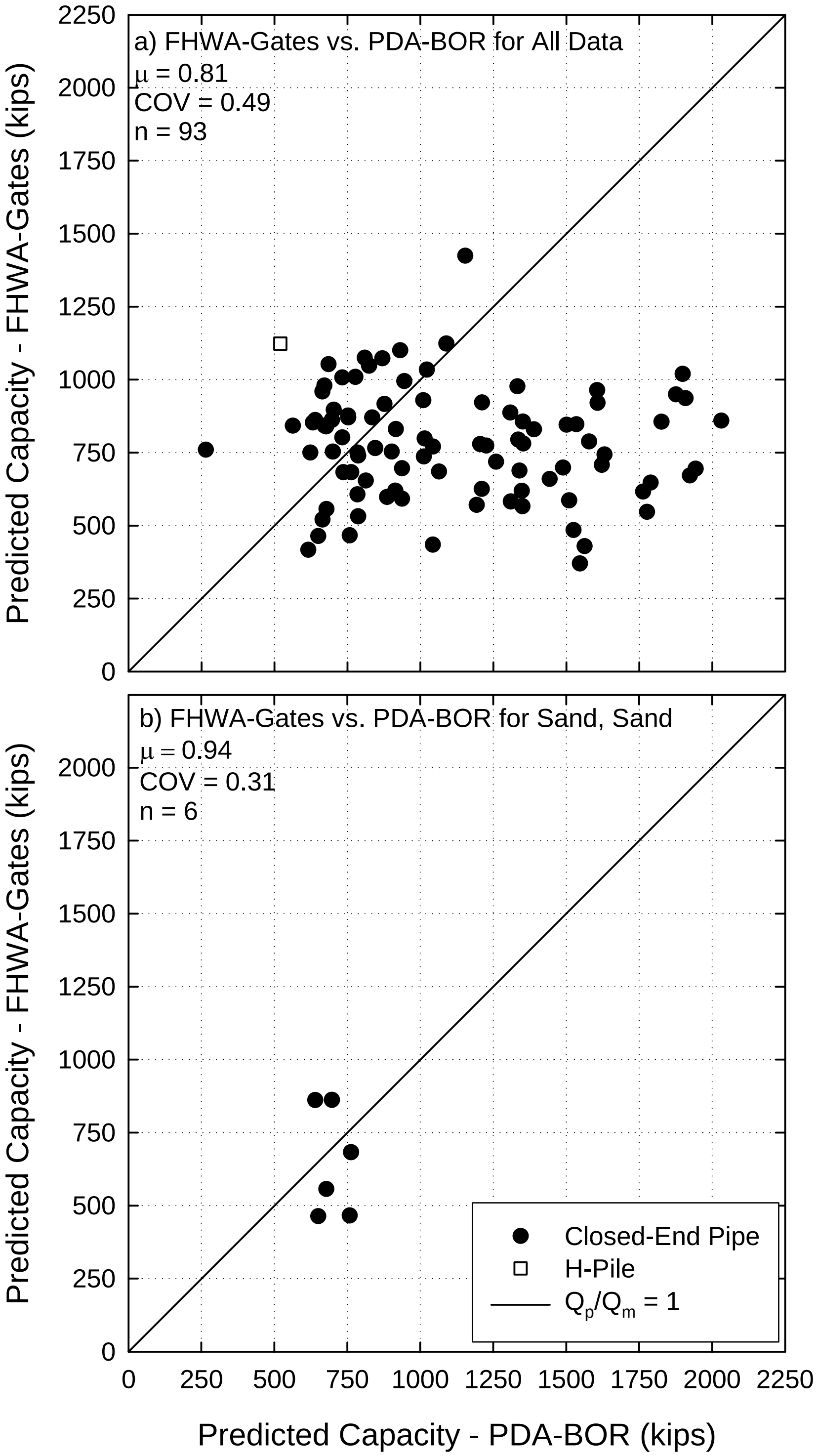


Figure 5.9. FHWA-Gates vs. PDA-BOR for All Data and Sand, Sand

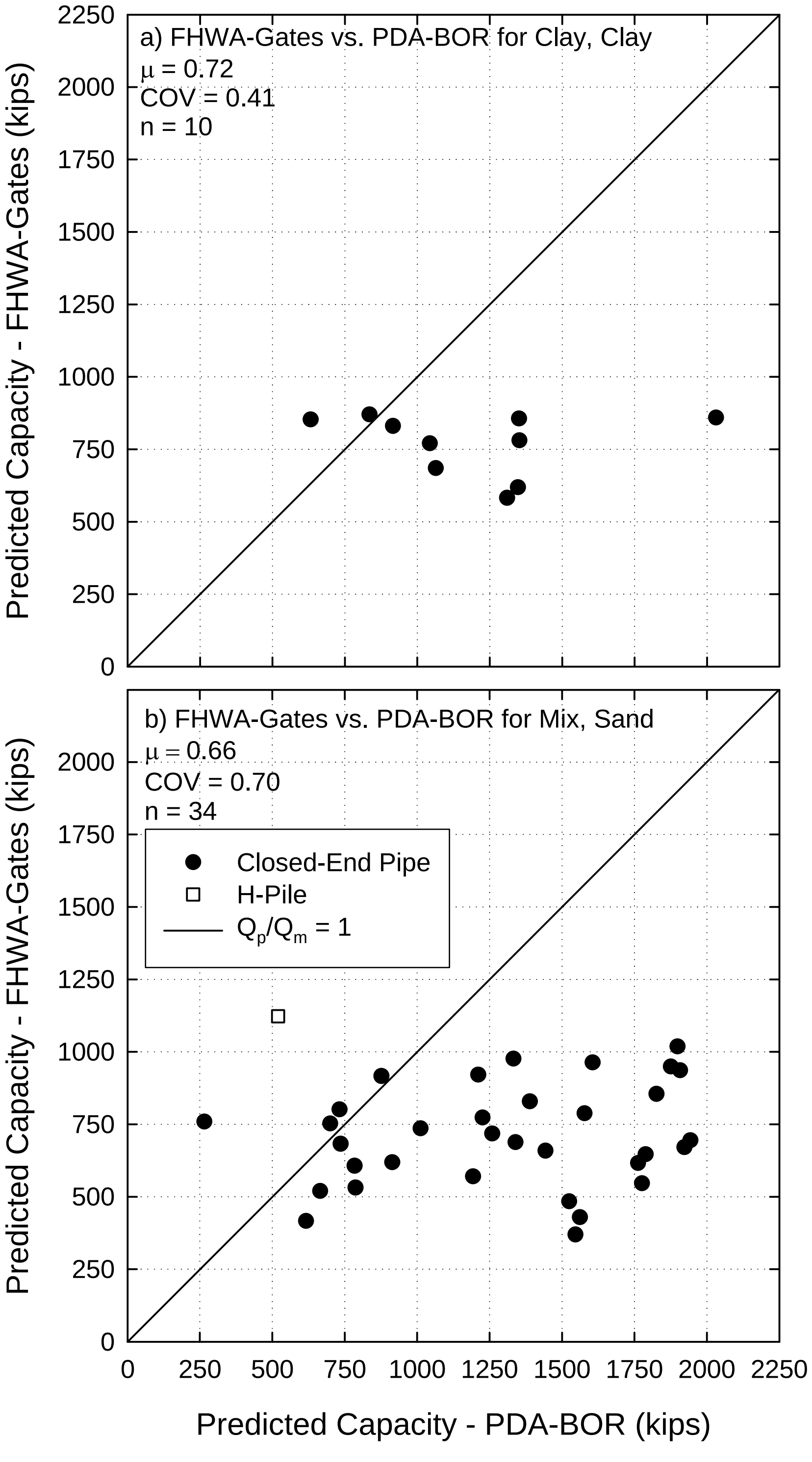


Figure 5.10. FHWA-Gates vs. PDA-BOR for Clay, Clay and Mix, Sand

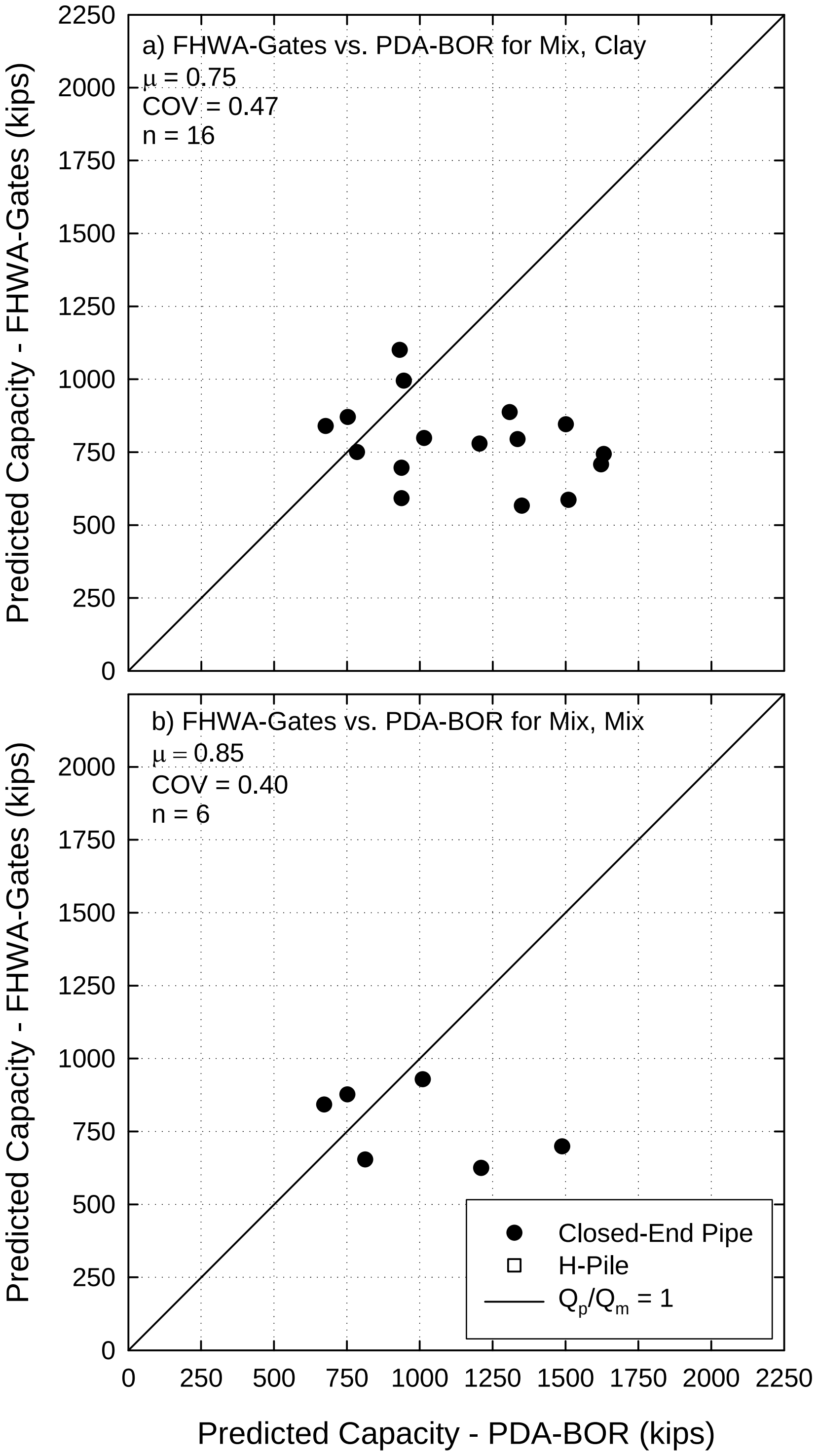


Figure 5.11. FHWA-Gates vs. PDA-BOR for Mix, Clay and Mix, Mix

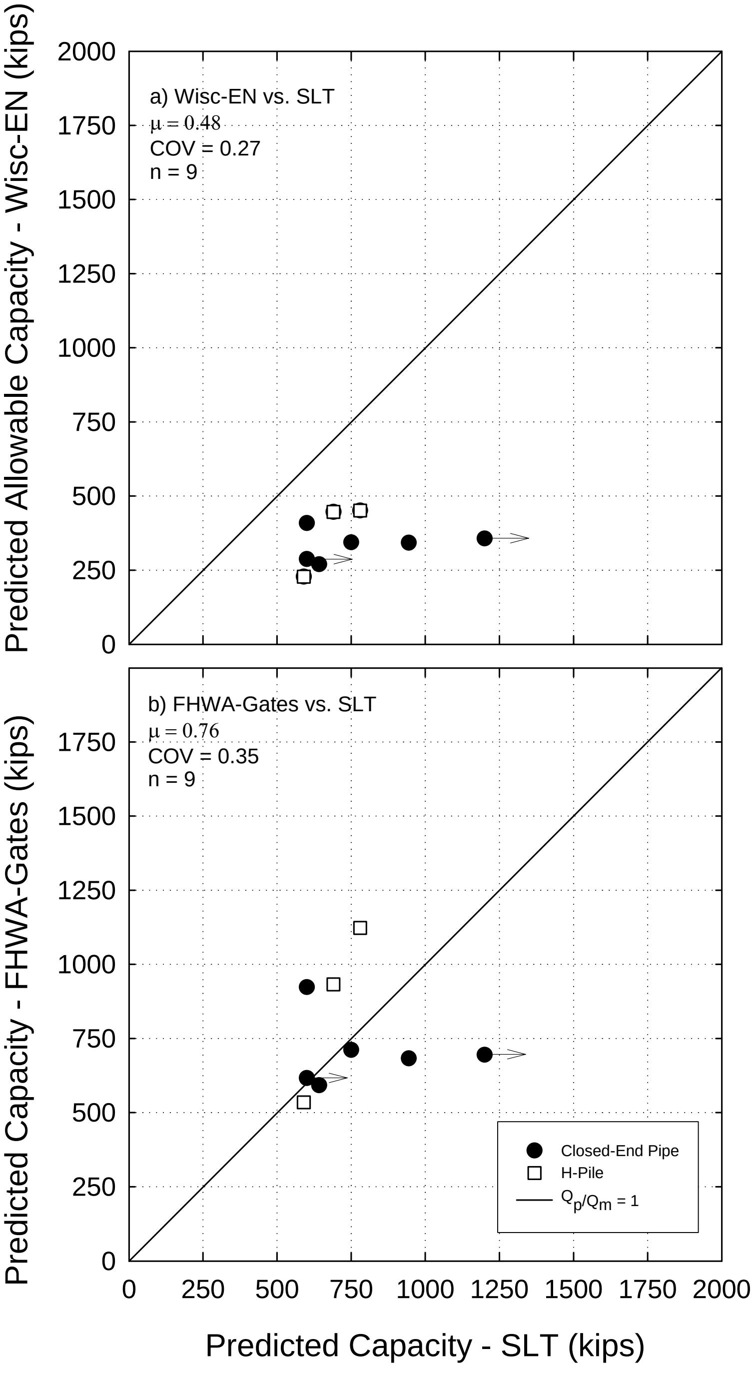


Figure 5.12. Wisc-EN and FHWA-Gates vs. SLT

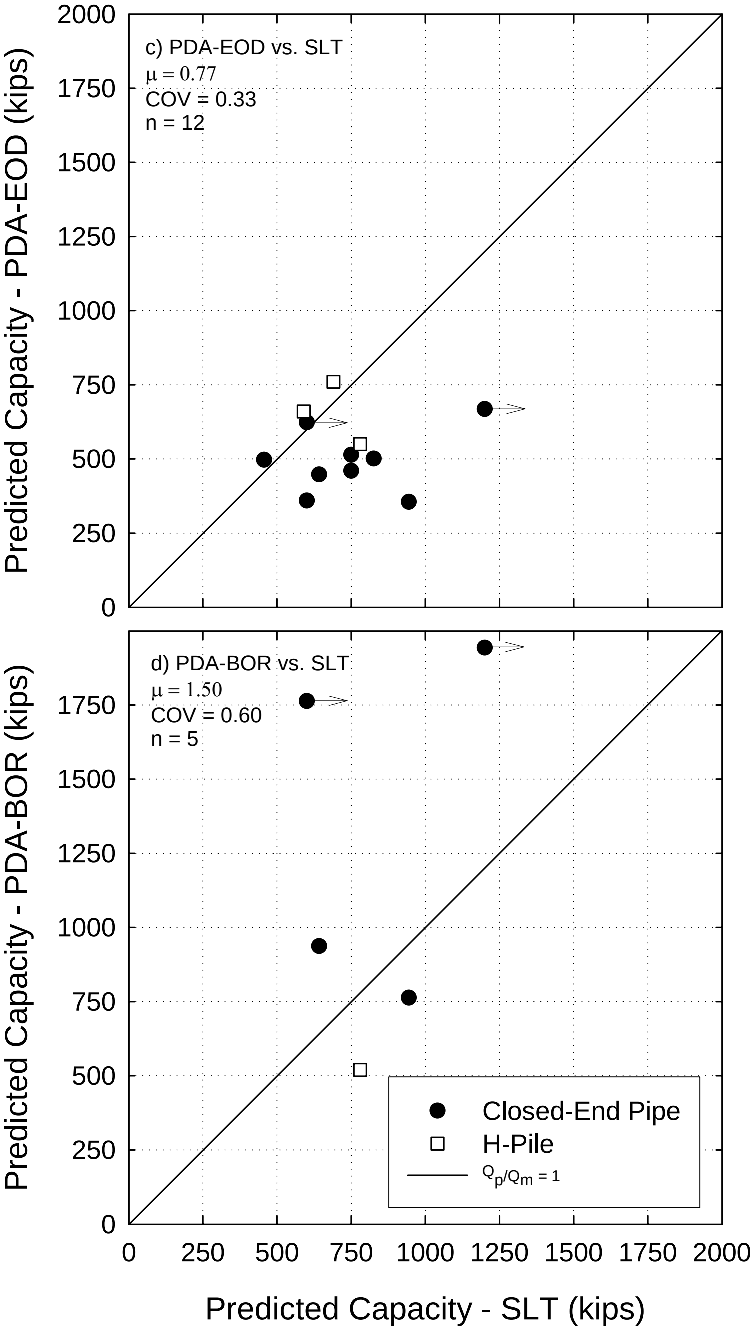


Figure 5.13. PDA-EOD and PDA-BOR vs. SLT

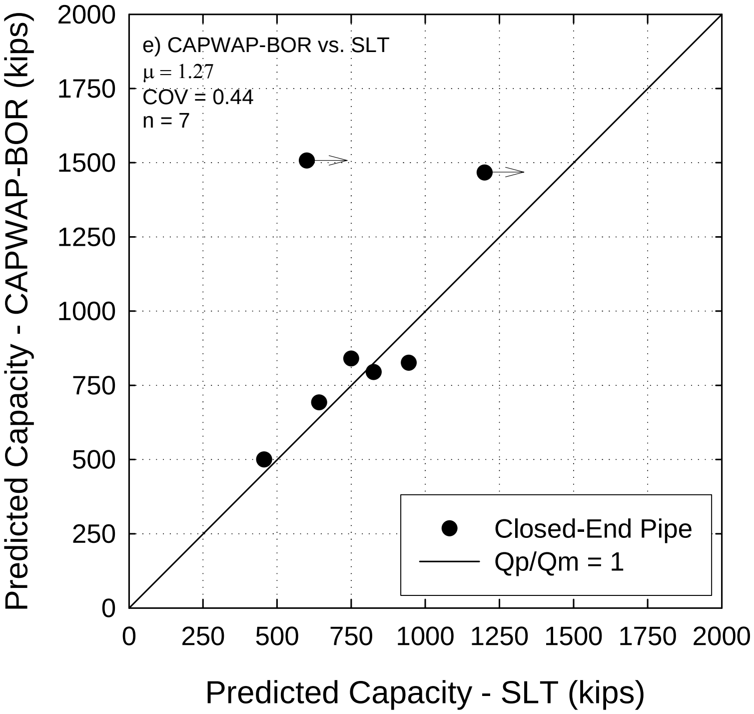


Figure 5.14. CAPWAP-BOR vs. SLT

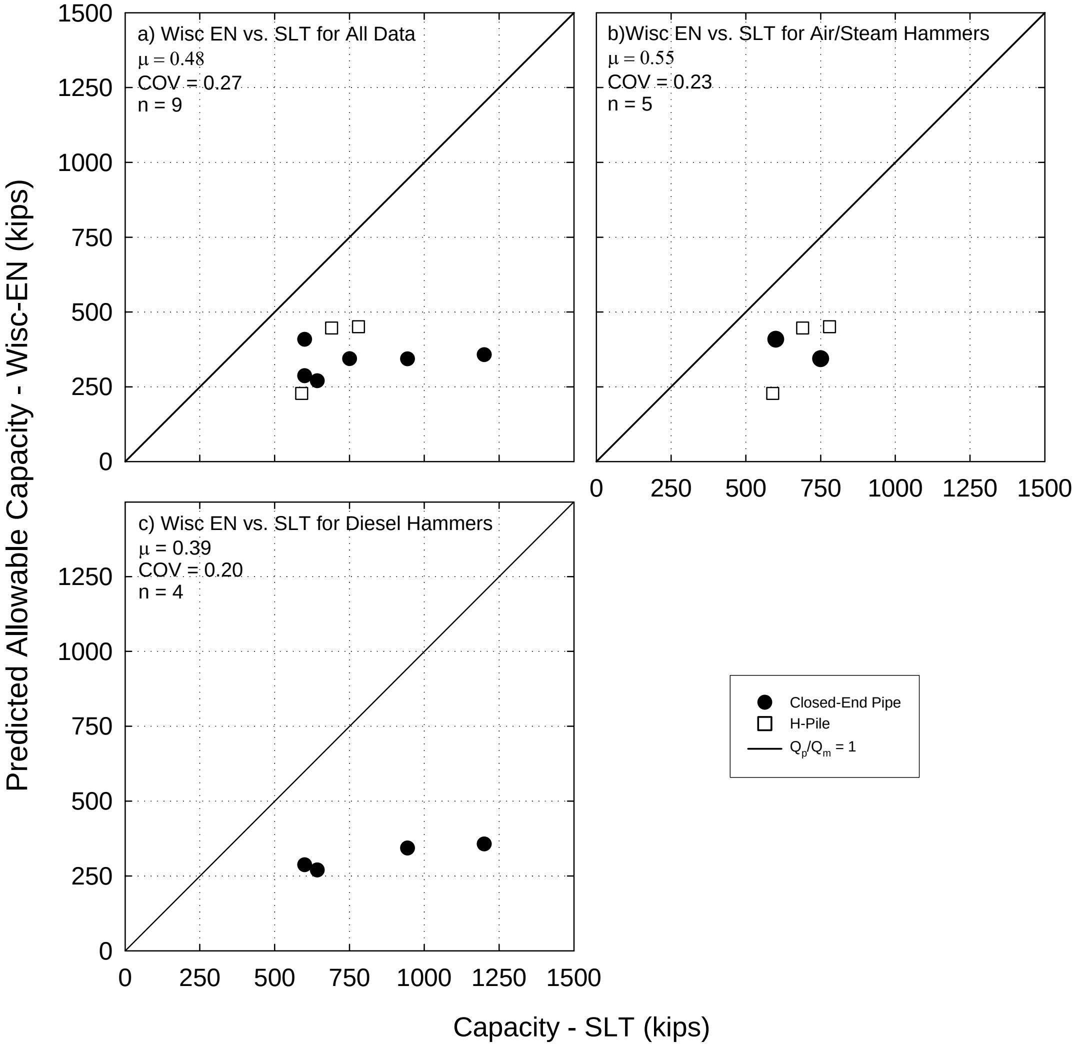


Figure 5.15. Wisc-EN vs. SLT Broken Down by Hammer Type

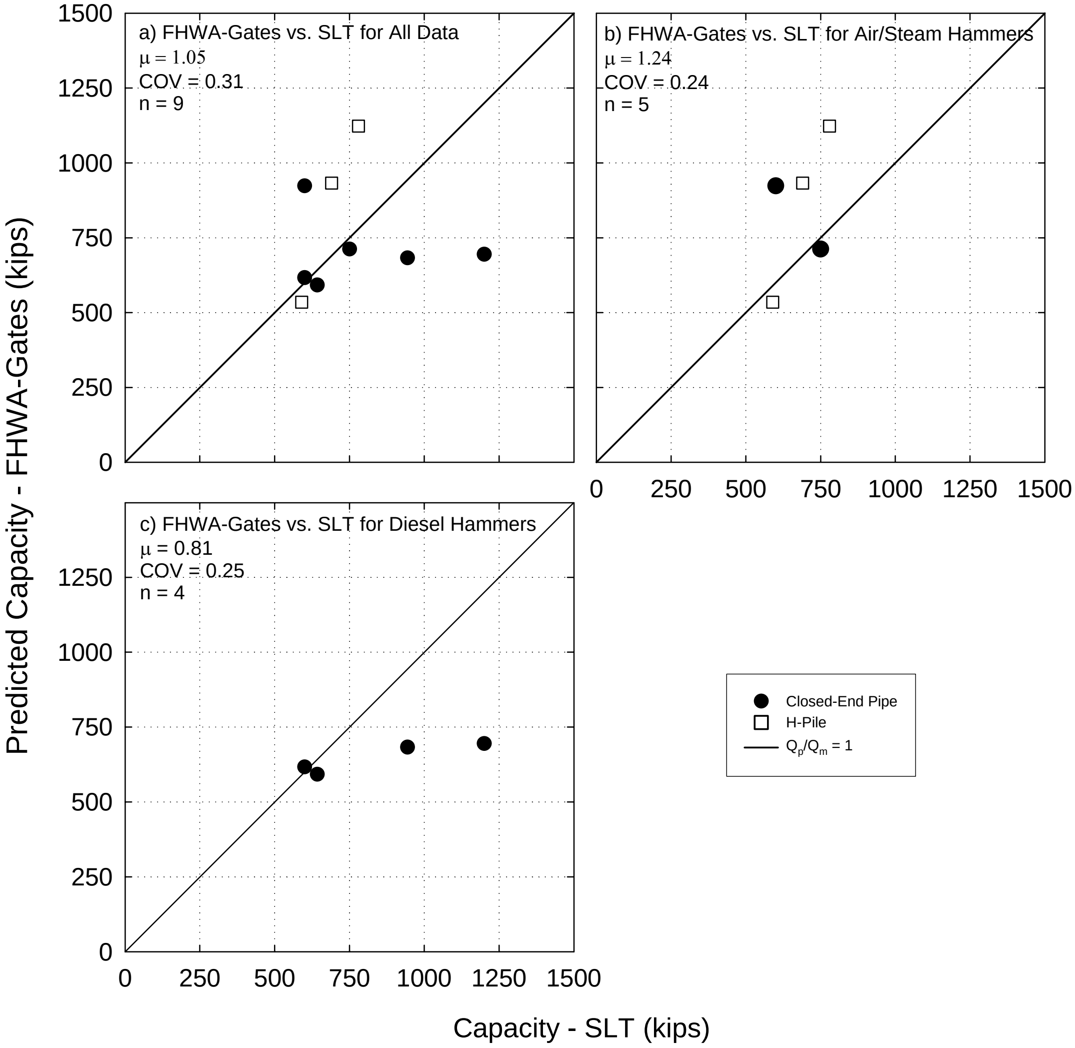


Figure 5.16. FHWA-Gates vs. SLT Broken Down by Hammer Type

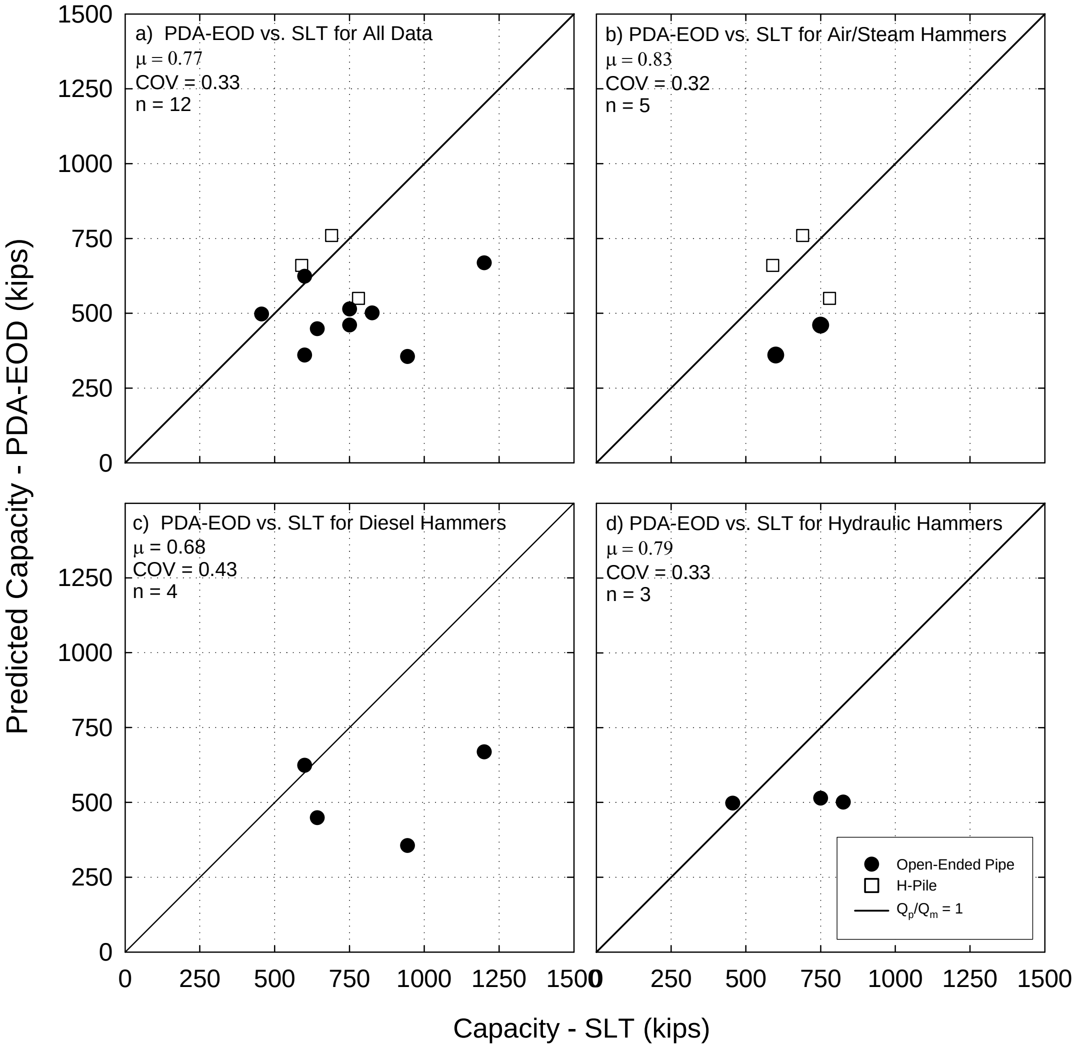


Figure 5.17. PDA-EOD vs. SLT Broken Down by Hammer Type

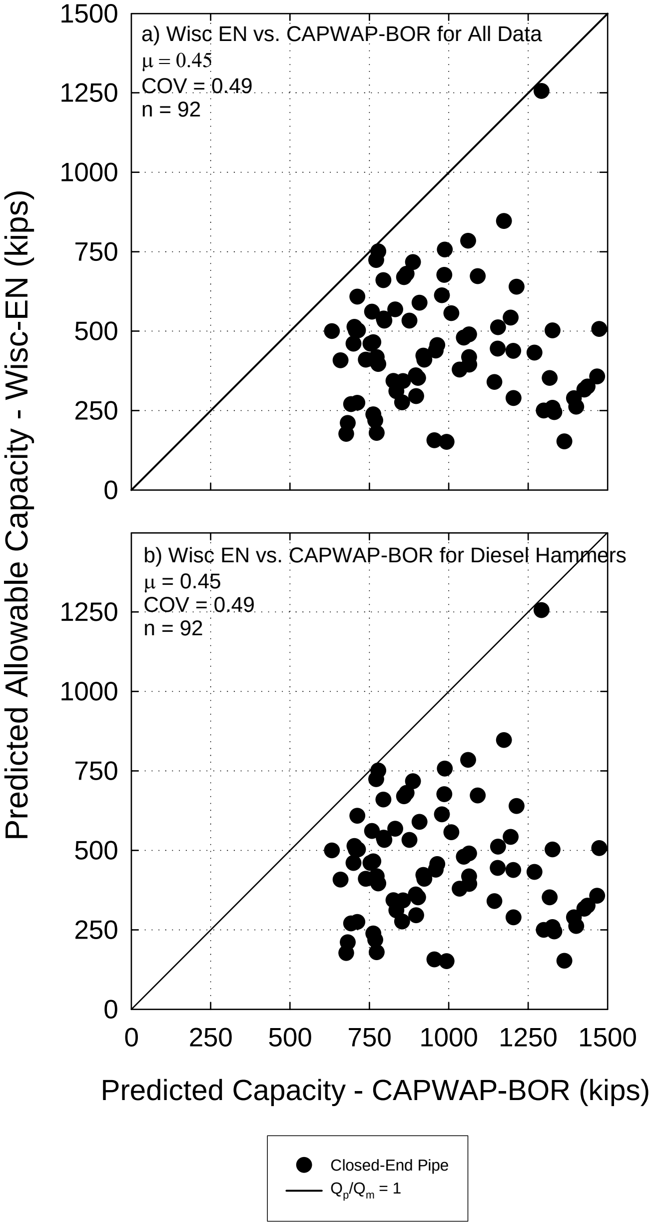


Figure 5.18. Wisc-EN vs. CAPWAP-BOR Broken Down by Hammer Type

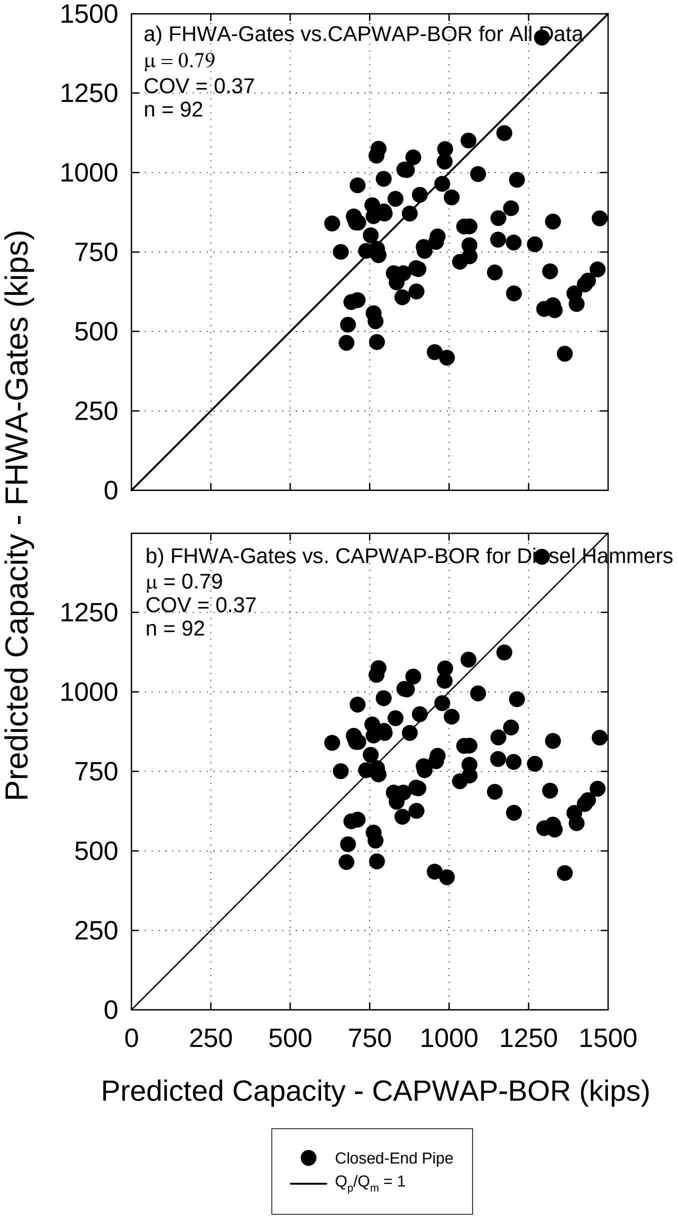


Figure 5.19. FHWA-Gates vs. CAPWAP-BOR Broken Down by Hammer Type

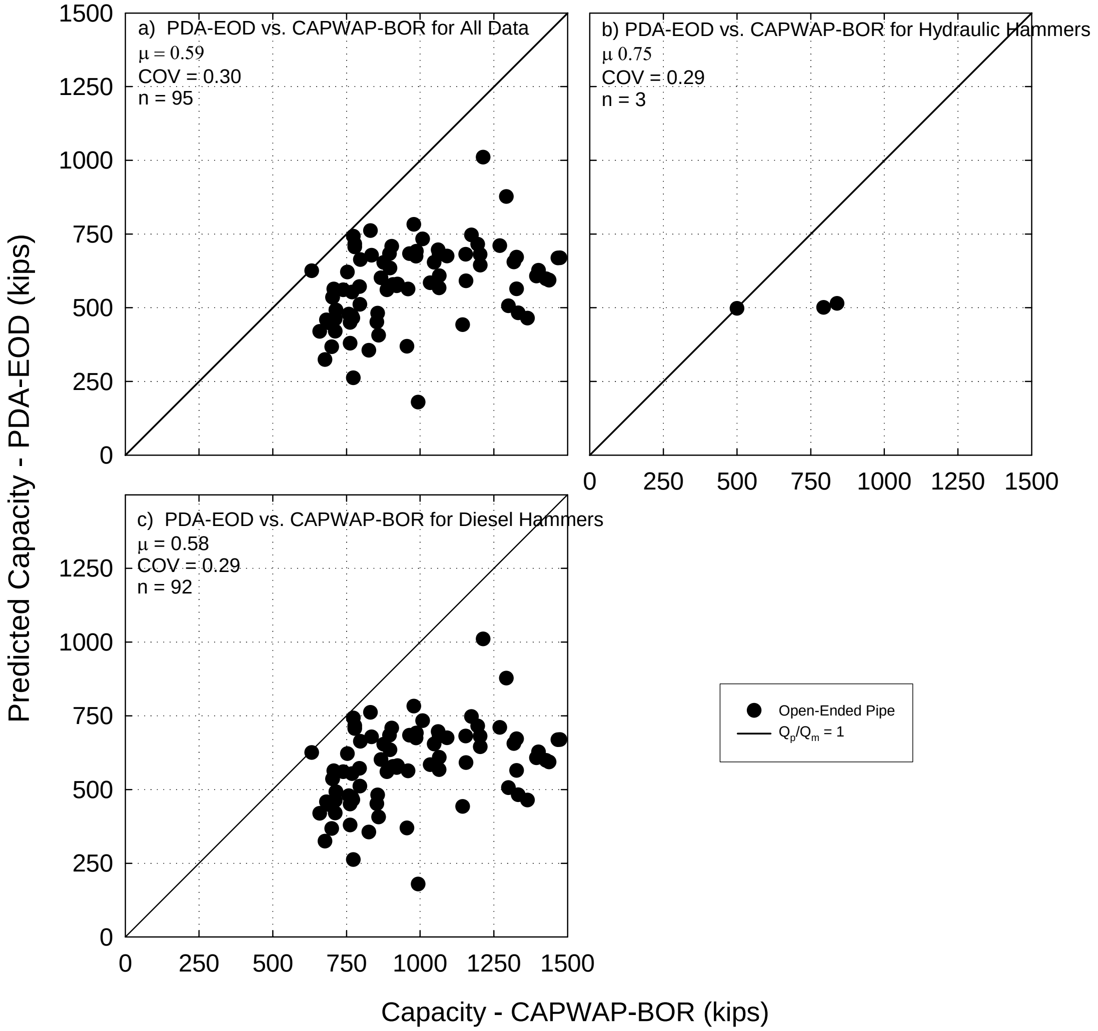


Figure 5.20. PDA-EOD vs. CAPWAP-BOR Broken Down by Hammer Type

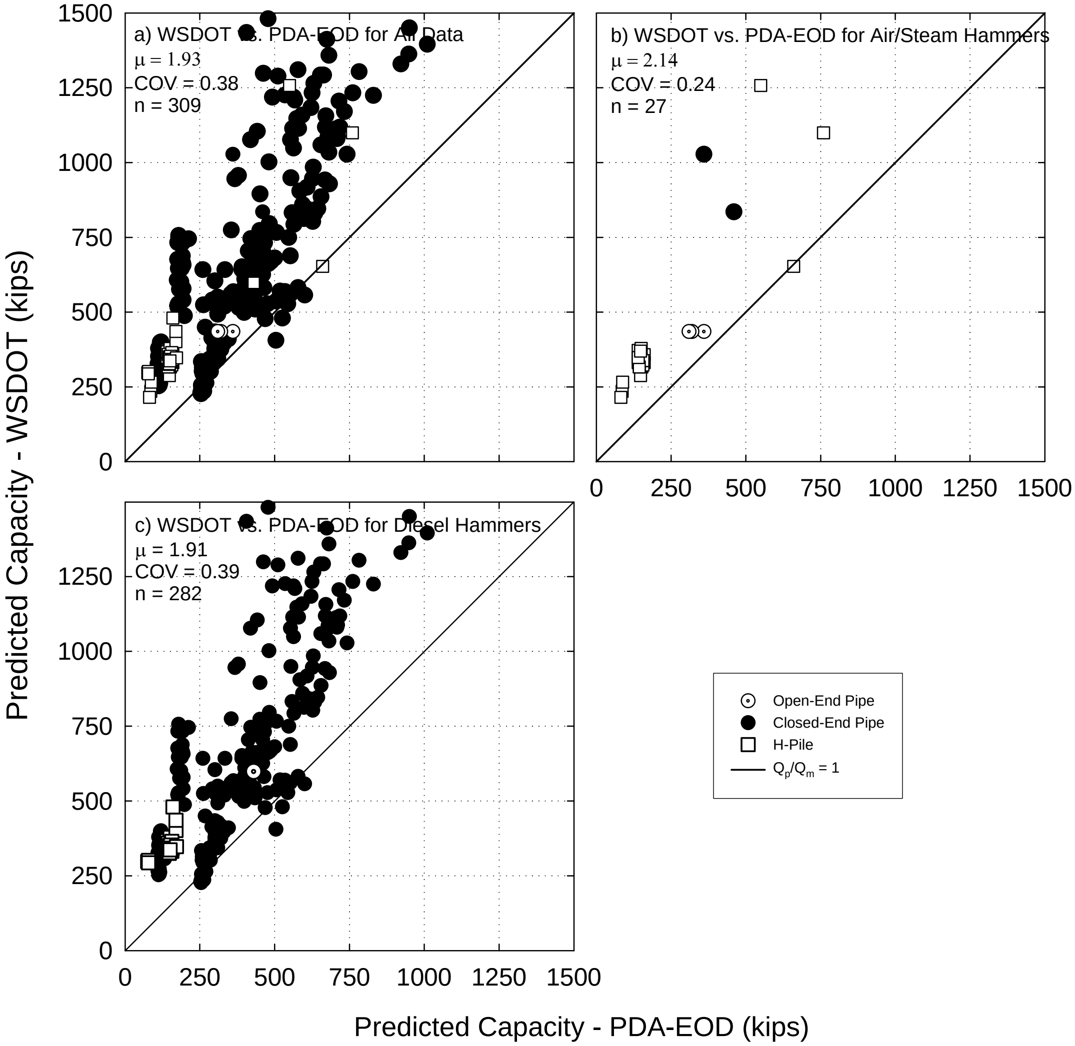


Figure 5.21. WSDOT vs. PDA-EOD Broken Down by Hammer Type

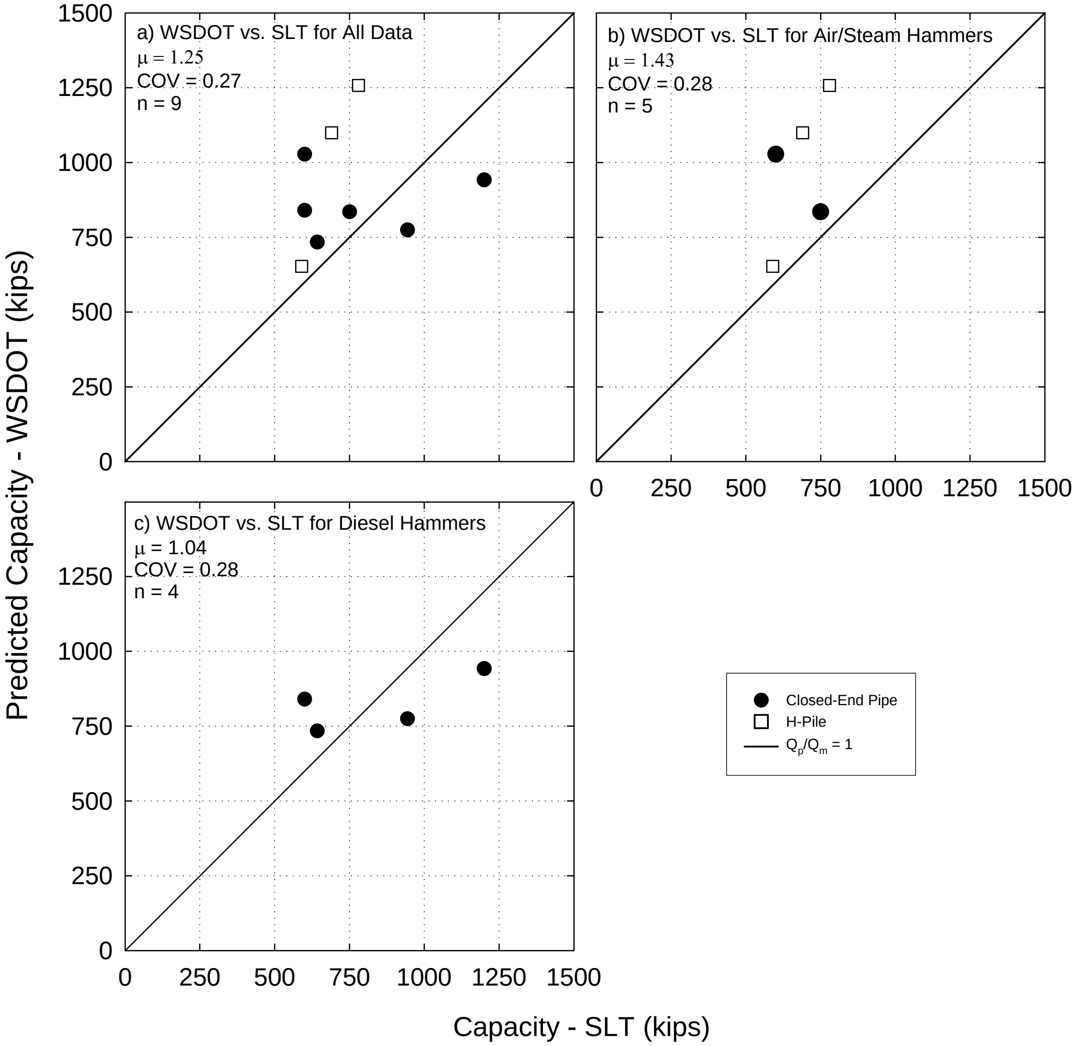


Figure 5.22. WSDOT vs. SLT Broken Down by Hammer Type

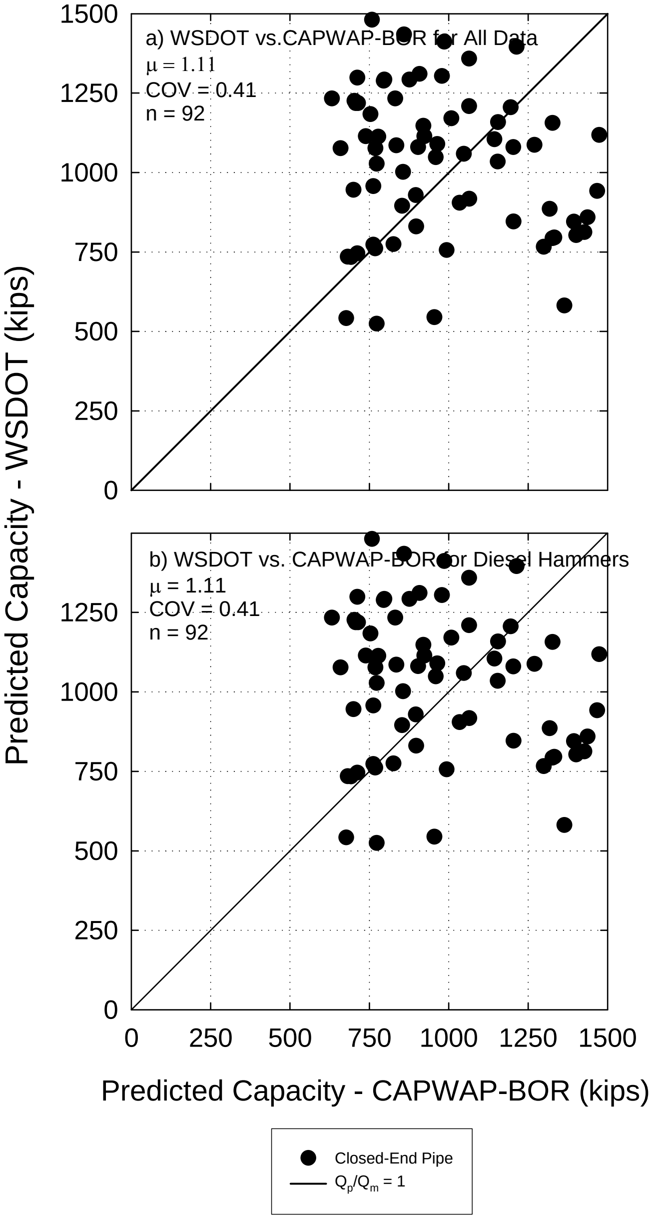


Figure 5.23. WSDOT vs. CAPWAP-BOR Broken Down by Hammer Type

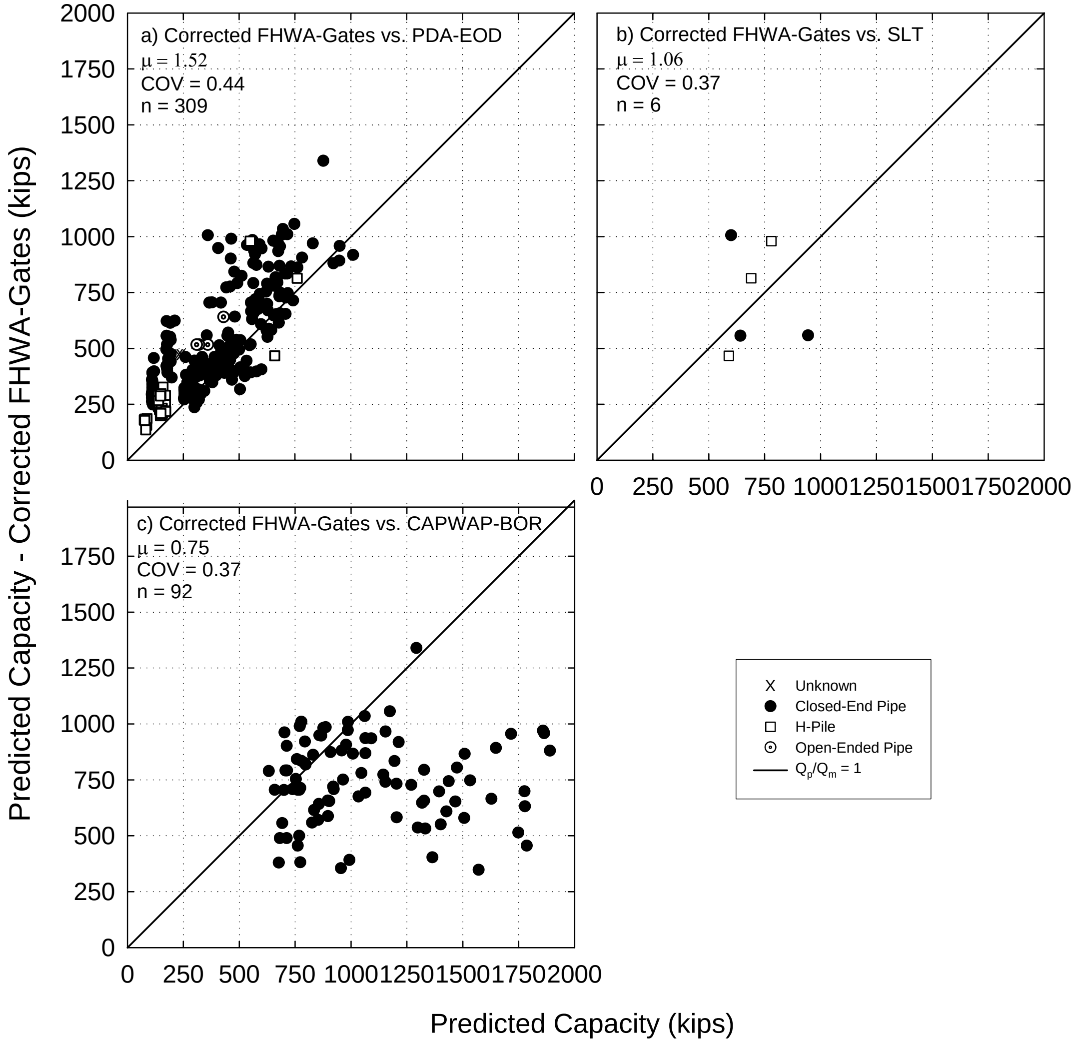


Figure 5.24. Corrected FHWA-Gates vs. Predicted Capacities

Chapter 6

6.0 RESISTANCE FACTORS AND IMPACT OF USING A SPECIFIC PREDICTIVE METHOD

6.1 INTRODUCTION

Two databases have been used to investigate the accuracy and precision of the following five predictive methods: EN-Wisc, FHWA-Gates, WSDOT, PDA, and a "corrected" FHWA-Gates. A higher degree of confidence is applied to the statistics from the first database because a static load test was conducted for each of these piles. The statistics determined in Chapters 4 and 5 will be used to compare the consequence of using a particular method. Comparisons will be developed for Factors of Safety and for Resistance factors. Analyses are also conducted to allow comparison of the efficiency for each of the methods.

6.2 SUMMARY OF PREDICTIVE METHODS

The mean value of Q_P/Q_M and the coefficient of variation, for each of the predictive methods are summarized below.

Mean	COV	Method
0.43	0.47	EN-Wisc
1.13	0.42	FHWA-Gates
0.73	0.40	PDA
1.11	0.39	WSDOT
1.02	0.36	"corrected" FWHA-Gates for piles <750 kips

The "accuracy" of a predictive method is associated with the mean value. Mean values closer to unity do a better job, on the average, of predicting capacity. All methods with mean values not equal to unity can be "corrected" by multiplying the predicted pile capacity by a factor equal to the inverse of the mean. 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 mean, the cov for a method cannot be improved by multiplying the predicted capacity by a constant. Accordingly, the cov will be used to identify desirable predictive methods.

The predictive methods listed on the previous page are arranged in order of decreasing cov, meaning that the EN-Wisc method is the least precise of the methods investigated, and the "corrected" FHWA-Gates is the most precise. The three methods in the middle, FHWA-Gates, PDA, and WSDOT exhibit similar cov's.

6.3 FACTORS OF SAFETY AND RELIABILITY

Greater values of Factor of Safety (FS) are used to increase the safety and reliability for a design. The statistical parameters can be used to quantitatively associate a FS with reliability as discussed in Long and Maniaci (2001). However, two assumptions are necessary to make these comparisons: 1) the load is known, and 2) the distribution of predicted capacity to measured capacity is log-normal. The first assumption is made for simplicity to allow comparison between the methods. The second assumption is a fair representative of distribution typically observed for predicted versus measured capacity.

A graph relating the required FS for a degree of reliability is shown in Figure 6.1. There are two horizontal axes: 1) Reliabilty Index, and 2) Reliabilty. The two axes are related theoretically. The reliability index is simply the number of standard deviations above the mean value, whereas the reliability is the probability the pile will not fail when subjected to the specified load. The Reliability Index is the metric preferred by most agencies and will be used herein. The graph allows the user to identify the FS required for a given degree of reliability. For example, using a FS = 1 with the EN-Wisc method results in a foundation with a reliability index of 2.1 and a corresponding reliability of over 98 percent. Factors of Safety required to achieve the same reliability would be 2.4, 1.5, 2.3, and 2.0 for FHWA-Gates, PDA, WSDOT, and corrected FHWA-Gates, respectively.

The graph illustrates that different predictive methods require different FS to achieve the same degree of reliability. These values for FS are affected significantly by the mean and cov of the predictive method.

6.4 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 NCHRP507 and are identified as: 1) the first order second moment method (FOSM), and 2) the first order reliability method (FORM).

6.4.1 First Order Second Moment (FOSM)

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

$$\phi = \frac{\lambda_R\left(\frac{\gamma_D Q_D}{Q_L}+\gamma_L\right)\sqrt{\left[\frac{\left(1+COV_{Q_D}^2+COV_{Q_L}^2\right)}{\left(1+COV_R^2\right)}\right]}}{\left(\frac{\lambda_{Q_D} Q_D}{Q_L}+\lambda_{Q_L}\right)\exp\left\{\beta_T\sqrt{\ln\left[\left(1+COV_R^2\right)\left(1+COV_{Q_D}^2+COV_{Q_L}^2\right)\right]}\right\}} \tag{6.1}$$

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 6.1:

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 3.5)
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 6.1 is 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 6.1.

Using Eqn. 6.1 with the statistical parameters in Table 6.1, the resistance factor was determined for several values of the Target Reliability Index (β_T). The results are shown in Fig. 6.2 for each of the predictive methods.

NCHRP507 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 6.1 provides values of the resistance factors for each of target reliability values of 2.33 and 3.0 for each of the predictive methods using the FOSM.

6.4.2 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 6.1, and requires an iterative procedure to determine reliability index based upon an assumed value for the resistance factor. The FORM method is the preferred method used for determining resistance factors in NCHRP507.

Shown in Fig. 6.3 are the results of FORM analyses. The resistance factors are slightly higher (approximately 10 percent higher) using the FORM and are presented in Table 6.2 for target reliability values of 2.33 and 3.0.

6.5 EFFICIENCY FOR THE METHODS AND RELIABILITY

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 error 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 the 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. 6.4 and 6.5 are plots of efficiency (ϕ/λ) for target reliability values between 2 and 3.5 for the FOSM method and FORM method, respectively. The efficiencies for the FORM method are slightly higher than for the FOSM method.

The graphs (Figs. 6.4 and 6.5) provide a means to compare the efficiency for different methods. For example, compare the efficiency of the Wisc-EN formula with the corrected FHWA-Gates method for a single pile. The efficiency is 0.18 for the EN-Wisc method at a reliability index of 3.0 whereas the efficiency is 0.32 for the corrected FHWA-Gates method. The ratio of 0.32/0.18 equals about 1.8 which means the Wisc-

EN method would require an additional capacity of 80 percent compared to the corrected FHWA-Gates.

6.6 IMPACT OF MOVING FROM FS DESIGN TO LRFD

The Wisconsin DOT currently uses a FS approach for foundation design and is considering migrating to LRFD. An approach is presented herein to attempt to assess how this will impact foundation design.

6.6.1 Factor of Safety Approach

Currently, the Wisconsin DOT uses the EN-Wisc driving formula for pile foundations. The safe bearing load for the pile (Ultimate Capacity/FS) is determined using the EN-Wisc method. The load on the pile is considered to be the sum of the live load plus the dead load. These loads are not factored loads.

$$Load \le Capacity(ENWisc) = \frac{UltimateCapacity}{FS} = \frac{UltimateCapacity}{\lambda} \qquad (6.2)$$

where λ is the average value of measured capacity divided by predicted capacity. The loads are taken to be the sum of live load and dead loads without any factors applied. The value of λ for the EN-Wisc method is 3.11 (Table 6.1); therefore, equation 6.2 simplifies to

$$3.11 * Load \le UltimateCapacity \qquad (6.3)$$

which means that the ultimate capacity is required to be at least 3.11 times the sum of dead load and live load.

6.6.2 Reliability Index for Factor of Safety Approach and LRFD

Equation 6.1 is used to establish an overall reliability for this approach (based on FOSM). The following parameters are used to be consistent with the current FS approach used by Wisconsin DOT:

1) a resistance factor equal to 1.0 is used to reflect the practice of using the EN-Wisc formula as a safe bearing load,

2) load factors for dead load and live load are equal to 1.0 to reflect the use of an unfactored load, and

3) statistical factors for EN-Wisc (Table 6.1) are used.

Using the values for parameters discussed above and Eqn. 6.1, a value for the reliability index (β_T) is determined to be 1.49 for the FOSM. A reliability index equal to 1.55 is determined using the same parameters along with the FORM. These values for reliability index are significantly less than the value of 2.33 recommended in current LRFD procedures. Requiring a higher degree of reliability implies that a migration to LRFD will impose a greater demand on bridge foundations.

A simple example is given below to estimate the increase in demand on the foundation required by a transition to LRFD. This example assumes that the EN-Wisc method will be used to determine capacity for the LRFD approach.

$$\gamma_{LL} * LL + \gamma_{DL} * DL \leq \phi(ENWisc) \tag{6.4}$$

Recognizing that the ultimate capacity is equal to the predicted capacity divided by the bias (λ), Eqn. 6.4 can be rewritten as

$$\gamma_{LL} * LL + \gamma_{DL} * DL \leq \left(\frac{\phi}{\lambda}\right) UltimateCapacity \tag{6.5}$$

LRFD uses load factors of 1.25 for dead load and 1.75 for live load. Using a ratio of dead load to live load equal to 2.0, the equivalent load factor is 1.42 and Eqn. 6.5 can be simplified to

$$1.42 * Load \leq \left(\frac{\phi}{\lambda}\right) UltimateCapacity \tag{6.6}$$

Results of this study indicate ϕ is 0.84 (FOSM) for the EN-Wisc formula at a reliability index equal to 2.33 and the bias is 3.11. Thus, Eqn 6.6 can be written as

$$5.26 * Load \leq UltimateCapacity \qquad (6.7)$$

Accordingly, the migration to LRFD will place a 69 percent (5.26/3.11=1.69) greater requirement on foundation capacity. If the same procedure is repeated using the FORM for ϕ (0.9), then there is a 58 percent greater requirement (4.9/3.11 = 1.58). These ratios represent a significant increase in demand for capacity.

6.6.3 Impact of Using a More Accurate Predictive Method

Some of the increase in required capacity can be mitigated by using a more efficient predictive method as identified in this current report. A more efficient method will require less excess capacity to meet the same level of reliability. A means to quantify the relative effect would be to determine the ultimate capacity required for a more efficient method and compare results with the EN-Wisc method.

The "corrected" FHWA-Gates method is used as an alternative predictive method. The resistance factor is 0.49 at a reliability index value of 2.33 (using FOSM), and the bias is 1.14 (from Table 6.1). Using these factors along with Eqn. 6.6,

$$1.42 * Load \leq \left(\frac{\phi}{\lambda}\right) UltimateCapacity = \left(\frac{0.49}{1.14}\right) UltimateCapacity \qquad (6.8)$$

which can be simplified to

$$3.30 * Load \leq UltimateCapacity \qquad (6.7)$$

The value of 3.30 times the load is 6 percent greater than the factor, 3.11, used in current Wisconsin DOT practice.

Accordingly, a switch from the current practice (Factor of Safety Approach) to LRFD will significantly increase the demand for foundation capacity, however, a simultaneous migration to a more accurate and precise method of prediction will mitigate the increased demand in terms of the overall foundation design.

The overall change in capacity has been determined for all predictive methods investigated in this study and is given in Table 6.3 as the ratio of ultimate capacity required for a predictive method/the ultimate capacity required using current Wisconsin DOT procedures. The ratios are determined for FOSM and FORM methods. Using FORM results in less change (ratios closer to 1.0) because resistance factors (and efficiency factors) are greater using this method. The two predictive methods, "corrected" FHWA-Gates and WSDOT, indicate less than a ten percent change in ultimate capacity using FORM results.

6.7 CONSIDERATION OF THE DISTRIBUTION FOR Q_M/Q_P

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 statistics and resistance factors based on a fit to the extremal data. This procedure is sometimes referred to as "fitting the tail" of the distribution. The distribution for the smallest 50 percent of the Q_M/Q_P data were used to determine the best fit.

6.7.1 Resistance Factors Based on Extremal Data

Figure 6.6 exhibits the cumulative distribution of Q_M/Q_P for the WSDOT predictive method using the pile load test data from the National Database discussed in Chapter 4. The statistics as given in Table 6.2 (bias = 1.07, COV = 0.45) provide a fit to all the data and the theoretical distribution is shown as a solid line in Fig. 6.6. The distribution of the data is approximated roughly by the solid line, however, the real distribution appears to be more bi-linear. The theoretical distribution indicates a greater probability for smaller values of Q_M/Q_P than the Q_M/Q_P data. A second line, shown as a dashed line, in Figure 6.6 is fit to the smaller values of Q_M/Q_P by adjusting the mean and COV. 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 (corrected-FHWA, WSDOT, and FHWA-Gates) and are shown in Table 6.4.

The National 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 very similar, but slightly lower as given in Table 6.5.

Based on fits to the extremal portion of the National Database with and without the Q_M/Q_P data from the Washington State data, the following recommendations for β_T = 2.33 are made for the three methods:

Method	ϕ
Corrected-FHWA	0.61
WSDOT	0.55
FHWA	0.47

6.7.2 Efficiency Factors Based on Extremal Data

Efficiencies for the different methods discussed in section 6.5 of this chapter were based on the overall best fit to the Q_M/Q_P data. Fitting extremal data increases the resistance factor, ϕ, and therefore, the efficiencies of these methods were re-evaluated for β_T = 2.33 and for using the FORM, and are shown in Table 6.6. The efficiency factors based on extremal data increase 25 to 30 percent for the corrected Gates and for the WSDOT methods, and improve about 20 percent for the FHWA-Gates method.

6.7.3 Impact on Capacity Demand using Efficiency Factors Based on Extremal Data

Section 6.6 used a simple approach to quantify the impact of transitioning from the Factor of Safety approach to the LRFD. The comparison is based on the "Capacity Demand" which is defined as the ratio of the ultimate capacity required for a foundation to the sum of the unfactored dead load and live load (Eqn. 6.6). The capacity demand depends on the load factors, the resistance factor, and the bias. The current FS approach using the EN-Wisc formula results in a Capacity Demand of 3.11. Section 6.6.3 compares the Capacity Demand for the other methods with the EN-Wisc method and results are shown in Table 6.3. The value of Capacity Demand decreases for the three formulas, FHWA-Gates, Corrected Gates, and WSDOT as shown in Table 6.7.

6.8 SUMMARY AND CONCLUSIONS

Resistance factors and efficiency of methods were developed and ranked for five predictive methods. The predictive methods listed in order of increasing efficiency are as follows: EN-Wisc, Gates-FHWA, PDA, WSDOT, and "corrected" FHWA-Gates. 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 $\beta_T = 2.33$ and 3.0 are provided in Tables 6.1 and 6.2 for the FOSM and FORM, respectively. These statistics were based on a fit to all the data, and assume the data are log-normally distributed. Resistance factors were also based on a refined fit to the extremal Q_M/Q_P data. The fit to the extremal data allow the predicted distribution of Q_M/Q_P to be more representative of the observed distribution at small probabilities. Accordingly, new and more appropriate resistance factors based on extremal data are given in Tables 6.4 and 6.5. Recommended resistance factors for the three formulae with the lowest degree of scatter are as follows:

Method	ϕ
Corrected-FHWA	0.61
WSDOT	0.55
FHWA	0.47

The impact of moving from the current foundation practice to LRFD will significantly increase the demand for foundation capacity by about fifty percent if the EN-Wisc method continues to be used with LRFD. However, the increase in capacity can be mitigated to a considerable degree by replacing the EN-Wisc method with a more efficient method, such as the "corrected" FHWA-Gates method or the WSDOT method. If the more accurate methods are used, the overall demand for foundation capacity should remain the same within about 15 percent.

Table 6.1 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	
			$\beta_T = 2.33$	$\beta_T = 3.0$
EN-Wisc	3.11	0.62	0.84	0.56
FHWA- Gates	1.09	0.50	0.39	0.28
PDA	1.67	0.50	0.60	0.42
WSDOT	1.07	0.45	0.42	0.31
“corrected” FWHA-Gates for piles <750 kips	1.14	0.41	0.49	0.37

Table 6.2 Statistical parameters and resistance factors for the Predictive Methods based on Q_M/Q_P values using FORM.

Predictive Method	bias, λ	cov	Resistance Factor, ϕ Using FORM	
			$\beta_T = 2.33$	$\beta_T = 3.0$
EN-Wisc	3.11	0.62	0.9	0.61
FHWA- Gates	1.09	0.50	0.42	0.31
PDA	1.67	0.50	0.64	0.47
WSDOT	1.07	0.45	0.46	0.34
"corrected" FWHA-Gates for piles <750 kips	1.14	0.41	0.54	0.42

Table 6.3 Ratio of Required Foundation Capacity (LRFD)/Required Foundation Capacity (existing Wisconsin DOT practice).

Predictive Method	Cap(LRFD)/Cap(existing) (FOSM)	Cap(LRFD)/Cap(existing) (FORM)
EN-Wisc	1.68	1.57
FHWA- Gates	1.27	1.18
PDA	1.27	1.18
WSDOT	1.15	1.07
“corrected” FWHA-Gates for piles <750 kips	1.04	0.96

Note: $\beta_T = 2.33$

Table 6.4 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
corrected-FHWA	1.04	0.31	0.63
WSDOT	0.88	0.28	0.56

Table 6.5 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
corrected-FHWA	1.01	0.33	0.59
WSDOT	1.02	0.27	0.54

Table 6.6 Comparison of Efficiency factors based on overall and extremal fits to Q_M/Q_P data with $\beta_T = 2.33$ and using FORM.

Predictive Method	**Efficiency (λ/ϕ)** **Fit to All Data**	**Efficiency (λ/ϕ)** **Fit to Extremal Data**
FHWA-Gates	0.43	0.54
corrected-FHWA	0.39	0.51
WSDOT	0.36	0.43

Table 6.7 Comparison of Capacity Demand based on overall and extremal fits to Q_M/Q_P data with $\beta_T = 2.33$ and using FORM (Capacity Demand for EN-Wisc is 5.26).

Predictive Method	**Ratio of Ultimate Capacity/Load** **Fit to All Data**	**Ratio of Ultimate Capacity/Load** **Fit to Extremal Data**
FHWA-Gates	3.97	3.55
corrected-FHWA	3.30	2.65
WSDOT	3.62	2.76

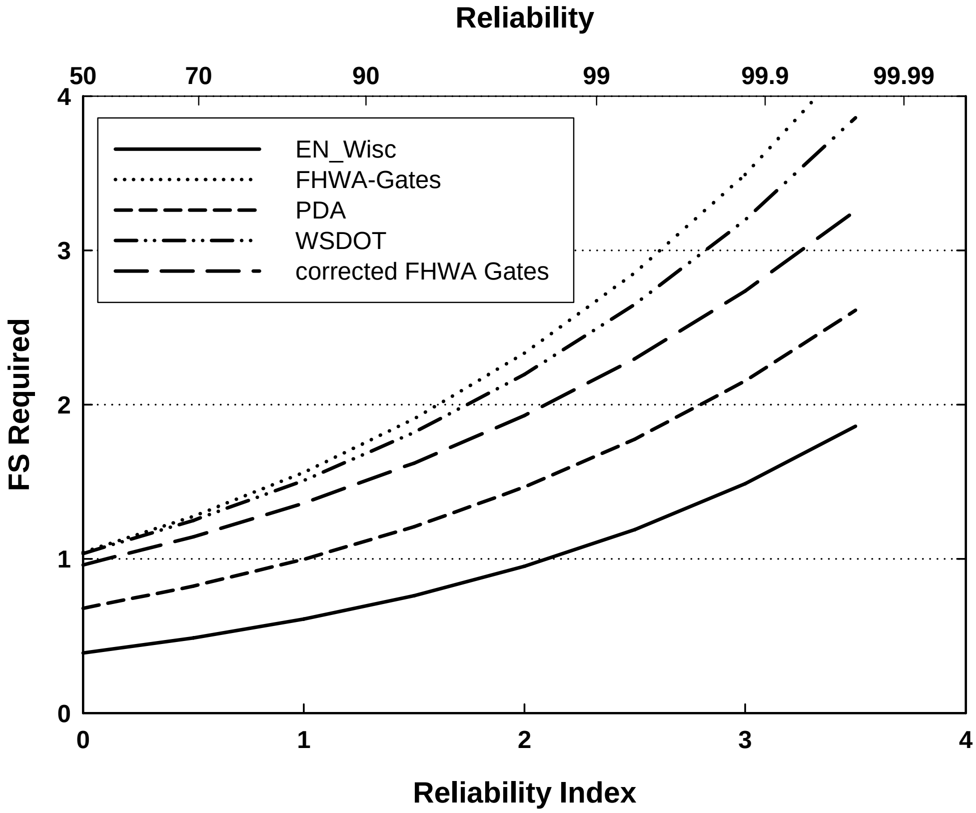


Figure 6.1 FS required versus Reliability for 5 predictive methods.

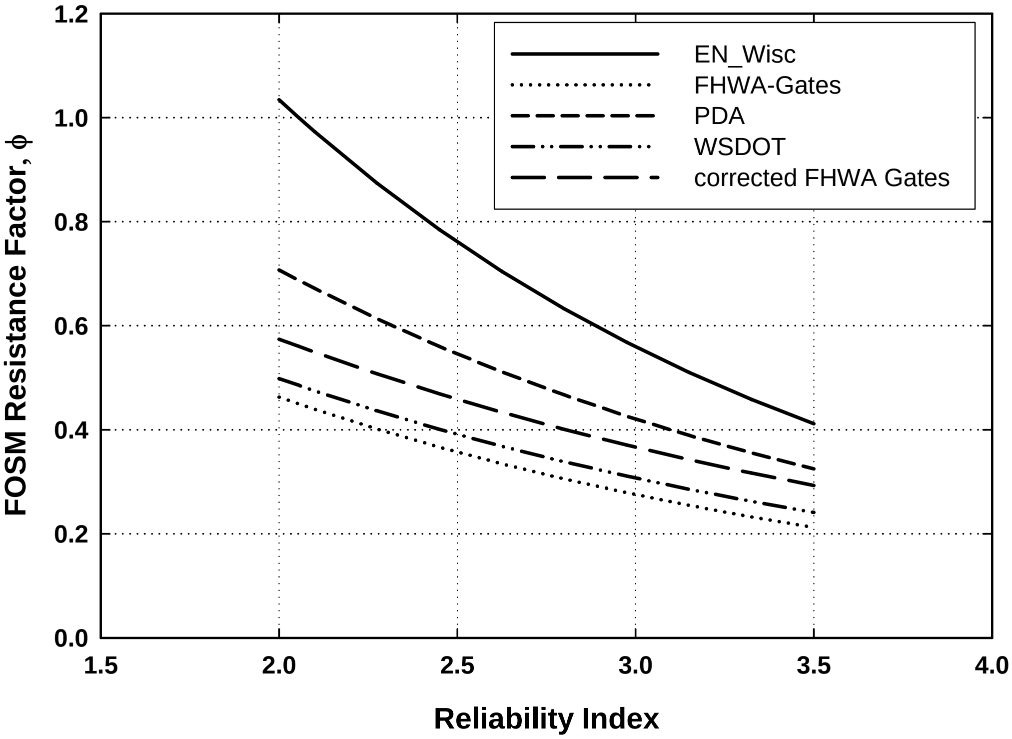


Figure 6.2 Resistance Factors versus Reliability Index for different predictive methods using FOSM.

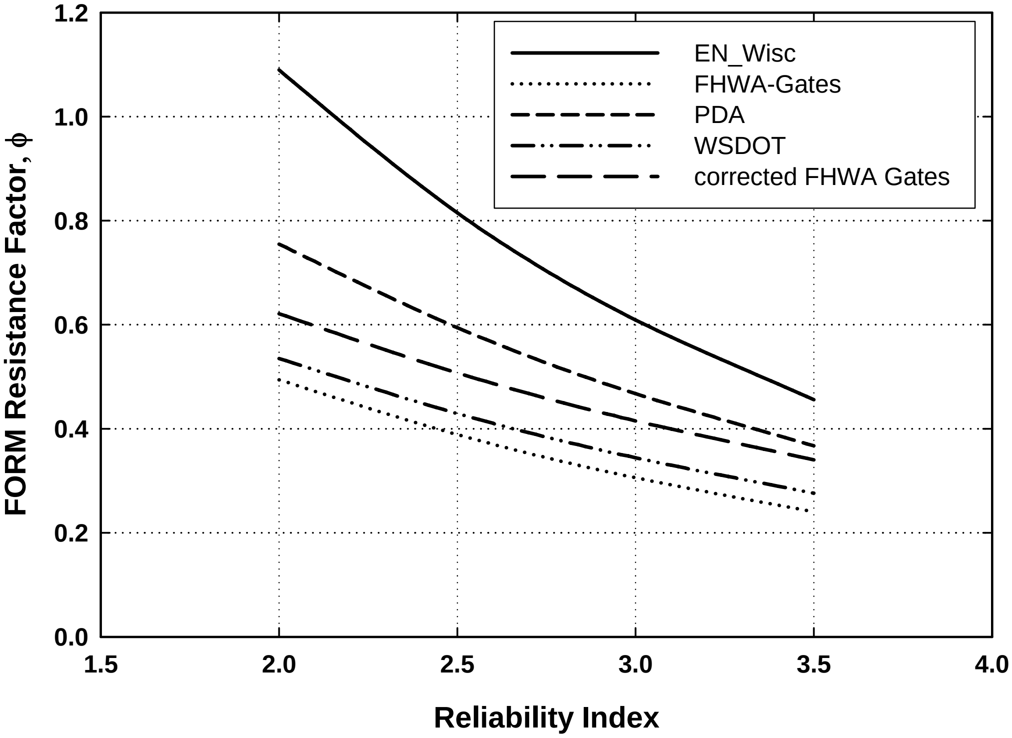


Figure 6.3 Resistance Factors versus Reliability Index for different predictive methods using FORM.

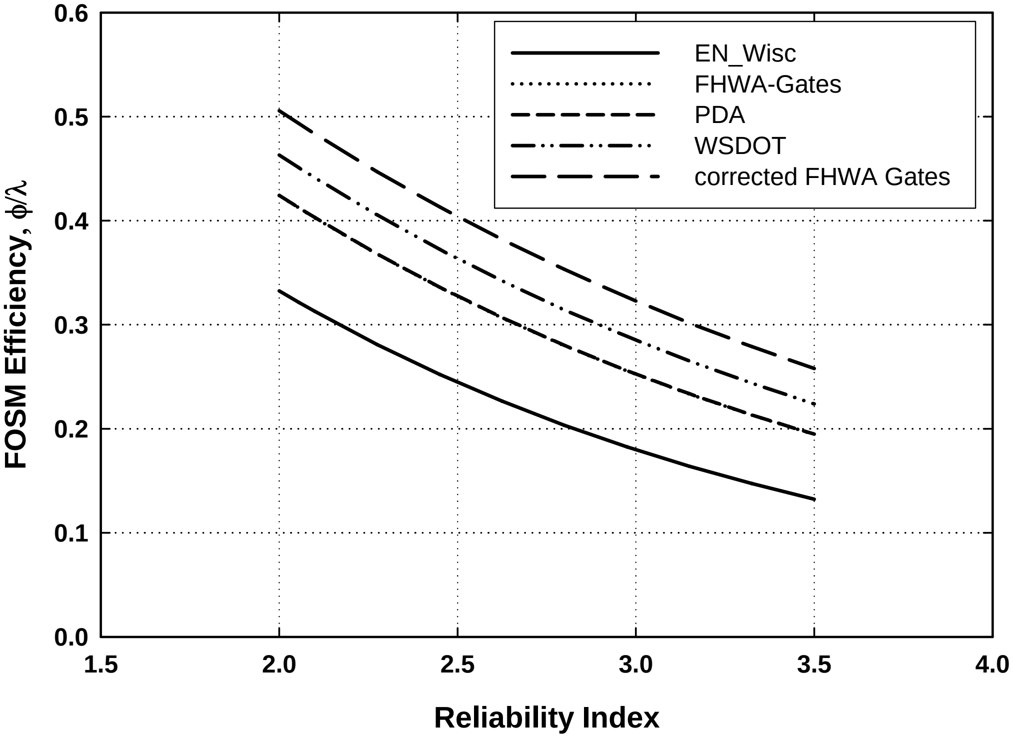


Figure 6.4 Efficiency versus Reliability Index for different predictive methods using FOSM.

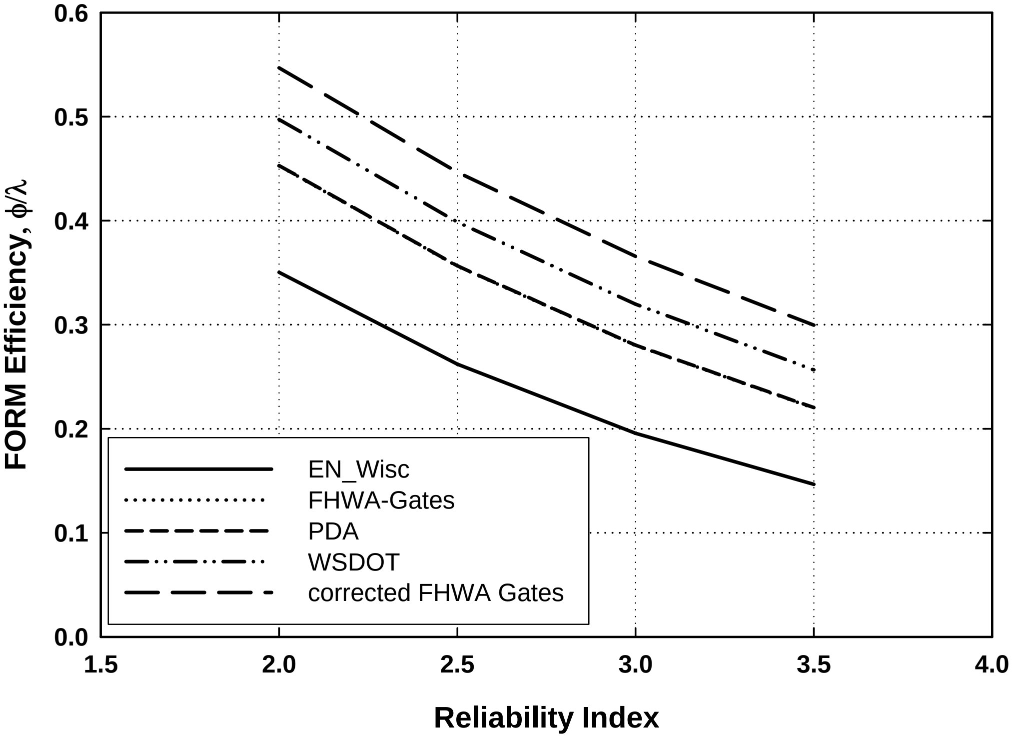


Figure 6.5 Efficiency versus Reliability Index for different predictive methods using FORM.

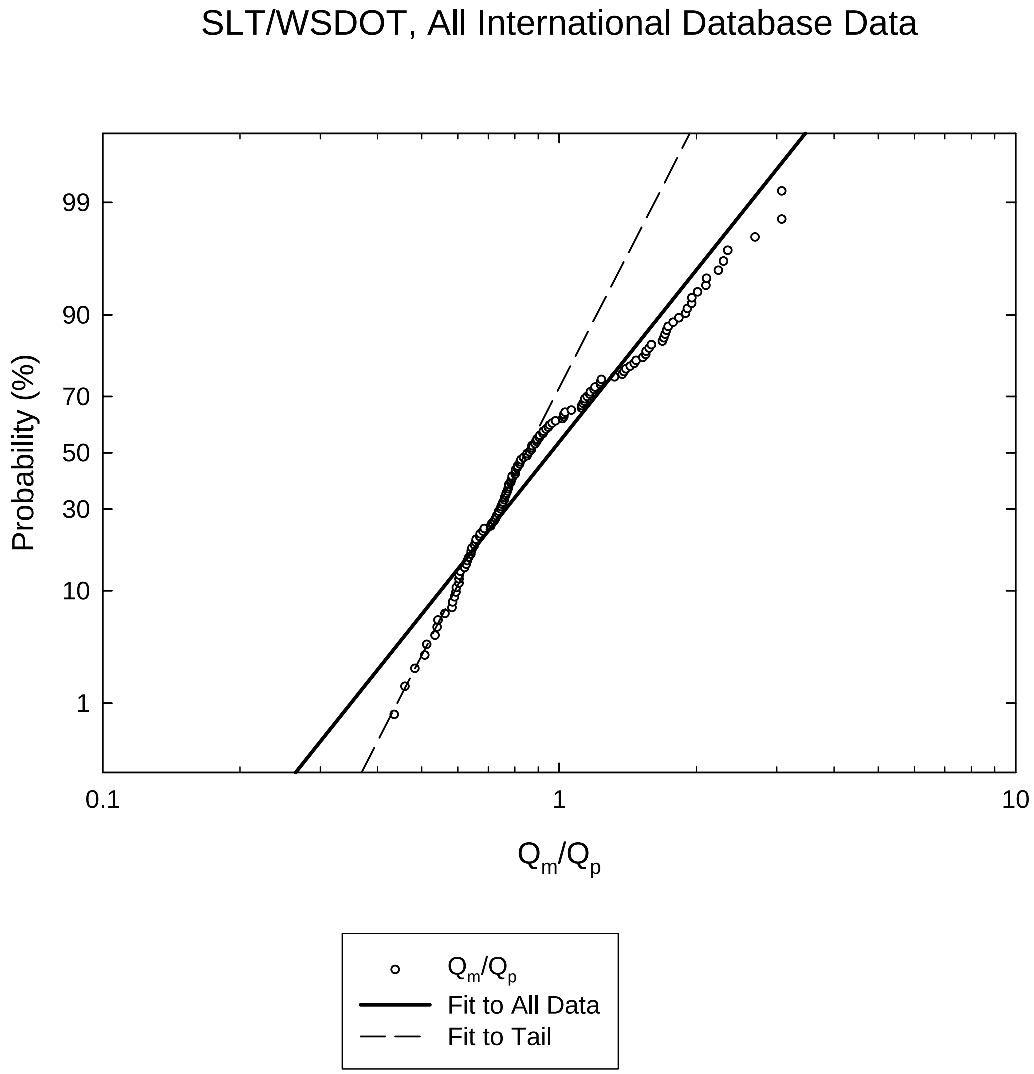


Figure 6.6. Cumulative distribution plot for WSDOT predictive method showing difference between fit to all data and fit to extremal data.

Chapter 7

7.0 SUMMARY AND CONCLUSIONS

Several methods are available for predicting axial pile capacity based upon the resistance of the pile during driving or during retapping. This study focused on four methods that use driving resistance to predict capacity: the Engineering News (EN-Wisc) formula, the FHWA-modified Gates formula (FHWA-Gates), the Washington State Department of Transportation formula (WSDOT), the Pile Driving Analyzer (PDA), and developed a fifth method, called the "corrected" FHWA-Gates. Major emphasis was given to load test results in which predicted capacity could be compared with capacity measured from a static load test.

The advantage of the FHWA-Gates, WSDOT, and Corrected FHWA-Gates is that predictions of pile capacity can be made with simple measurements from visual observation. While the dynamic formulae are simple to use, they do not model the mechanics of pile driving and they do not measure the energy being delivered by the pile driving hammer. The PDA method requires special equipment to monitor, record, and interpret the pile head accelerations and strains during driving and can determine with reasonable accuracy the energy delivered by the pile hammer. Furthermore, the PDA models the mechanics of the driving process more accurately than the pile driving formulae. Regardless of the advantages and disadvantages for each of these methods, the accuracy and precision for each of these predictive methods were investigated by comparing predicted and measured capacity from several datasets of load tests.

Datasets containing load test case histories were collected to investigate how well methods predict axial capacity of piles. These databases contained details on the behavior during driving, the pile type, the pile hammer, soil conditions, and load capacities from different sources, such as a static load test, or CAPWAP. Only steel H-piles, pipe piles, and metal shell piles are collected and used in this study.

The first collection of loadtest compiles results of several smaller load test databases. The databases include those developed by Flaate (1964), Olson and Flaate (1967), Fragaszy et al. (1988), by the FHWA (Rausche et al. 1996), and by Allen(2007) and Paikowsky (NCHRP 507). A total of 156 load tests were collected for this database.

The second collection was compiled from data provided by the Wisconsin Department of Transportation. The data comes from several locations within the State. A total of 316 piles were collected from the Marquette Interchange, the Sixth Street Viaduct, Arrowhead Bridge, Bridgeport, Prescott Bridge, the Clairemont Avenue Bridge, the Fort Atkinson Bypass, the Trempeauleau River Bridge, the Wisconsin River Bridge, the Chippewa River Bridge, La Crosse, and the South Beltline in Madison.

The ratio of predicted capacity (Q_p) to measured capacity (Q_m) was used as the metric to quantify how well or poorly a predictive method performs. Statistics for each of the predictive methods were used to quantify the accuracy and precision for several pile driving formulas. In addition to assessing the accuracy of existing methods, modifications were imposed on the FHWA-Gates method to improve its predictions. The FHWA-Gates method tended to overpredict at low capacities and underpredict at capacities greater than 750 kips. Additionally, the performance was also investigated for assessing the effect of different pile types, pile hammers, and soil. All these factors were combined to develop a "corrected" FHWA Gates method. The corrected FHWA-Gates applies adjustment factors to the FHWA-Gates method as follows: 1) F_o - an overall correction factor, 2) F_H - a correction factor to account for the hammer used to drive the pile, 3) F_S - a correction factor to account for the soil surrounding the pile, 4) F_P - a correction factor to account for the type of pile being driven. The specific correction factors are given in Table 4.10.

A summary of the statistics (for Q_P/Q_M) associated with each of the methods is given below:

Q_M/Q_P Mean	COV	Method
0.43	0.47	Wisc-EN
1.11	0.39	WSDOT
1.13	0.42	FHWA-Gates
0.73	0.40	PDA
1.20	0.40	FHWA-Gates for all piles <750 kips
1.02	0.36	"corrected" FHWA-Gates for piles <750 kips

The Wisc-EN formula significantly under-predicts capacity (mean = 0.43), and this is expected because it is the only method herein that predicts a safe bearing load (a factor of safety inherent with its use). The other methods predict ultimate bearing capacity. The scatter (COV = 0.47)) associated with the EN-Wisc method is the greatest and therefore, the EN-Wisc method is the least precise of all the methods.

The WSDOT method exhibited a slight tendency to overpredict capacity and exhibited the greatest precision (lowest cov) for all the methods except the corrected FHWA-Gates. The WSDOT method seemed to predict capacity with equal adeptness across the range of capacities and deserves consideration as a simple dynamic formula.

The FHWA-Gates method tends to overpredict axial pile capacity for small loads and underpredict capacity for loads greater than 750 kips. The method results in a mean value of 1.13 and a cov equal to 0.42. The degree of scatter, as indicated by the value of the cov, is greater than the WSDOT method, but significantly less than the EN-Wisc method.

The PDA capacity determined for end-of-driving conditions tends to underpredict axial pile capacity. The ratio of predicted to measured capacity was 0.7 and the method exhibits a cov of 0.40 which is very close to the scatter observed for WSDOT, FHWA-Gates and "corrected" FHWA-Gates.

The second database contains records for 316 piles driven only in Wisconsin. Only a few cases contained static load tests but there were several cases in which CAPWAP analyses were conducted on restrikes. The limited number of static load tests and

CAPWAP analyses for piles with axial capacities less than 750kips were not enough to develop correction factors for the corrected-FHWA Gates. However, predicted and measured capacities for these cases were in good agreement with the results from the first database.

Chapter 6 developed resistance factors and efficiency of methods and ranked the five predictive methods. The predictive methods listed in order of increasing efficiency are as follows: EN-Wisc, Gates-FHWA, PDA, WSDOT, and “corrected” FHWA-Gates. Resistance factors were determined for each of the methods for reliability index values β_T = 2.33 and 3.0 and are given in Tables 6.1 and 6.2 for the First Order Second Moment (FOSM) method and for the Factor of Reliability Method (FORM), respectively. A refinement for determining resistance factors was implemented in Chapter six by fitting the extremal values of Q_M/Q_P. A fit to the extreme values provides a more accurate representation of the distribution at low levels of probability, which is the portion of distribution that determined resistance factor. Resistance factors were determined for the three methods exhibiting the least scatter (Tables 6.4 and 6.5). The resistance factors for the three methods based on a fit to extremal data, and using a target reliability index, β_T = 2.33, and using the Factor of Reliability Method (FORM) are as follows:

Method	ϕ
Corrected-FHWA	0.61
WSDOT	0.55
FHWA	0.47

Comparisons were also developed in Chapter 6 to show the differences between design based on Factors of Safety (existing Wisconsin DOT approach) and LRFD. The impact of moving from current foundation practice to LRFD will significantly increase the demand for foundation capacity by about fifty percent if the EN-Wisc method continues to be used with LRFD. However, the increase in capacity can be mitigated to a considerable degree by replacing the EN-Wisc method with a more efficient method, such as the “corrected” FHWA-Gates method or the WSDOT method. If the more accurate methods are used, the overall demand for foundation capacity should be within 15 percent of current practice.

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