Implementation Report

Expanded Database for Service Limit State Calibration of Immediate Settlement of Bridge Foundations on Soil

January 2018

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16. Abstract

This implementation report presents an expanded database for calibration of the *SE* load factor for foundation movements in the *AASHTO LRFD Bridge Design Specifications*. The expanded database includes information from several state Departments of Transportation as well as other sources. Statistics are presented based on data from each source. Recommended values of *SE* load factors are developed. The effect of local geology and subsurface investigation techniques on the predicted values of *SE* load factors is discussed. This report will also serve as a useful reference for future researchers as well as agencies desiring to develop *SE* load factors based on local methods that are better suited to their regional geologies and subsurface investigation techniques.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Executive Summary

Selected elements of the second Strategic Highway Research Program (SHRP2) are being advanced into practice primarily through the Implementation Assistance Program (IAP) sponsored by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). The IAP provides technical and financial support to transportation agencies to encourage widespread adoption and use of research initially conducted through the Transportation Research Board.

Service Limit State Design for Bridges (R19B) is a SHRP2 Solution whose objectives include the development of design and detailing guidance, calibration of service limit states (SLSs) to provide 100-year bridge life, and a framework for further development of calibrated SLSs. Along with several structural limit states, a framework was developed for calibration of uncertainty in foundation movements within the context of the load and resistance factor design (LRFD) approach. A comprehensive report for the R19B project was issued in 2015 (Kulicki et al., 2015). Subsequently, based on a request by AASHTO T-5 and T-15 committees, a standalone "white paper" was developed by Samtani and Kulicki (2016) to document the foundation movements portion of the R19B work that was updated in 2018 to include results of additional parametric analyses. In Kulicki et al. (2015) and Samtani and Kulicki (2018), the calibration framework was demonstrated using a database of 20 points obtained from an FHWA study by Gifford et al. (1987) for 10 bridges in the northeastern United States.

This report presents an expanded database that includes a total of 80 data points. Additional data were obtained from several state Departments of Transportation and other sources. Statistics are presented based on data from each source. Recommended values of *SE* load factors are developed. The effect of local geology and subsurface investigation techniques on the predicted values of *SE* load factors is discussed.

This report will also serve as a useful reference for future researchers as well as agencies desiring to develop *SE* load factors based on local methods that are better suited to their regional geologies and subsurface investigation techniques.

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Acronyms and Abbreviations

X	accuracy ($X = S_P/S_M$)
z	standard normal variable (variate)
β	reliability index
γ_{SE}	load factor for *SE* load; movement load factor
λ	bias ($= 1/X = S_M/S_P$)
μ	arithmetic mean
$\mu_{LNA\text{-}X}$	arithmetic mean of ln(X) values
$\mu_{LNA\text{-}\lambda}$	arithmetic mean of ln(λ) values
σ	arithmetic standard deviation
$\sigma_{LNA\text{-}X}$	arithmetic standard deviation of ln(X) values
$\sigma_{LNA\text{-}\lambda}$	arithmetic standard deviation of ln(λ) values
AASHTO	American Association of State Highway and Transportation Officials
CDF	cumulative distribution function
CPT	cone penetration test
COV	coefficient of variation
DOT	Department of Transportation
FHWA	Federal Highway Administration
IAP	Implementation Assistance Program
in.	inch
ln	natural logarithm; lognormal
ln(X)	natural logarithm (lognormal) of accuracy, X, values
ln(λ)	natural logarithm (lognormal) of bias, λ, values
LRFD	load and resistance factor design
N	number of data points
N-value	blows per foot of penetration in standard penetration fest
S	foundation settlement (vertical movement)
S_M	measured settlement
S_P	predicted (calculated) settlement

SE	load factor for foundation movements
SHRP2	Second Strategic Highway Research Program
SLS	service limit state
SPT	standard penetration test
SR	settlement ratio
TRB	Transportation Research Board
U.S.	United States
WSDOT	Washington State Department of Transportation

Chapter 1. Introduction

1.1 SHRP2 Project Description

Selected elements of the second Strategic Highway Research Program (SHRP2) are being advanced into practice primarily through the Implementation Assistance Program (IAP) sponsored by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). The IAP provides technical and financial support to transportation agencies to encourage widespread adoption and use of research initially conducted through the Transportation Research Board (TRB).

Service Limit State Design for Bridges (R19B) is a SHRP2 Solution whose objectives include the development of design and detailing guidance, calibration of service limit states (SLSs) to provide 100-year bridge life, and a framework for further development of calibrated SLSs. Along with several structural limit states, a framework was developed for calibration of uncertainty in foundation movements within the context of the load and resistance factor design (LRFD) approach. A comprehensive report for R19B was issued in 2015 (Kulicki et al., 2015).

During the development of the R19B report as well as subsequent to it, input from the T-15 AASHTO Subcommittee on Bridges and Structures resulted in the need for additional analyses and clarifications relative to what was contained in Kulicki et al. (2015) to facilitate implementation of those results in the *AASHTO LRFD* Bridge Design Specifications. This resulted in the development of a report titled *Incorporation of Foundation Deformations in AASHTO LRFD Bridge Design Process* - First Edition by Samtani and Kulicki (2016).

1.2 Purpose for Report

Subsequent to the issue of the report by Samtani and Kulicki (2016), additional data were collected and analyzed to verify the calibrations for proposed load factors for foundation movements, *SE*. The purpose of this report is to document these additional data, evaluate the data, and to develop the final recommended values of the *SE* load factor(s). Additional parametric studies were performed to evaluate the effect of a range of *SE* load factors using a reliability index of 1.0 (irreversible limit state). The results of these parametric analyses in form of additional design examples are included in Samtani and Kulicki (2018) titled *Incorporation of Foundation Movements in AASHTO LRFD Bridge Design Process* - Second Edition, that represents an updated version of Samtani and Kulicki (2016).

The current report should be used in conjunction with Samtani and Kulicki (2018). It is not the intent of this report to repeat material from that report, but rather to document the expanded database, and from that database, develop the recommended load factor(s). Thus, it is recommended that the reader of this report procure a copy of Samtani and Kulicki (2018).

1.3 Need for Report

The calibrations for foundation movements and the recommended values for *SE* load factors (γ_{SE}) in Kulicki et al. (2015) and Samtani and Kulicki (2018) were based on a database of 20 data points from a report by Gifford et al. (1987) that concentrated on bridges in the northeastern United States. This was due to a variety of reasons including, but not limited to, (a) scope and budget that were limited to development of a general framework and its demonstration of implementation through the available open-source, high-quality data that did not require detailed additional processing, and (b) additional data processing that would be required to bring data from other sources to a level and format needed for calibration.

During the IAP and as part of the discussions related to the potential implementation in the *AASHTO LRFD* Bridge Design Specifications, more data were provided by the Washington State Department of Transportation (WSDOT). While processing the WSDOT data, it was also desired to process the data from other sources (for example, Ohio and South Carolina Departments of Transportation [DOTs]), a task that was not done as part of the original R19B work due to reasons mentioned earlier. Thus, data from these sources were also mined and processed to bring the information to a level and format that is amenable for calibrations.

Once the additional data were processed and the calibration processes in Kulicki et al. (2015) and Samtani and Kulicki (2018) were verified and further extended, the need to document these additional processes was identified. This report is in response to the need that, as stated in Section 1.2, will assist in the implementation of the R19B project in the *AASHTO LRFD Bridge Design Specifications* as well as serve as a valuable reference for future use by other researchers.

Chapter 2. Problem Description

The framework for calibration of foundation movements was demonstrated in Kulicki et al. (2015) and Samtani and Kulicki (2018) using a database for bridge spread footings from Gifford et al. (1987). The salient features of the database based on Gifford et al. (1987) are as follows:

- A total of 20 data points were used.
- All the data points showed measured immediate settlement values smaller than 1.0 inch. The minimum value was 0.23 inch and the maximum value was 0.94 inch.
- All data were from the northeastern United States.

As documented in Samtani and Kulicki (2018), the scatter in the data based on Gifford et al. (1987) is large. Further, because the data were obtained from the northeastern United States, that data may have only represented a certain regional geology.

To address the above limitations, it was desired to test and validate the proposed calibration framework and the values of *SE* load factors in Kulicki et al. (2015) and Samtani and Kulicki (2018) by expanding the database to include case histories from different areas of the United States as well as projects where settlements larger than 1.0 inch were measured.

Chapter 3. Data Summary

This chapter summarizes the data sources used in this report. More information about the data sources is included in Appendix A. The interested reader should consult the references to these sources for details regarding the original collection, processing, and reporting of the data.

As noted in Samtani et al. (2010), the geotechnical literature contains a large amount of field performance data for spread footings for constructed facilities. However, much of the data are related to smaller-size footings that are typical for buildings. The footings for bridges are large compared to those for buildings. The size of the footings for bridges is generally controlled by tolerable settlements (that is, SLS) rather than bearing failure (that is, ultimate or strength limit state). Samtani et al. (2010) provide an extensive database based on large footings. In this database, information from the United States as well as European sources was included. These data are summarized in Table 3-1 and Table 3-2.

In addition to the data from Samtani et al. (2010), more recent data developed by Allen (2018) are included in Table 3-1. The large settlements reported by Allen (2018) were measured under fills or footing/fill combinations. It is difficult to assess the accuracy of settlement prediction methods considering only the large settlement range because most of the large settlement data are from projects in one part of the country (that is, the Pacific Northwest). Such data were necessary to evaluate whether the significant scatter in settlement data observed for smaller settlements as discussed in Chapter 5 is also observed at large settlements. Further, the data for large settlements were needed to reduce or eliminate correlation (dependency) between variables used in calibration of *SE* load factor as discussed in Appendix B. In fact, the limitations of the smaller data sets make parsing the data to provide the accuracy of these methods for specific regions difficult. Hence, the primary focus of the calibrations conducted for this study is on all of the data rather than the individual data sets. However, the individual regional data sets can be used as a starting point for future, more region-specific, calibrations.

More information for each of the data sources in Tables 3-1 and 3-2 is included in Appendix A. Data from projects where only immediate settlements occurred were considered for calibration in this report. Subsurface conditions for various data sources include different types of geologies and soils. The soil types included cohesionless soils above and below the water table and unsaturated cohesive soils above the water table that did not experience long-term consolidation settlement.

Table 3-1. Summary of U.S. Data Sources

Data Source	Features
Gifford et al. (1987)	Data from this source were used in Samtani and Kulicki (2018) and are based on the measurement of immediate settlements on bridges in states in the northeastern United States. A total of 20 usable data points with measured settlement data ranging from 0.23 inch to 0.94 inch were available. Predictions for both the Schmertmann and Hough methods were based on standard penetration tests (SPTs).
Baus (1992)	Data were developed by the South Carolina DOT. The data were based on measurements of immediate settlements under footings of several bridges. A total of 11 usable data points with measured settlement data ranging from 0.38 inch to 2.15 inches were available. The SPTs and cone penetration tests (CPTs) were performed in proximity (side-by-side) at each monitoring location. The data in Baus (1992) relied on the use of only the CPTs for predicting settlements based on the Schmertmann method and SPTs for the Hough method. However, CPTs at two locations were not available and Baus (1992) did not include values of predicted settlement based on the Schmertmann method for those two points. Because the Schmertmann method is also used with the SPTs, data from these projects were further processed by the authors to develop additional predictions for the Schmertmann method based on results of the SPTs. Thus, for the Schmertmann method, an additional 11 points were obtained.
Briaud and Gibbens (1997)	Data were based on five large-scale load tests performed as part of a research project for the FHWA at Texas A&M University. Each load test was carried out on a square footing. Thus, five data points are available from this source. The SPT data were used for both the Schmertmann and Hough methods.
Sargand et al. (1999); Sargand and Masada (2006)	Data were developed by the Ohio DOT. The data were based on measurements of immediate settlements under footings of several bridges. A total of 12 usable data points with measured settlement data ranging from 0.27 inch to 1.06 inches were available. Data for both the Schmertmann and the Hough methods are based on SPT information.
Allen (2018)	Data were developed by WSDOT based on measurements of immediate settlements of tunnel footings under deep fill, mechanically stabilized earth walls, and approach fills for bridge structures. A total of 13 usable data points with measured settlement ranging from 0.20 inch to 41.0 inches were available. For the Hough method, the SPT information was used. For the Schmertmann method, 4 of the 13 data points were developed using the CPT information because the SPTs at locations corresponding to these points had some N-values (blows/foot) of 0 and 1, and for such cases the Schmertmann method gives spurious results. It should also be noted that N-value = 0 at this site does not represent the presence of voids due to, for example, landslides, but is simply the result of the alluvial depositional environment that created the deep very loose soil conditions.

Table 3-2. Summary of European Data Sources

Data Source	Features
Gifford et al. (1987)	The source for these data (Gifford et al. 1987) is the same as that for the 20 U.S. data points shown in Table 3-1. However, Gifford et al. (1987) also collected analyzed data from European sources in a manner that is consistent with the methods used for the other U.S.-based data sources. Settlement data from the following European sources were obtained: • DeBeer (1948): Five data points from Belgium • Levy and Morton (1974): One data point from England • DeBeer and Martens (1956): Two data points from Belgium • Wennerstrand (1979): One data point from Sweden • Bergdahl and Ottoson (1982): One data point from Sweden Thus, a total of 10 data points were available. Gifford et al. (1987) analyzed the data from these sources based on the Schmertmann method and three other methods (Peck and Bazaraa, 1969, D'Appolonia et al., 1968, and Oweis, 1979). Predicted data for the Hough method were not provided. Thus, all 10 data points are for the Schmertmann method, which was also based on the CPT information.

Settlement estimates for each case in the database were made using the following two settlement prediction methods:

- Schmertmann: Method by Schmertmann et al. (1978)
- Hough: Method by Hough (1959)

Based on the information in Table 3-1, Table 3-2, and data in Appendix A, the following is a summary of usable data points for the Schmertmann and Hough methods:

- Based on U.S. data sources in Table 3-1:
  - 70 data points for the Schmertmann method with the following breakdown based on the subsurface information used for predicting the settlements:
    - 57 data points based on the SPT method
    - 13 data points based on the CPT method
  - 61 data points for the Hough method based on the SPT method
- Based on European data sources in Table 3-2:
  - 10 data points for the Schmertmann method, all of which were based on the CPT method
  - No data points for the Hough method

Chapter 4. Calibration Approach

The calibration approach for *SE* load factor, γ_{SE}, is detailed in Samtani and Kulicki (2018). In Samtani and Kulicki (2018), the data were analyzed in terms of accuracy, *X* (also known as Settlement Ratio, *SR*), which is defined as the ratio of calculated to measured settlement. However, the data can also be analyzed in terms of bias, λ, which is defined as the ratio of the measured to the calculated settlement. Thus, bias is the inverse of accuracy (that is, $\lambda = 1/X$). Appendix A discusses the interrelationships between the statistics based on *X* and λ. It is recognized that measured full-scale settlements, and bias values derived from them, are influenced by various sources of uncertainty. These include the types of measurements used to characterize the soil, spatial variability of the soils present and their properties, and design model error. The calibrations conducted herein make the assumption that the full-scale data and site characterizations are adequately captured through the variability in the bias (or accuracy) values. However, where both SPT and CPT data were available, those cases were parsed into separate data sets for these two types of subsurface data. A more detailed discussion of these issues as they affect geotechnical LRFD calibration is provided in Allen (2005) and Allen et al. (2005).

The distribution of the accuracy and bias data is nonnormal. Consistent with past practice for LRFD calibrations, a lognormal distribution is used for modeling these nonnormal data, as discussed in Chapter 5. Using nonlinear regression techniques, Samtani and Kulicki (2018) developed closed-form solutions to determine the *SE* load factor. These solutions are as follows:

- When the data are analyzed in terms of accuracy, *X*, the *SE* load factor γ_{SE} can be computed using Equation 4-1:

  $$\gamma_{SE} = e^{J} \quad \text{where } J = \beta(\sigma_{LNA\text{-}X}) - \mu_{LNA\text{-}X} \qquad (4\text{-}1)$$

  where β is the reliability index, $\mu_{LNA\text{-}X}$ is the arithmetic mean value of ln(*X*) data, and, $\sigma_{LNA\text{-}X}$ is the arithmetic standard deviation of ln(*X*) data.

- When the data are analyzed in terms of bias, λ, the *SE* load factor γ_{SE} can be computed using Equation 4-2:

  $$\gamma_{SE} = e^{K} \quad \text{where } K = \beta(\sigma_{LNA\text{-}\lambda}) + \mu_{LNA\text{-}\lambda} \qquad (4\text{-}2)$$

  where β is as previously defined, $\mu_{LNA\text{-}\lambda}$, is the arithmetic mean value of ln(λ) data, and, $\sigma_{LNA\text{-}\lambda}$ is the arithmetic standard deviation of ln(λ) data.

In this report, data are processed in terms of both accuracy and bias to permit future researchers the flexibility to use either method as appropriate.

Chapter 5. Summary of Data Statistics

This chapter summarizes the data used for the calibrations presented in Chapter 6. Appendix A includes detailed data sets and statistics for each data source described in Chapter 3 as well as various combinations of data from all sources. Appendix B presents the results of correlation analysis for each data set in Appendix A to evaluate the strength of correlation between bias and predicted settlement values. Based on the correlation analysis, it was observed that when data sets are combined, the bias and predicted settlement values tend to be uncorrelated (desirable in this case) because combined data sets have many (for example, more than 30 to 40) data points along with an adequate representation of large settlements. However, for individual data sets, the bias and predicted settlements tend to be correlated due to fewer data points and lack of a wide enough range in settlements, which could result in an inaccurate calibration of the *SE* load factor. Accordingly, this chapter presents information and statistics based on combined data sets.

Measured versus predicted settlement values for all SPT-based settlement predictions for both the Hough and the Schmertmann methods are provided on Figure 5-1. The data presented on Figure 5-1 suggest that the scatter in the data tends to be larger at smaller settlements. Figure 5-2 presents the data on Figure 5-1 in an alternative format that better illustrates the scatter and trend in the settlement prediction bias (that is, measured/predicted) values. In this format, a bias value smaller than 1.0 indicates conservative predictions and vice versa. A solid horizontal line at a bias of 1.0 is shown on the figure. The closer the data are to a bias of 1.0, the better the prediction. Further, the closer the trend in the data is to the horizontal, the better the prediction, and the closer the prediction is to being uncorrelated with the bias. The short dashed and long dashed vertical lines on the figure demark predicted settlements of 0.5 inch and 2.0 inches, respectively. Based on Figure 5-2, the following general observations can be made:

- Data scatter increases substantially at settlement predictions smaller than approximately 0.5 inch (left of the short dashed vertical line).
- Data scatter decreases substantially at settlement predictions larger than approximately 0.5 inch (right of the short dashed vertical line).
- Both prediction methods tend to become progressively more unconservative (that is, measured larger than predicted) as the settlement values reduce below 0.5 inch.
- Both methods tend to become overly conservative between predicted settlement of approximately 0.5 inch and 2.0 inches, and the level of conservatism appears to reduce as the predicted settlement increases beyond 2.0 inches.
- For predicted settlements larger than approximately 0.5 inch, the data points corresponding to the Hough method are more tightly clustered in contrast to the data points for the Schmertmann method. This indicates a smaller spread in data for the Hough method that is corroborated by smaller coefficient of variation (COV) values (see Tables 5-1 through 5-4 for COV values and other statistics).

- The Hough method generally tends to be more conservative than the Schmertmann method, especially for settlement estimates smaller than approximately 1.0 inch. For settlement estimates larger than 1.0 inch, both methods are approximately the same with regard to degree of conservatism.

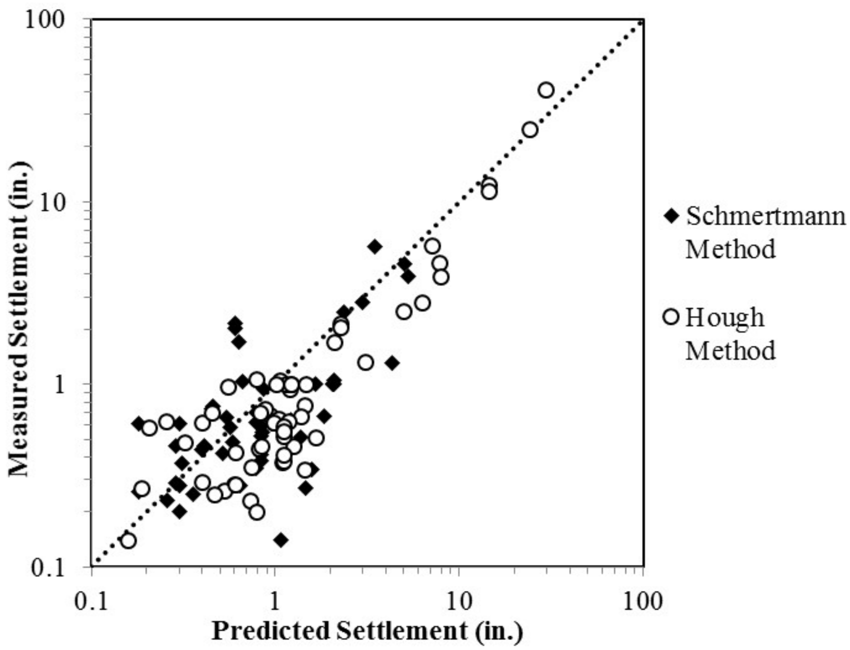


Figure 5-1. Predicted and measured settlement values for all SPT data-based predictions.

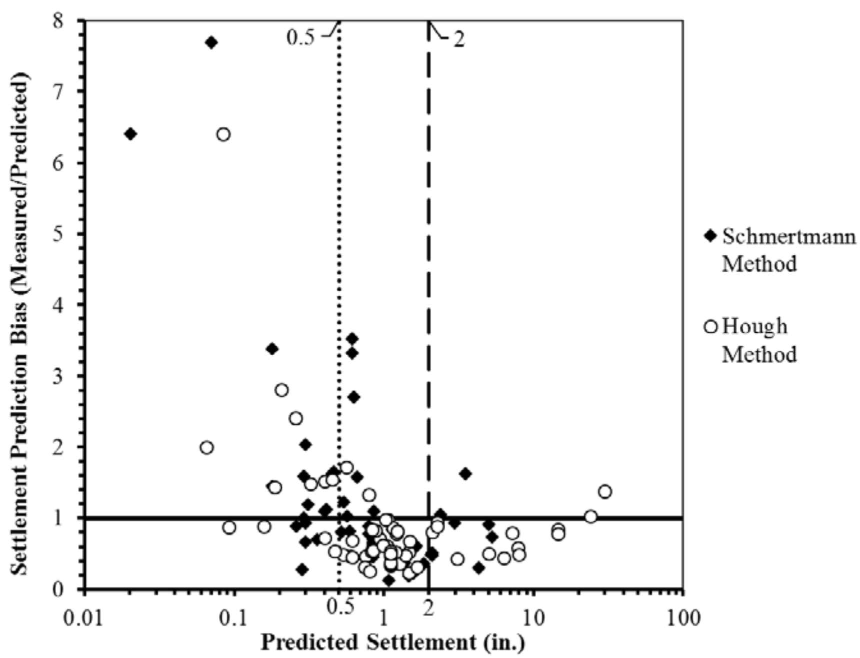


Figure 5-2. Settlement prediction bias (measured/predicted) as a function of predicted settlement value for all SPT data-based predictions.

These observations suggest that regardless of the prediction method, designers should carefully interpret predicted total settlement values smaller than approximately 0.5 inch, particularly for cases where small settlements can significantly affect bridge structures (for example, shear and moment in rigid frame structures and short-span stiff structures). At such small settlements, neither method has the ability to reliably predict settlement with a reasonable accuracy and sufficiently accurate measurement of settlements (for example, survey methods) may not be possible.

The original calibration for the SLS for foundation settlement was conducted using the method accuracy *X* (that is, predicted/measured settlement value). The reason for doing this is fully explained in Samtani and Kulicki (2018). However, the method bias λ (that is, measured/predicted settlement value) can also be used to conduct the calibrations described in Chapter 6 and is more familiar to those doing LRFD calibration (for example, Allen et al. 2005). Both approaches will result in the same *SE* load factor. Both approaches are considered in this report.

Tables 5-1 to 5-4 summarize statistics for SPT predictions only (all U.S. sources, except the CPT predictions in Baus, 1992, and Allen, 2018) for the combined data sets used for calibration purposes in Chapter 6. Note that Baus (1992) and Allen (2018) datasets include different data points based on SPT and CPT, and only the SPT based data points are considered in Tables 5-1 to 5-4. Tables 5-1 and 5-2 include statistics for all SPT data. Tables 5-3 and 5-4 include statistics for all SPT data after filtering out data points corresponding to predicted settlements smaller than 0.5 inch. The following notations are used in the tables:

- N = number of values in the data set
- μ = arithmetic mean of normal values
- σ = arithmetic standard deviation of normal values
- COV = coefficient of variation (=σ/μ) of normal values
- μ_{LNA} = arithmetic mean of lognormal, ln, values
- σ_{LNA} = arithmetic standard deviation of lognormal, ln, values
- COV_{LNA} = coefficient of variation of lognormal, ln, values (=σ_{LNA}/μ_{LNA})

The tables for arithmetic values enable a designer to evaluate the following:

- Relative level of conservatism of different methods by comparison of mean values, μ. The closer the mean value of Accuracy, *X*, or bias value, λ, is to 1.0, the less conservative the prediction method.
- The relative spread in the data around the mean values by comparison of COV values. The larger the COV value, the larger the spread of the data around the mean value.

In all cases, the COV for the Hough method is significantly smaller than the COV for the Schmertmann method, indicating the Hough method provides more reliable predictions. For both methods, the COV values for settlements larger than 0.5 inch are significantly smaller than the COV values when all settlements are considered. This will be important when estimating the *SE* load factor (γ_{SE}).

Table 5-1. Statistics for *X* and λ for Data Based on SPT from All U.S. Sources

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	57	61	57	61
μ	1.563	1.623	1.205	0.900
σ	1.312	0.857	1.356	0.878
COV	84.0%	52.8%	112.6%	97.5%

Table 5-2. Statistics for ln(*X*) and ln(λ) for Data Based on SPT from All U.S. Sources

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	57	61	57	61
μ_{LNA}	0.164	0.330	-0.164	-0.330
σ_{LNA}	0.790	0.607	0.790	0.607
COV_{LNA}	4.806	1.840	-4.806	-1.840

Table 5-3. Statistics for *X* and λ for Predicted Data Larger than 0.5 inch Based on SPT from All U.S. Sources

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	40	49	40	49
μ	1.828	1.824	0.875	0.658
σ	1.407	0.808	0.748	0.298
COV	77.0%	44.3%	85.5%	45.3%

Table 5-4. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 inch Based on SPT from All U.S. Sources

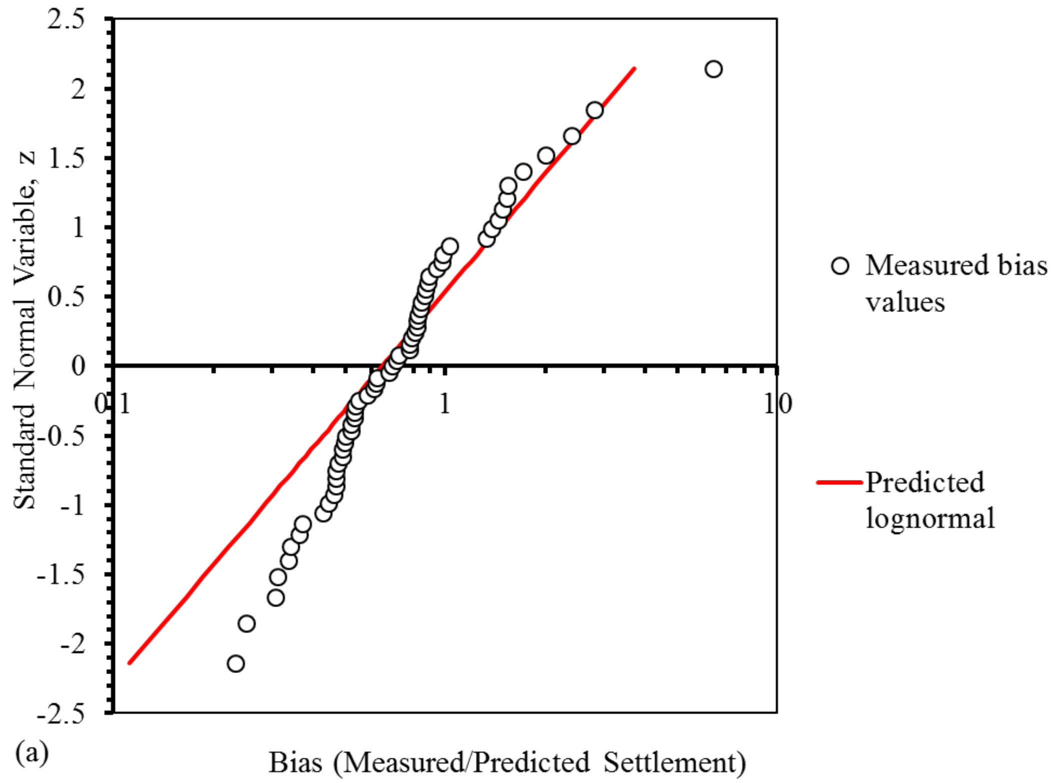
Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	40	49	40	49
μ_{LNA}	0.379	0.510	-0.379	-0.510
σ_{LNA}	0.685	0.433	0.685	0.433
COV_{LNA}	1.807	0.850	-1.807	-0.850

Tables 5-1 to 5-4 include data based on SPTs from U.S. sources only. A similar summary of statistics for the CPT-based Schmertmann method predictions is provided in Sections A.7 and A.8 of Appendix A. A preliminary evaluation of the Schmertmann method predictions based on the use of CPT and SPT data is included in Appendix C. However, the size of the CPT data set is small, with an associated concern about a weak to moderate correlation between bias and predicted settlement values as discussed in Appendix B. Therefore, statistical characterization of the CPT-based Schmertmann method data set in Appendix C should be considered approximate. For these reasons, data based only on SPTs are considered in this report for calibration of *SE* load factors.

For probabilistic calibration of *SE* load factors, it is important to select an appropriate probability distribution function (for example, normal, lognormal, etc.) of the data. The initial evaluation of whether the data are normally or nonnormally distributed can be performed by plotting the cumulative distribution function (CDF) of the data (Allen et al., 2005). The CDFs for the bias data included in Tables 5-1 through 5-4 are presented on Figures 5-3 through 5-6. Plots of both bias and ln(bias) are provided for each data set.

If the COV value based on arithmetic mean and standard deviation values is small (smaller than about 20 percent), the normal and lognormal distributions are similar for practical purposes. In such a case, the mean and standard deviation values for a lognormal distribution can be approximately predicted from the mean and standard deviation values for normal distribution by correlations developed by Benjamin and Cornell (1970) and reported by others (for example, Nowak and Collins [2000] and Allen et al. [2005]). The correlations for lognormal distribution can also be found in Samtani and Kulicki (2018). As can be seen from Figure 5-3 (for the Hough method) and Figure 5-4 (for the Schmertmann method) for the larger data sets that include settlement predictions smaller than 0.5 inch, the difference between fitting a predicted lognormal CDF to the bias data and a normal CDF of the ln(bias) data can be significant. Fitting a predicted lognormal CDF to arithmetic bias values involves the approximation based on correlations described previously that becomes more obvious as the COV increases well beyond 20 percent. In such cases, fitting a normal CDF to ln(bias) is more accurate. However, as can be seen from Figure 5-5 (for the Hough method) and Figure 5-6 (for the Schmertmann method) for the data sets in which settlement predictions smaller than 0.5 inch are excluded, there is a much smaller difference between the two approaches due to the lower COVs, and in such cases, the use of predicted lognormal distribution can work well.

Based on the above observations, it can be concluded that (a) the bias data have a nonnormal distribution and (b) a lognormal distribution appears to be adequate for the purpose of calibration of the *SE* load factors. These conclusions are consistent with similar conclusions based on accuracy data in Samtani and Kulicki (2018).



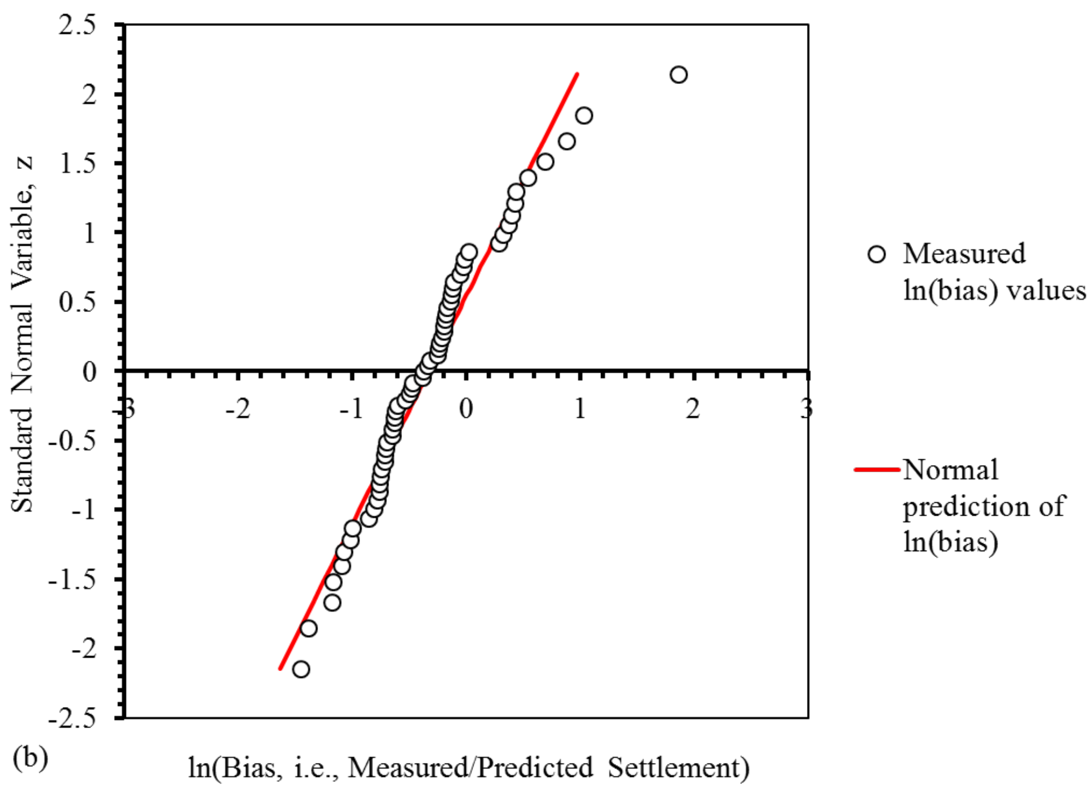


Figure 5-3. CDF of settlement prediction bias (measured/predicted) for all SPT data based on Hough method predictions: (a) bias, (b) ln(bias).

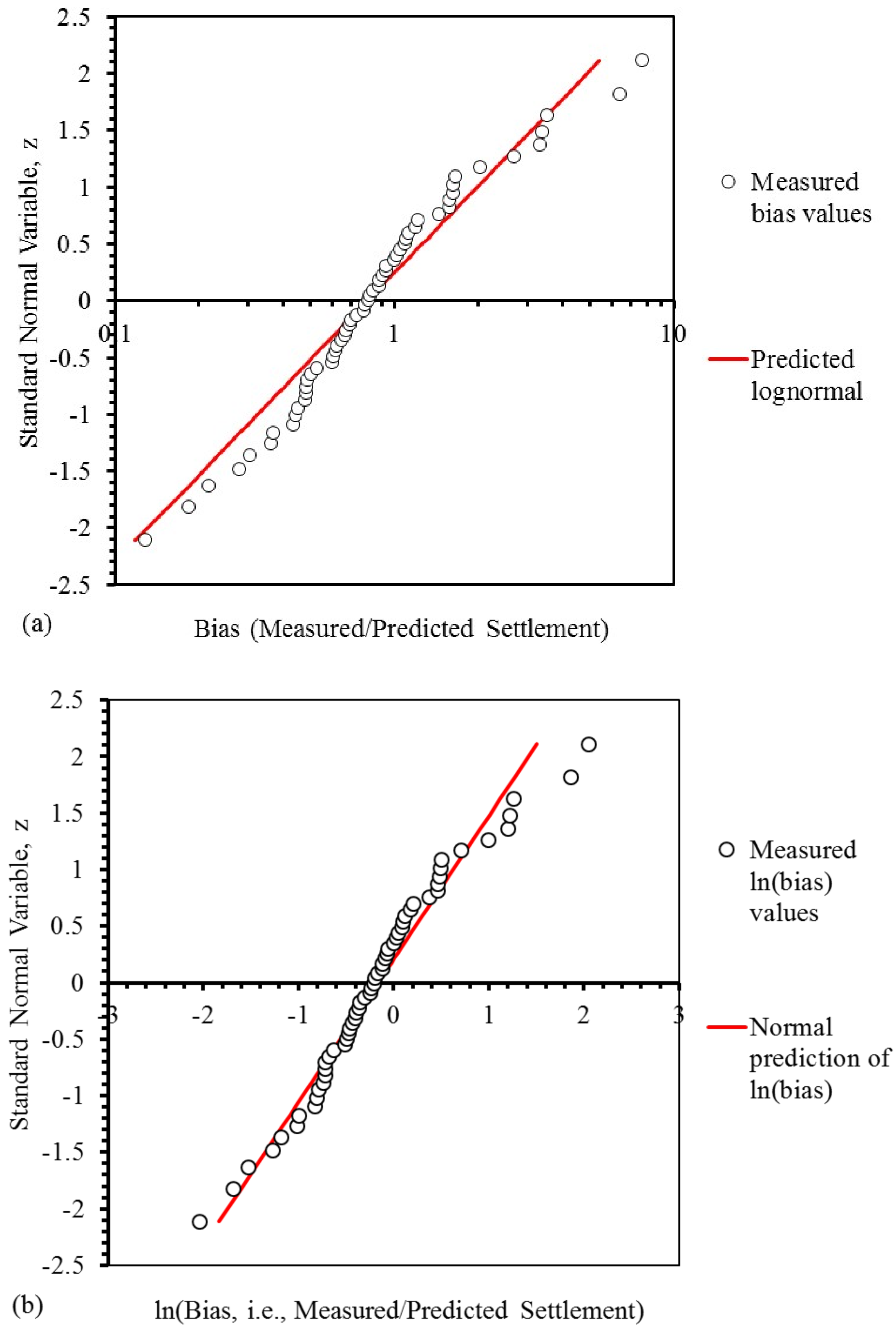


Figure 5-4. CDF of settlement prediction bias (measured/predicted) for all SPT data based on Schmertmann method predictions: (a) bias, (b) ln(bias).

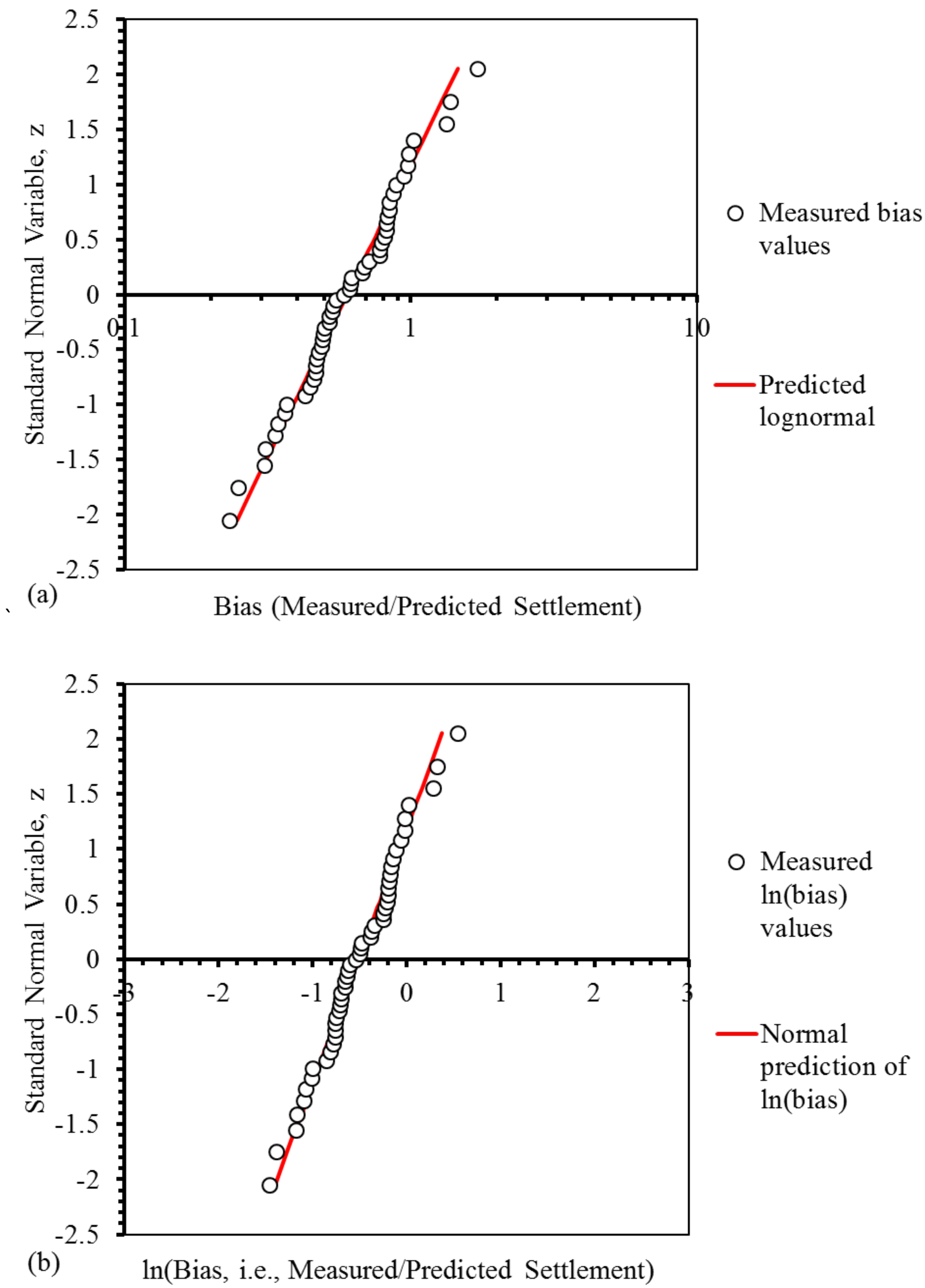


Figure 5-5. CDF of settlement prediction bias (measured/predicted) for SPT data based on Hough method predictions larger than 0.5 inch: (a) bias, (b) ln(bias).

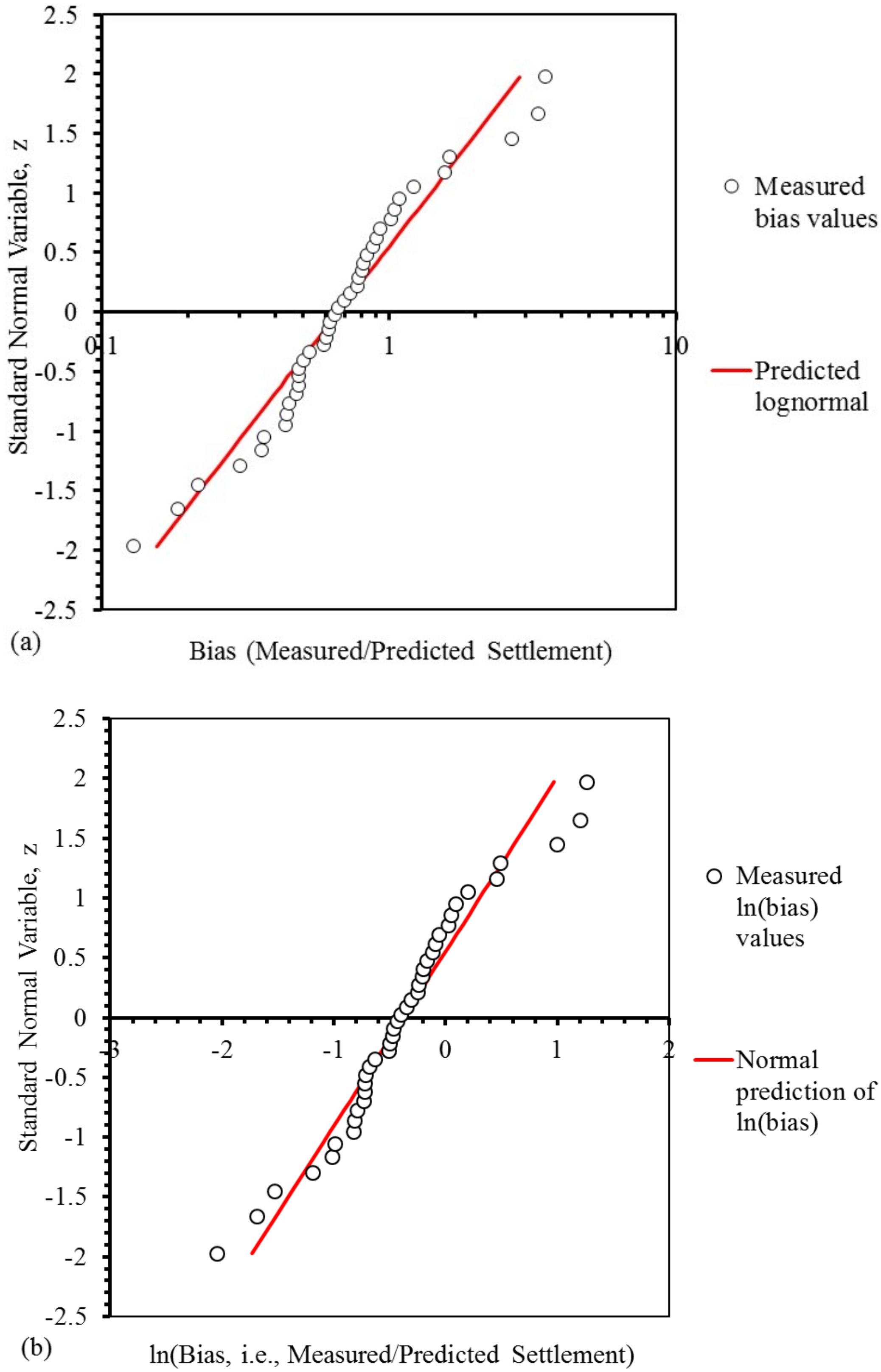


Figure 5-6. CDF of settlement prediction bias (measured/predicted) for SPT data based on Schmertmann method predictions larger than 0.5 inch: (a) bias, (b) ln(bias).

Chapter 6. Calibration Results

Using the closed form solutions in Chapter 4 and the lognormal (ln) statistics in Chapter 5, Table 6-1 summarizes the calibration results for *SE* load factor, γ_{SE}, corresponding to a reliability index, β, of 1.00. See Appendix D for a background on the choice of this value of reliability index.

Table 6-1. *SE* Load Factors for Reliability Index β=1.00

Case	Data Set (see note)	Data Points for Schmertmann	Data Points for Hough	Table No. for Lognormal (ln) Statistics	SE Load Factor for Schmertmann	SE Load Factor for Hough
1	All sources (that is, unfiltered) using SPT data only	57	61	5.2	1.87	1.32
2	All sources using SPT data only, but excluding predicted settlements smaller than 0.5 in.	40	49	5.4	1.36	0.93

Note: See Table 3-1, Table 3-2, Chapter 5, and Appendix A for more information on each dataset.

The following observations are based on the calibration results presented in Table 6-1:

- The *SE* load factors when all the SPT-based data are considered are larger than for the cases in which data with predicted settlements smaller than 0.5 inch are excluded. The data that were filtered out (that is, predicted settlements smaller than 0.5 inch) have more scatter compared with the data in which the predicted settlements are larger than 0.5 inch. Thus, the filtering process reduced the scatter in the data set, which in turn reduced the *SE* load factors.
- The *SE* load factors for the Schmertmann method are larger than those for the Hough method. This is consistent with the observations in Chapter 5 that the COVs for the Schmertmann method are larger than those for the Hough method.
- Although the Schmertmann and Hough methods were developed with structural footings in mind, geotechnical designers often use these methods to evaluate immediate settlements for wide and tall embankment fills as well as mechanically stabilized earth walls that are primarily fill with reinforcements. Settlements under such fill structures can be large and exceed several inches. While either the Schmertmann method or the Hough method could be used for structural footings based on local experience, the FHWA Soils and Foundations manual (Samtani and Nowatzki, 2006) suggests that the Hough method may be more appropriate than the Schmertmann method when evaluating settlement under fills. The projects included in the Allen (2018) data source involve large fills. Allen (2018) notes that WSDOT used the Hough method to evaluate the settlements for these projects and found satisfactory comparison with measured values. Although these fill settlement data are included in this report to reflect the current state of the practice by many geotechnical designers, the authors recommend careful

interpretation of the results of settlement analysis using the Schmertmann method, and possibly the Hough method, for fill structures. Instrumentation and monitoring should be considered to verify predicted large settlements under fill structures.

Chapter 7. Summary and Recommendations

This report presents an expanded database for service limit state calibration of immediate settlement of bridge foundations on soil. A total of 80 data points were collected from various sources and analyzed to develop *SE* load factors for the Schmertmann method and the Hough method for predicting immediate settlements. Chapter 6 presents the results of the calibrations along with discussions of the results. Table 7-1 summarizes the computed and recommended load factors for reliability index, β, of 1.00.

Table 7-1. *SE* Load Factors from Table 6-1 and Recommended *SE* Load Factors

Method	*SE* Load Factor Based on Consideration of All Data Using SPTs	*SE* Load Factor Based on Filtering Out Predicted Settlement < 0.5 in. Using SPTs	Recommended *SE* Load Factor
Schmertmann	1.87	1.36	1.40
Hough	1.32	0.93	1.00

Based on the information in Table 7-1 and discussions in previous chapters, the following summary statements can be made regarding the *SE* load factors:

- The *SE* load factors are smaller for the case in which predicted settlements smaller than 0.5 inch are excluded. This is to be expected because there is a larger scatter in the data related to predicted settlements smaller than 0.5 inch (see discussions in Chapter 5).
- The *SE* load factors for the Hough method are smaller than those for the Schmertmann method. This is consistent with the observation in Chapter 5 that there is more scatter in the data corresponding to the Schmertmann method than the Hough method. This observation also reflects the smaller COV for the Hough method than that for the Schmertmann method.
- The recommended *SE* load factors are rounded up to 0.05 and are generally not allowed to be smaller than 1.0 to be consistent with other load factors in the *AASHTO LRFD Bridge Design Specifications* (2017).
- For a reliability index of 1.00, Samtani and Kulicki (2018) recommended *SE* values of 1.70 and 1.00 for Schmertmann and Hough methods, respectively, based on 20 data points from the dataset from Gifford et al. (1987) developed based on bridges in the northeast United States. The *SE* values in Table 7-1 are based on a much larger database that includes data from different regions of the United States as well as settlements larger than 1.0 inch. The number of data points and the range of settlements considered in the calibration are important as discussed in Section B.5 of Appendix B. Therefore, the recommended *SE* values in Table 7-1 are proposed for implementation in *AASHTO LRFD Bridge Design Specifications*. Refer to Section B.5 in Appendix B for discussion of key points related to calibration of *SE* load factors.

The calibration process for *SE* load factors is based on specific analytical models such as Schmertmann and Hough. Thus, the recommended calibrated load factors reflect the uncertainty in the predictions by such analytical methods. The level of uncertainty in predicted settlements is also a function of the type of subsurface investigations (for example, SPT or CPT) as discussed earlier and in Appendix C. Regardless of the type of investigations, the proposed *SE* load factors assume that the designer has properly characterized the site variability (for example, “low,” “medium,” or “high”) based on the level of subsurface investigations required by Article 10.4 of *AASHTO LRFD Bridge Design Specifications*. In cases of “high” site variability, use of S-0 concept (where S is the foundation settlement) as discussed in Samtani et al. (2010) and Samtani and Kulicki (2018) may be warranted to account for uncertainties in subsurface conditions.

Induced force effects (for example, shear and moment) are realized due to differential settlements across the bridge superstructure (see Samtani and Kulicki, 2018, for detailed examples and discussions). Differential settlements are computed for each span and along each substructure element for evaluation of the induced force effects. Because of the scatter in the predicted settlement data smaller than 0.5 inch, it is difficult to reliably estimate differential settlements at such small settlements. Thus, to be consistent with the recommended *SE* load factors shown in Table 7-1, for cases where the predicted total immediate settlements are smaller than approximately 0.5 inch, it is recommended that differential foundation settlement of a minimum of 0.5 inch be used to evaluate the induced force effects, unless the foundation is located on rock or rock-like soil, in which case the settlement estimation procedures described in this report are not applicable.

The effect of *SE* load factor on the force effects (for example, shear and moment) in the bridge design was studied in detail by Samtani and Kulicki (2018) through parametric studies on a set of actual bridges that were reanalyzed using a range of *SE* load factors and settlements. The results of these parametric studies are summarized in Appendix D. Based on these studies, an increase in the *SE* load factor by 40 percent (for example, increasing the value from 1.25 to 1.75) results in less than 2 percent increase in controlling force effects for the typical criteria that limit the settlement to less than approximately 1.0 inch. Thus, the recommended load factor of 1.40 for the Schmertmann method, by itself, is not expected to result in significant changes in controlling force effects in bridge design. However, consideration of uncertainty in the foundation movements in the form of an *SE* load factor in conjunction with the construction-point concept can lead to more cost-effective foundations as discussed in Samtani and Kulicki (2018).

7.1 Calibration of Load Factors for Local Methods

The calibration results presented in this report represent an “average” for the United States because data from several locales were used to develop the statistics needed for calibration. Differences in the compressibility of soil due to local geology are likely, and the data presented in Appendix A, in spite of the limitations of small data sets identified in Appendix B, appear to support the general trends of the results discussed in Chapter 5. Nevertheless, it is important to consider local practices and experiences for estimating settlement. For example, the Florida DOT has found through experience that using one third of the predicted settlement by the Schmertmann method appears to correlate better with their observations. The Arizona DOT has found that the Hough method appears to overpredict the settlement by a factor of approximately 2; therefore, the Schmertmann method is used in Arizona DOT practice. However, WSDOT has found that the Hough method appears to correlate well with their observations, unless the soil is over-consolidated, in which case the Hough method settlement estimate may be reduced by a factor of up to 1.5 for dense sandy soils (WSDOT, 2015). Therefore, local agencies should strive to develop databases based on their local geologies and practices such as the use of CPTs versus SPTs for subsurface investigations and local variations of settlement prediction methods.

When a local agency desires to develop the *SE* load factor based on local practices, it is important to develop a high-quality database. Guidance for instrumentation and monitoring to develop measured data is included in Samtani et al. (2010). Guidance for developing databases for LRFD calibrations is included in Allen et al. (2005) and Appendix B. Once a database is developed, the procedures documented in this report can be used to develop the load factors based on local methods.

7.2 Future Research and Implementation

One use of the calibration implementation processes described in this report is further research and development of *SE* load factors for other types of movements, for features such as retaining structures, and use of other movement calculation methods than those documented herein. For example, the lateral movement of deep foundations can be calibrated using predicted data from methods such as the *P-y* method and the strain wedge method compared against measured data from load tests.

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Appendix A
Databases

Appendix A. Databases

This appendix documents the data sets for each data source listed in Tables 3-1 and 3-2. For each data source, the following items are documented in this appendix:

- Summary of the projects along with site location data in a tabular format
- A table with measured settlement values along with predicted (that is, calculated) settlement values based on the Schmertmann and the Hough methods
- A table with values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods
- A table with lognormal (ln) values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods

The following notations are used in the tables:

- N = number of data points
- μ = arithmetic mean of normal values
- σ = arithmetic standard deviation of normal values
- COV = coefficient of variation (=σ/μ) of normal values
- μ_{LNA} = arithmetic mean of lognormal, ln, values
- σ_{LNA} = arithmetic standard deviation of lognormal, ln, values
- COV_{LNA} = coefficient of variation of lognormal, ln, values (=σ_{LNA}/μ_{LNA})

As explained in Chapter 4, bias is the inverse of accuracy; that is, $\lambda = 1/X$. As indicated in Chapter 5, lognormal (ln) distributions are used to model the spread of foundation movements data.

Since $\lambda = 1/X$, $\ln(\lambda)$ and $\ln(X)$ are correlated as follows:

$$\ln(\lambda) = \ln(1/X) = \ln(X^{-1}) = -\ln(X) \qquad \text{A-1}$$

Based on the above equation, the following statistics can be expected for $\ln(\lambda)$ data in comparison with $\ln(X)$ data:

Minimum $\ln(\lambda)$ = - Maximum $\ln(X)$

Maximum $\ln(\lambda)$ = - Minimum $\ln(X)$

Arithmetic mean of ln values: $\mu_{LNA\text{-}\lambda}$ for λ = - $\mu_{LNA\text{-}X}$ for X

Arithmetic standard deviation of ln values: $\sigma_{LNA\text{-}\lambda}$ for λ = $\sigma_{LNA\text{-}X}$ for X

Coefficient of variation of ln values: $COV_{LNA\text{-}\lambda}$ for λ = - $COV_{LNA\text{-}X}$ for X

Data statistics for both Accuracy, X, and Bias, λ, included in this appendix are found to be in accordance with the above comparisons.

The numbers in tables in which computed data are presented are extended to the fifth or sixth significant figure. It is not the intent to imply that the level of accuracy of five to six significant figures is required for statistics. The only reason for this level of reporting is to help researchers verify the final results for load factors with their computational programs (for example, spreadsheets). In Chapter 6, the final load factors are reported to three significant figures and then further rounded up as shown in Chapter 7.

A.1 Data Source: Gifford et al. (1987)

Gifford et al. (1987) present results of a Federal Highway Administration (FHWA) study to evaluate the performance of spread footings for bridges. A dataset for vertical settlements of footings measured at 20 footings for 10 instrumented bridges in the northeastern United States is presented. The bridges included five simple-span and five continuous-beam structures. Table A.1.1 summarizes the site location information for the bridges. Each site number in Table A.1.1 represents a footing supporting a single substructure unit (abutment or pier). Sites #12, #13, and #18 were not included because construction problems at these sites resulted in disturbance of the subgrade soils, and short-term settlement was increased. Data for a footing at Site #19 appear to be anomalous and have been excluded in this table.

Four of the instrumented bridges were single-span structures. Two two-span and three four-span bridges were also monitored in addition to a single five-span structure. Nine of the structures were designed to carry highway traffic, while one four-span bridge carried railroad traffic across an Interstate highway. The subsurface conditions were characterized by cohesionless soils (sand or silt).

Measured and predicted values of settlements were reported in Gifford et al. (1987) for several settlement prediction methods. Table A.1.2 contains the measured settlement values along with predicted settlement values based on the Schmertmann and Hough methods. It appears that the predictions were based on results of standard penetration tests (SPTs) in almost all cases, or where cone penetration tests (CPTs) were available, they were converted to equivalent SPT N-values (blows/foot) using Schmertmann correlations to perform the settlement analyses. Based on information in Table A.1.2, the following tables were developed:

- Table A.1.3 contains values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.1.2.
- Table A.1.4 contains the lognormal (ln) values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.1.3.
- Table A.1.5 contains statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.1.3.
- Table A.1.6 contains statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.1.4.

- Table A.1.7 contains statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.1.2 and Table A.1.3.
- Table A.1.8 contains statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.1.2 and Table A.1.4.

Figure A.1.1 illustrates the relationship between the measured and predicted values for both the Schmertmann and Hough methods for this data set. If the methods provide a perfect prediction, all the data would be located on the one-to-one correspondence line. For this data set, it appears that the Hough method provides more conservative predicted settlements compared to the Schmertmann method. On the other hand, the Schmertmann method can be more unconservative compared to the Hough method. Refer to Appendix B for correlation analysis of the data.

Refer to Gifford et al. (1987) for detailed information.

Table A.1.1. Site Location Data for U.S. Sources from Gifford et al. (1987)

Site	Project	Feature	Location	Element
#1	Highway VT127, Burlington, VT	Bridge	Abutment 1	Footing
#2	Highway VT127, Burlington, VT	Bridge	Abutment 2	Footing
#3	Dickerman Road, Cheshire, CT	Bridge	Abutment 1	Footing
#4	Dickerman Road, Cheshire, CT	Bridge	Abutment 2	Footing
#5	Dickerman Road, Cheshire, CT	Bridge	Center Pier	Footing
#6	Branch Avenue, Providence, RI	Bridge	West Abutment	Footing
#7	Branch Avenue, Providence, RI	Bridge	East Abutment	Footing
#8	Branch Avenue, Providence, RI	Bridge	Pier 1 North	Footing
#9	Branch Avenue, Providence, RI	Bridge	Pier 1 South	Footing
#10	Branch Avenue, Providence, RI	Bridge	Pier 2 North	Footing
#11	Branch Avenue, Providence, RI	Bridge	Pier 2 South	Footing
#14	Route 28, Colliersville, NY	Bridge	South Abutment	Footing
#15	Route 28, Colliersville, NY	Bridge	North Abutment	Footing
#16	Route 146, Uxbridge, MA	Bridge	North Abutment	Footing
#17	Route 146, Uxbridge, MA	Bridge	South Abutment	Footing
#20	Conrail over I-86, Manchester, CT	Bridge	Abutment 2	Footing
#21	Tolland Turnpike, Manchester, CT	Bridge	Abutment 1	Footing
#22	Tolland Turnpike, Manchester, CT	Bridge	Abutment 2	Footing
#23	Route 84, Manchester, CT	Bridge	Abutment 1	Footing
#24	Route 84, Manchester, CT	Bridge	Abutment 2	Footing

Note: Gifford et al. (1987) notes that data for footings at Sites #12, #13, and #18 were not included because construction problems at these sites resulted in disturbance of the subgrade soils, and short-term settlement was increased. Data for footing at Site #19 appear to be anomalous and have been excluded in this table.

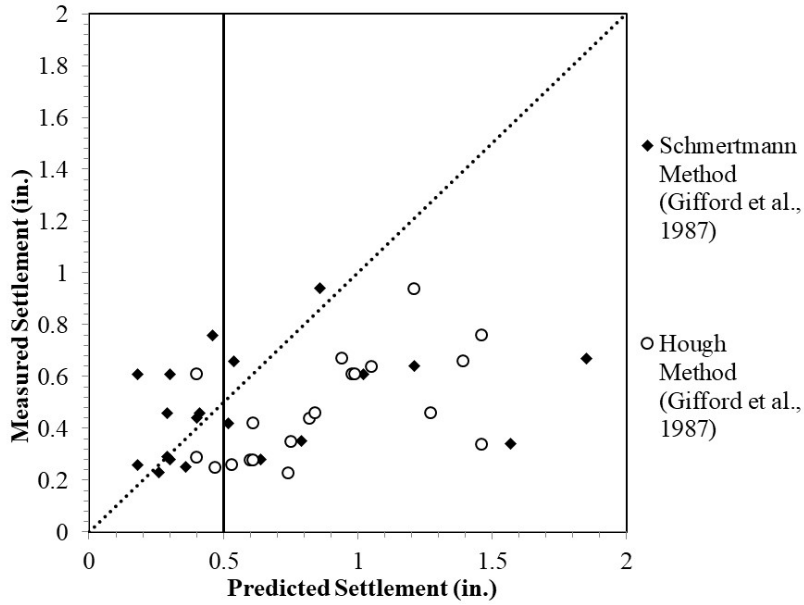

Figure A.1.1. Measured versus predicted settlement for the Schmertmann and Hough methods for the Gifford et al. (1987) dataset (20 data points for each method).

Table A.1.2. Data for Measured and Predicted Settlements for U.S. Sources from Gifford et al. (1987)

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann	Predicted Settlement, S_P, in., Hough
#1	0.35	0.79	0.75
#2	0.67	1.85	0.94
#3	0.94	0.86	1.21
#4	0.76	0.46	1.46
#5	0.61	0.30	0.98
#6	0.42	0.52	0.61
#7	0.61	0.18	0.40
#8	0.28	0.30	0.60
#9	0.26	0.18	0.53
#10	0.29	0.29	0.40
#11	0.25	0.36	0.47
#14	0.46	0.41	1.27
#15	0.34	1.57	1.46
#16	0.23	0.26	0.74
#17	0.44	0.40	0.82
#20	0.64	1.21	1.05
#21	0.46	0.29	0.84
#22	0.66	0.54	1.39
#23	0.61	1.02	0.99
#24	0.28	0.64	0.61

Table A.1.3. Accuracy (*X*) and Bias (λ) Values Based on Data for U.S. Sources from Gifford et al. (1987) in Table A.1.2

Site	Accuracy, *X* Schmertmann	Accuracy, *X* Hough	Bias, λ Schmertmann	Bias, λ Hough
#1	2.2571	2.1429	0.4430	0.4667
#2	2.7612	1.4030	0.3622	0.7128
#3	0.9149	1.2872	1.0930	0.7769
#4	0.6053	1.9211	1.6522	0.5205
#5	0.4918	1.6066	2.0333	0.6224
#6	1.2381	1.4524	0.8077	0.6885
#7	0.2951	0.6557	3.3889	1.5250
#8	1.0714	2.1429	0.9333	0.4667
#9	0.6923	2.0385	1.4444	0.4906
#10	1.0000	1.3793	1.0000	0.7250
#11	1.4400	1.8800	0.6944	0.5319
#14	0.8913	2.7609	1.1220	0.3622
#15	4.6176	4.2941	0.2166	0.2329
#16	1.1304	3.2174	0.8846	0.3108
#17	0.9091	1.8636	1.1000	0.5366
#20	1.8906	1.6406	0.5289	0.6095
#21	0.6304	1.8261	1.5862	0.5476
#22	0.8182	2.1061	1.2222	0.4748
#23	1.6721	1.6230	0.5980	0.6162
#24	2.2857	2.1786	0.4375	0.4590

Table A.1.4. Lognormal of Accuracy (*X*) and Bias (λ) Values Based on Data for U.S. Sources from Gifford et al. (1987) in Table A.1.3

Site	ln(*X*) Schmertmann	ln(*X*) Hough	ln(λ) Schmertmann	ln(λ) Hough
#1	0.8141	0.7621	-0.8141	-0.7621
#2	1.0157	0.3386	-1.0157	-0.3386
#3	-0.0889	0.2525	0.0889	-0.2525
#4	-0.5021	0.6529	0.5021	-0.6529
#5	-0.7097	0.4741	0.7097	-0.4741
#6	0.2136	0.3732	-0.2136	-0.3732
#7	-1.2205	-0.4220	1.2205	0.4220
#8	0.0690	0.7621	-0.0690	-0.7621
#9	-0.3677	0.7122	0.3677	-0.7122
#10	0.0000	0.3216	0.0000	-0.3216
#11	0.3646	0.6313	-0.3646	-0.6313
#14	-0.1151	1.0155	0.1151	-1.0155
#15	1.5299	1.4572	-1.5299	-1.4572
#16	0.1226	1.1686	-0.1226	-1.1686
#17	-0.0953	0.6225	0.0953	-0.6225
#20	0.6369	0.4951	-0.6369	-0.4951
#21	-0.4613	0.6022	0.4613	-0.6022
#22	-0.2007	0.7448	0.2007	-0.7448
#23	0.5141	0.4842	-0.5141	-0.4842
#24	0.8267	0.7787	-0.8267	-0.7787

Table A.1.5. Statistics for *X* and λ for Gifford et al. (1987) Database Based on Data in Table A.1.3

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	20	20	20	20
Minimum	0.2951	0.6557	0.2166	0.2329
Maximum	4.6176	4.2941	3.3889	1.5250
μ	1.3806	1.9710	1.0774	0.5838
σ	1.0064	0.7693	0.7212	0.2610
COV	0.7290	0.3903	0.6694	0.4471

Table A.1.6. Statistics for ln(*X*) and ln(λ) for Gifford et al. (1987) Database Based on Data in Table A.1.4

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	20	20	20	20
Minimum	-1.2205	-0.4220	-1.5299	-1.4572
Maximum	1.5299	1.4572	1.2205	0.4220
μ_{LNA}	0.1173	0.6114	-0.1173	-0.6114
σ_{LNA}	0.6479	0.3807	0.6479	0.3807
COV_{LNA}	5.5238	0.6227	-5.5238	-0.6227

Table A.1.7. Statistics for *X* and λ for Predicted Data Larger than 0.5 Inch from Gifford et al. (1987) Database Based on Data in Table A.1.2 and Table A.1.3

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	9	17	9	17
Minimum	0.8182	1.2872	0.2166	0.2329
Maximum	4.6176	4.2941	1.2222	0.7769
μ	2.0506	2.0885	0.6344	0.5232
σ	1.1635	0.7467	0.3396	0.1422
COV	0.5674	0.3575	0.5353	0.2718

Table A.1.8. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from Gifford et al. (1987) Database Based on Data in Table A.1.2 and Table A.1.4

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	9	17	9	17
Minimum	-0.2007	0.2525	-1.5299	-1.4572
Maximum	1.5299	1.4572	0.2007	-0.2525
μ_{LNA}	0.5846	0.6880	-0.5846	-0.6880
σ_{LNA}	0.5484	0.3063	0.5484	0.3063
COV_{LNA}	0.9382	0.4452	-0.9382	-0.4452

A.2 Data Source: Baus (1992)

Baus (1992) presents results from a highway bridge spread footing settlement monitoring program undertaken by the South Carolina Department of Highways and Public Transportation, now known as the South Carolina Department of Transportation. Settlements of spread footings were monitored at three highway bridge projects. Two bridges had 5 bents (that is, 4-span bridge), and one bridge had 19 bents (that is, 18-span bridge). Table A.2.1 summarizes the site information for the bridges. The first two bridges (Sites #1 to #8) are located in the Middle Coastal Plain of the Atlantic Coastal Plains Physiographic Province. The third bridge corresponding to Sites #9 to #11 is located in the Upper Coastal Plain of the Atlantic Coastal Plains Physiographic Province. The subsurface conditions were characterized by cohesionless soils (sand or silt) with occasional low-plasticity clays. At each of the monitored locations, both SPTs and CPTs were performed, thereby offering an opportunity for side-by-side comparisons of settlement predictions based on these subsurface investigation techniques.

Measured and predicted values of settlements were reported in Baus (1992) for several settlement prediction methods. Table A.2.2 contains the measured settlement values along with predicted settlement values based on the Schmertmann method using SPT and CPT data. CPTs were not available at Sites #7 and #8; hence, the predicted values for the Schmertmann method were not provided by Baus (1992). Because SPT data were available at all sites, additional analyses were performed for this report, and predicted settlement values for the Schmertmann method based on SPT results were developed. Table A.2.3 provides measured settlement values along with predicted settlement values based on the Schmertmann method and the Hough method using SPT data. Based on information in Tables A.2.2 and A.2.3, the following tables were developed:

- Table A.2.4 contains values of Accuracy, X, and Bias, λ, for the Schmertmann method using SPT and CPT data in Table A.2.2.
- Table A.2.5 contains statistics for Accuracy, X, and Bias, λ, for the Schmertmann method and the Hough method using SPT data in Table A.2.3.
- Table A.2.6 contains the lognormal (ln) values of Accuracy, X, and Bias, λ, for the Schmertmann method using SPT and CPT data in Table A.2.4.
- Table A.2.7 contains statistics for lognormal (ln) values of Accuracy, X, and Bias, λ, for the Schmertmann method and the Hough method based on SPT data in Table A.2.5.
- Table A.2.8 contains statistics for Accuracy, X, and Bias, λ, for the Schmertmann method using SPT and CPT data in Table A.2.4.
- Table A.2.9 contains the statistics for lognormal (ln) values of Accuracy, X, and Bias, λ, for the Schmertmann method using SPT and CPT data in Table A.2.6.
- Table A.2.10 contains statistics for Accuracy, X, and Bias, λ, for the Schmertmann method and the Hough method using SPT data in Table A.2.5.

- Table A.2.11 contains statistics for the lognormal (ln) values of Accuracy, *X*, and Bias, λ, for the Schmertmann method and the Hough method based using SPT data in Table A.2.7.
- Table A.2.12 contains statistics for Accuracy, *X*, and Bias, λ, for the Schmertmann method using SPT and CPT data based on predicted settlements larger than 0.5 inch in Table A.2.2 and Table A.2.4.
- Table A.2.13 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for the Schmertmann method using SPT and CPT data based on predicted settlements larger than 0.5 inch in Table A.2.2 and Table A.2.6.
- Table A.2.14 contains values of Accuracy, *X*, and Bias, λ, for the Schmertmann method and the Hough method using SPT data based on predicted settlements larger than 0.5 inch in Table A.2.3 and Table A.2.5.
- Table A.2.15 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for the Schmertmann method and the Hough method based using SPT data based on predicted settlements larger than 0.5 inch in Table A.2.3 and Table A.2.7.

The data for the Schmertmann method based on CPT and SPT results permit a direct comparison of the effect of subsurface investigation techniques on the *SE* load factor, γ_{SE}, as discussed in Appendix C.

Figure A.2.1 illustrates the relationship for this data set between the measured and predicted values for both the Schmertmann method using either SPT values or CPT values as input for the settlement predictions. Figure A.2.2 illustrates the relationship for this data set between the measured and predicted values for both the Schmertmann and Hough methods based on only SPT data. If the methods provide a perfect prediction, all the data would be located on the one-to-one correspondence line. No specific trends for both methods are observed on these figures. Refer to Appendix B for correlation analysis of the data.

Refer to Baus (1992) for detailed information.

Table A.2.1. Site Location Data from Baus (1992)

Site	Project	Feature	Location	Element
#1	US 501 Bypass over US 501, Marion County, SC	Bridge	Bent 3	Footing 1
#2	US 501 Bypass over US 501, Marion County, SC	Bridge	Bent 3	Footing 4
#3	SC 38 Twin Overpasses over US 301 and Seaboard System Rail Road, Dillon County, SC	Bridge	Bent 3	Eastbound Lane (EBL), Footing 1
#4	SC 38 Twin Overpasses over US 301 and Seaboard System Rail Road, Dillon County, SC	Bridge	Bent 3	Eastbound Lane (EBL), Footing 3
#5	SC 38 Twin Overpasses over US 301 and Seaboard System Rail Road, Dillon County, SC	Bridge	Bent 3	Westbound Lane (WBL), Footing 1
#6	SC 38 Twin Overpasses over US 301 and Seaboard System Rail Road, Dillon County, SC	Bridge	Bent 3	Westbound Lane (WBL), Footing 3
#7	SC 38 Twin Overpasses over US 301 and Seaboard System Rail Road, Dillon County, SC	Bridge	Bent 4	Eastbound Lane (EBL), Footing 1
#8	SC 38 Twin Overpasses over US 301 and Seaboard System Rail Road, Dillon County, SC	Bridge	Bent 4	Eastbound Lane (EBL), Footing 3
#9	SC 77 Twin Overpasses over Jackson Boulevard and Wildcat Creek, Richland County, SC	Bridge	Bent 2	Southbound Lane (SBL), Footing 1
#10	SC 77 Twin Overpasses over Jackson Boulevard and Wildcat Creek, Richland County, SC	Bridge	Bent 2	Northbound Lane (NBL), Footing 1
#11	SC 77 Twin Overpasses over Jackson Boulevard and Wildcat Creek, Richland County, SC	Bridge	Bent 2	Northbound Lane (NBL), Footing 4

Table A.2.2. Data for Measured and Predicted Settlements from Baus (1992) Using SPT and CPT for the Schmertmann Method

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann (SPT)	Predicted Settlement, S_P, in., Schmertmann (CPT)
#1	0.51	1.38	1.88
#2	0.62	0.99	1.81
#3	0.52	0.84	1.10
#4	0.59	0.84	1.10
#5	0.38	0.84	1.10
#6	0.41	0.84	1.10
#7	2.15	0.61	–
#8	2.03	0.61	–
#9	0.55	0.85	0.66
#10	1.04	0.66	0.65
#11	0.73	0.45	0.43

Note: The predictions using the Schmertmann method were based on both SPTs (developed by the authors) and CPTs. CPT data were not available for Sites #6 and #7; hence, Baus (1992) did not report predictions for the Schmertmann method for those sites.

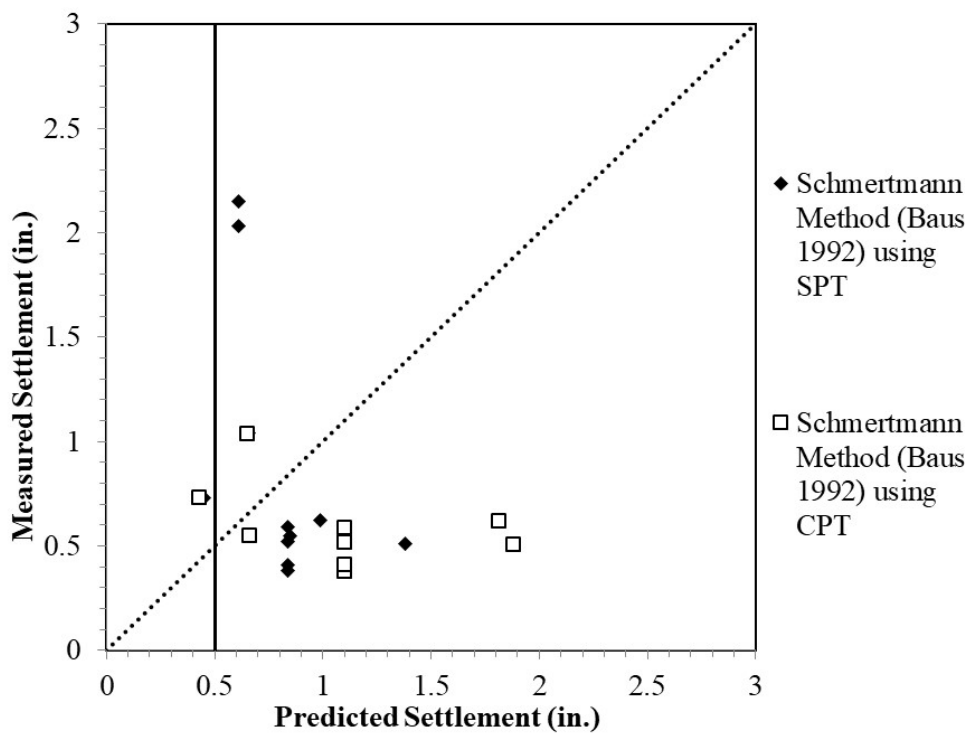

Figure A.2.1. Measured versus predicted settlement for the Schmertmann method for the Baus (1992) data set using SPTs and CPTs (11 data points for SPT settlement prediction and 9 data points for CPT settlement prediction).

Table A.2.3. Data for Measured and Predicted Settlements for the Schmertmann Method and the Hough Method Using SPT Data from Baus (1992)

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann (SPT)	Predicted Settlement, S_P, in., Hough (SPT)
#1	0.51	1.38	1.66
#2	0.62	0.99	1.19
#3	0.52	0.84	1.11
#4	0.59	0.84	1.11
#5	0.38	0.84	1.11
#6	0.41	0.84	1.11
#7	2.15	0.61	2.28
#8	2.03	0.61	2.28
#9	0.55	0.85	1.11
#10	1.04	0.66	1.06
#11	0.73	0.45	0.88

Note: The predictions using the Hough method were based on SPTs. The predictions using the Schmertmann method were developed by the authors using SPT data from Baus (1992).

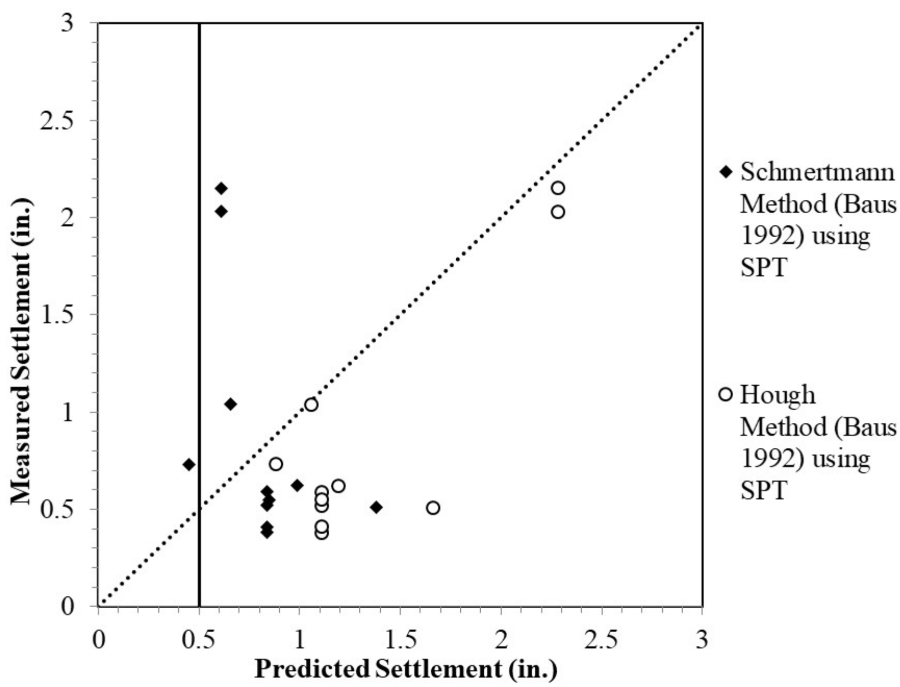

Figure A.2.2. Measured versus predicted settlement for the Schmertmann and Hough methods for the Baus (1992) data set using SPTs (11 data points for each method).

Table A.2.4. Accuracy (*X*) and Bias (λ) Values for the Schmertmann Method Based on SPT and CPT Data from Baus (1992) in Table A.2.2

Site	Schmertmann (SPT) *X*	Schmertmann (CPT) *X*	Schmertmann (SPT) λ	Schmertmann (CPT) λ
#1	2.7059	3.6863	0.3696	0.2713
#2	1.5968	2.9194	0.6263	0.3425
#3	1.6154	2.1154	0.6190	0.4727
#4	1.4237	1.8644	0.7024	0.5364
#5	2.2105	2.8947	0.4524	0.3455
#6	2.0488	2.6829	0.4881	0.3727
#7	0.2837	–	3.5246	–
#8	0.3005	–	3.3279	–
#9	1.5455	1.2000	0.6471	0.8333
#10	0.6346	0.6250	1.5758	1.6000
#11	0.6164	0.5890	1.6222	1.6977

Table A.2.5. Accuracy (*X*) and Bias (λ) Values for the Schmertmann Method and the Hough Method Using SPT Data from Baus (1992) in Table A.2.3

Site	Schmertmann (SPT) *X*	Hough (SPT) *X*	Schmertmann (SPT) λ	Hough (SPT) λ
#1	2.7059	3.2549	0.3696	0.3072
#2	1.5968	1.9194	0.6263	0.5210
#3	1.6154	2.1346	0.6190	0.4685
#4	1.4237	1.8814	0.7024	0.5315
#5	2.2105	2.9211	0.4524	0.3423
#6	2.0488	2.7073	0.4881	0.3694
#7	0.2837	1.0605	3.5246	0.9430
#8	0.3005	1.1232	3.3279	0.8904
#9	1.5455	2.0182	0.6471	0.4955
#10	0.6346	1.0192	1.5758	0.9811
#11	0.6164	1.2055	1.6222	0.8295

Table A.2.6. Lognormal of Accuracy (*X*) and Bias (λ) Values for the Schmertmann Method Based on SPT and CPT Data from Baus (1992) in Table A.2.4

Site	Schmertmann (SPT) ln(*X*)	Schmertmann (CPT) ln(*X*)	Schmertmann (SPT) ln(λ)	Schmertmann (CPT) ln(λ)
#1	0.9954	1.3046	-0.9954	-1.3046
#2	0.4680	1.0714	-0.4680	-1.0714
#3	0.4796	0.7492	-0.4796	-0.7492
#4	0.3533	0.6229	-0.3533	-0.6229
#5	0.7932	1.0629	-0.7932	-1.0629
#6	0.7172	0.9869	-0.7172	-0.9869
#7	-1.2598	–	1.2598	–
#8	-1.2023	–	1.2023	–
#9	0.4353	0.1823	-0.4353	-0.1823
#10	-0.4547	-0.4700	0.4547	0.4700
#11	-0.4838	-0.5293	0.4838	0.5293

Table A.2.7. Lognormal of Accuracy (*X*) and Bias (λ) Values for the Schmertmann Method and the Hough Method Using SPT Based on Data from Baus (1992) in Table A.2.5

Site	Schmertmann (SPT) ln(*X*)	Hough (SPT) ln(*X*)	Schmertmann (SPT) ln(λ)	Hough (SPT) ln(λ)
#1	0.9954	1.1802	-0.9954	-1.1802
#2	0.4680	0.6520	-0.4680	-0.6520
#3	0.4796	0.7583	-0.4796	-0.7583
#4	0.3533	0.6320	-0.3533	-0.6320
#5	0.7932	1.0719	-0.7932	-1.0719
#6	0.7172	0.9960	-0.7172	-0.9960
#7	-1.2598	0.0587	1.2598	-0.0587
#8	-1.2023	0.1161	1.2023	-0.1161
#9	0.4353	0.7022	-0.4353	-0.7022
#10	-0.4547	0.0190	0.4547	-0.0190
#11	-0.4838	0.1869	0.4838	-0.1869

Table A.2.8. Statistics for *X* and λ for Baus (1992) Database Based on Data in Table A.2.4

Statistic	For *X* of Schmertmann (SPT)	For *X* of Schmertmann (CPT)	For λ of Schmertmann (SPT)	For λ of Schmertmann (CPT)
N	11	9	11	9
Minimum	0.2837	0.5890	0.3696	0.2713
Maximum	2.7059	3.6863	3.5246	1.6977
μ	1.3620	2.0641	1.2687	0.7191
σ	0.8080	1.0881	1.1478	0.5526
COV	0.5933	0.5272	0.9047	0.7684

Table A.2.9. Statistics for ln(*X*) and ln(λ) for Baus (1992) Database Based on Data in Table A.2.6

Statistic	For ln(*X*) of Schmertmann (SPT)	For ln(*X*) of Schmertmann (CPT)	For ln(λ) of Schmertmann (SPT)	For ln(λ) of Schmertmann (CPT)
N	11	9	11	9
Minimum	-1.2598	-0.5293	-0.9954	-1.3046
Maximum	0.9954	1.3046	1.2598	0.5293
μ_{LNA}	0.0765	0.5534	-0.0765	-0.5534
σ_{LNA}	0.7942	0.6783	0.7942	0.6783
COV_{LNA}	10.3821	1.2256	-10.3821	-1.2256

Table A.2.10. Statistics for *X* and λ for Baus (1992) Database Using SPTs Based on Data in Table A.2.5

Statistic	For *X* of Schmertmann (SPT)	For *X* of Hough (SPT)	For λ of Schmertmann (SPT)	For λ of Hough (SPT)
N	11	11	11	11
Minimum	0.2837	1.0192	0.3696	0.3072
Maximum	2.7059	3.2549	3.5246	0.9811
μ	1.3620	1.9314	1.2687	0.6072
σ	0.8080	0.7846	1.1478	0.2537
COV	0.5933	0.4062	0.9047	0.4178

Table A.2.11. Statistics for ln(*X*) and ln(λ) for Baus (1992) Database Using SPTs Based on Data in Table A.2.7

Statistic	For ln(*X*) of Schmertmann (SPT)	For ln(*X*) of Hough (SPT)	For ln(λ) of Schmertmann (SPT)	For ln(λ) of Hough (SPT)
N	11	11	11	11
Minimum	-1.2598	0.0190	-0.9954	-1.1802
Maximum	0.9954	1.1802	1.2598	-0.0190
μ_{LNA}	0.0765	0.5794	-0.0765	-0.5794
σ_{LNA}	0.7942	0.4226	0.7942	0.4226
COV_{LNA}	10.3821	0.7294	-10.3821	-0.7294

Table A.2.12. Statistics for *X* and λ for Predicted Data Larger than 0.5 Inch from Baus (1992) Database Based on Data in Table A.2.2 and Table A.2.4

Statistic	For *X* of Schmertmann (SPT)	For *X* of Schmertmann (CPT)	For λ of Schmertmann (SPT)	For λ of Schmertmann (CPT)
N	10	8	10	8
Minimum	0.2837	0.6250	0.3696	0.2713
Maximum	2.7059	3.6863	3.5246	1.6000
μ	1.4365	2.2485	1.2333	0.5968
σ	0.8109	1.0017	1.2036	0.4417
COV	0.5645	0.4455	0.9759	0.7400

Table A.2.13. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from Baus (1992) Database Based on Data in Table A.2.2 and Table A.2.6

Statistic	For ln(*X*) of Schmertmann (SPT)	For ln(*X*) of Schmertmann (CPT)	For ln(λ) of Schmertmann (SPT)	For ln(λ) of Schmertmann (CPT)
N	10	8	10	8
Minimum	-1.2598	-0.4700	-0.9954	-1.3046
Maximum	0.9954	1.3046	1.2598	0.4700
μ_{LNA}	0.1325	0.6888	-0.1325	-0.6888
σ_{LNA}	0.8139	0.5809	0.8139	0.5809
COV_{LNA}	6.1414	0.8433	-6.1414	-0.8433

Table A.2.14. Statistics for *X* and λ for Predicted Data Larger than 0.5 Inch from Baus (1992) Database Using SPTs Based on Data in Table A.2.3 and Table A.2.5

Statistic	For *X* of Schmertmann (SPT)	For *X* of Hough (SPT)	For λ of Schmertmann (SPT)	For λ of Hough (SPT)
N	10	11	10	11
Minimum	0.2837	1.0192	0.3696	0.3072
Maximum	2.7059	3.2549	3.5246	0.9811
μ	1.4365	1.9314	1.2333	0.6072
σ	0.8109	0.7846	1.2036	0.2537
COV	0.5645	0.4062	0.9759	0.4178

Table A.2.15. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from Baus (1992) Database Using SPTs Based on Data in Table A.2.3 and Table A.2.7

Statistic	For ln(*X*) of Schmertmann (SPT)	For ln(*X*) of Hough (SPT)	For ln(λ) of Schmertmann (SPT)	For ln(λ) of Hough (SPT)
N	10	11	10	11
Minimum	-1.2598	0.0190	-0.9954	-1.1802
Maximum	0.9954	1.1802	1.2598	-0.0190
μ_{LNA}	0.1325	0.5794	-0.1325	-0.5794
σ_{LNA}	0.8139	0.4226	0.8139	0.4226
COV_{LNA}	6.1414	0.7294	-6.1414	-0.7294

A.3 Data Source: Briaud and Gibbens (1997)

Briaud and Gibbens (1997) provide the results of a research project sponsored by the FHWA that included a series of load tests performed on five square spread footings. The load test program was performed at the National Geotechnical Experimentation Site (NGES) on the Texas A&M University (TAMU) Riverside Campus, near College Station, Texas. Load settlement curves were developed based on concentric loads applied to each footing. The data from the load tests were compared against results obtained from a symposium held as part of the American Society of Civil Engineers Settlement '94 conference, which invited settlement predictions by different prediction methods for a comparative evaluation.

Table A.3.1 summarizes the site location information for the five footings. Subsurface investigations were performed by many different techniques, and the soil at the site is a medium dense, fairly uniform, silty fine silica sand.

Load-settlement curves were developed based on incremental loads that were progressively applied to each footing, and settlements to several inches were measured. The loads corresponding to 1.0 inch of measured settlement were used to develop predictions based on the Schmertmann and Hough methods using average SPT test results. Table A.3.2 contains the measured settlement values along with predicted settlement values based on the Schmertmann and Hough methods. Based on information in Table A.3.2, the following tables were developed:

- Table A.3.3 contains values of Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.3.2.
- Table A.3.4 contains the lognormal (ln) values of Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.3.3.
- Table A.3.5 contains statistics for Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.3.3.
- Table A.3.6 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.3.4.
- Table A.3.7 contains statistics for Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.3.2 and Table A.3.3. Because all predicted values were larger than 0.5 inch, the data in Table A.3.7 are the same as the data in Table A.3.5.
- Table A.3.8 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.3.2 and Table A.3.4. Because all predicted values were larger than 0.5 inch, the data in Table A.3.8 are the same as the data in Table A.3.6.

Figure A.3.1 illustrates the relationship between the measured and predicted values for both the Schmertmann and Hough methods for this data set. If the methods provide a perfect prediction, all the data would be located on the one-to-one correspondence line. In general, the Hough method provided a closer prediction than the Schmertmann method, and both methods were conservative. Refer to Appendix B for correlation analysis of the data.

Refer to Briaud and Gibbens (1997) for detailed information.

Table A.3.1. Site Location Data from Briaud and Gibbens (1997)

Site	Project	Feature	Location	Element
#1	FHWA: Performance of Footings on Sand	Load test	NGES-TAMU	Footing F1 (North)
#2	FHWA: Performance of Footings on Sand	Load test	NGES-TAMU	Footing F2
#3	FHWA: Performance of Footings on Sand	Load test	NGES-TAMU	Footing F3 (South)
#4	FHWA: Performance of Footings on Sand	Load test	NGES-TAMU	Footing F4
#5	FHWA: Performance of Footings on Sand	Load test	NGES-TAMU	Footing F5

Note: NGES-TAMU refers to the National Geotechnical Experimentation Site located on the Texas A&M University Riverside Campus near College Station, Texas.

Table A.3.2. Data for Measured and Predicted Settlements from Briaud and Gibbens (1997)

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann	Predicted Settlement, S_P, in., Hough (SPT)
#1	1.00	2.06	1.22
#2	1.00	1.65	1.16
#3	1.00	2.06	1.22
#4	1.00	2.09	1.48
#5	1.00	1.49	1.03

Note: The predictions were performed by the authors using SPT and load data provided in Briaud and Gibbens (1997).

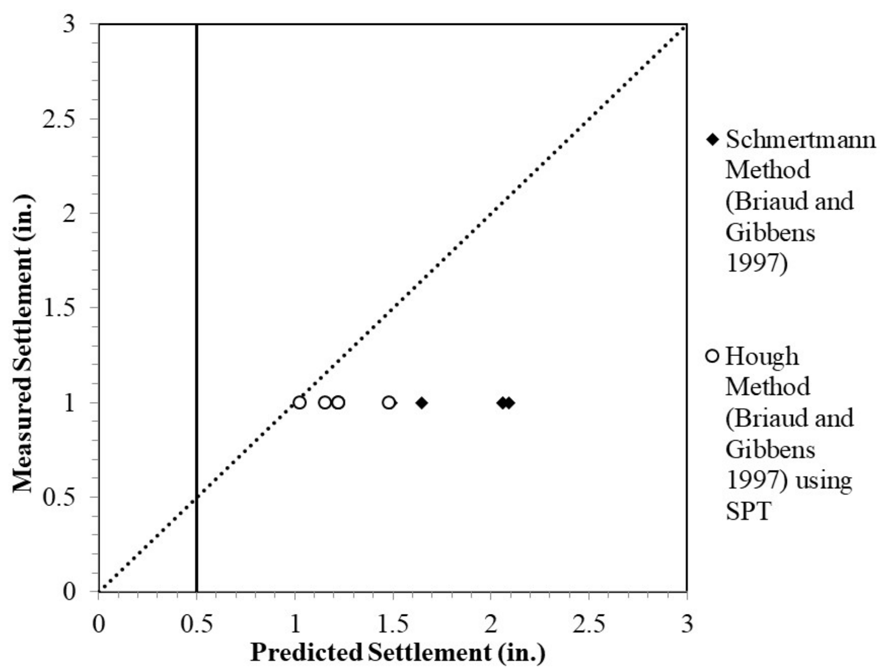

Figure A.3.1. Measured versus predicted settlement for the Schmertmann and Hough methods for the Briaud and Gibbens (1997) data set using SPTs (five data points for each method).

Table A.3.3. Accuracy (X) and Bias (λ) Values Based on Data from Briaud and Gibbens (1997) in Table A.3.2

Site	Accuracy, X Schmertmann	Accuracy, X Hough	Bias, λ Schmertmann	Bias, λ Hough
#1	2.0600	1.2200	0.4854	0.8197
#2	1.6460	1.1550	0.6075	0.8658
#3	2.0600	1.2200	0.4854	0.8197
#4	2.0900	1.4770	0.4785	0.6770
#5	1.4900	1.0250	0.6711	0.9756

Table A.3.4. Lognormal of Accuracy (X) and Bias (λ) Values Based on Data from Briaud and Gibbens (1997) in Table A.3.3

Site	$\ln(X)$ Schmertmann	$\ln(X)$ Hough	$\ln(\lambda)$ Schmertmann	$\ln(\lambda)$ Hough
#1	0.7227	0.1989	-0.7227	-0.1989
#2	0.4983	0.1441	-0.4983	-0.1441
#3	0.7227	0.1989	-0.7227	-0.1989
#4	0.7372	0.3900	-0.7372	-0.3900
#5	0.3988	0.0247	-0.3988	-0.0247

Table A.3.5. Statistics for X and λ for Briaud and Gibbens (1997) Database Based on Data in Table A.3.3

Statistic	For X of Schmertmann	For X of Hough	For λ of Schmertmann	For λ of Hough
N	5	5	5	5
Minimum	1.4900	1.0250	0.4785	0.6770
Maximum	2.0900	1.4770	0.6711	0.9756
μ	1.8692	1.2194	0.5456	0.8316
σ	0.2807	0.1645	0.0885	0.1073
COV	0.1502	0.1349	0.1622	0.1291

Table A.3.6. Statistics for ln(*X*) and ln(λ) for Briaud and Gibbens (1997) Database Based on Data in Table A.3.4

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	5	5	5	5
Minimum	0.3988	0.0247	-0.7372	-0.3900
Maximum	0.7372	0.3900	-0.3988	-0.0247
μ_{LNA}	0.6159	0.1913	-0.6159	-0.1913
σ_{LNA}	0.1569	0.1319	0.1569	0.1319
COV_{LNA}	0.2547	0.6895	-0.2547	-0.6895

Table A.3.7. Statistics for *X* and λ for Predicted Data Larger than 0.5 Inch from Briaud and Gibbens (1997) Database Based on Data in Table A.3.2 and Table A.3.3

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	5	5	5	5
Minimum	1.4900	1.0250	0.4785	0.6770
Maximum	2.0900	1.4770	0.6711	0.9756
μ	1.8692	1.2194	0.5456	0.8316
σ	0.2807	0.1645	0.0885	0.1073
COV	0.1502	0.1349	0.1622	0.1291

Table A.3.8. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from Briaud and Gibbens (1997) Database Based on Table A.3.2 and Table A.3.4

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	5	5	5	5
Minimum	0.3988	0.0247	-0.7372	-0.3900
Maximum	0.7372	0.3900	-0.3988	-0.0247
μ_{LNA}	0.6159	0.1913	-0.6159	-0.1913
σ_{LNA}	0.1569	0.1319	0.1569	0.1319
COV_{LNA}	0.2547	0.6895	-0.2547	-0.6895

A.4 Data Source: Sargand et al. (1999) and Sargand and Masada (2006)

Sargand et al. (1999) present results of a research study undertaken by the Ohio Department of Transportation (ODOT) to evaluate the performance of spread footings for bridges. Five bridge projects were identified and were labeled Bridge A to Bridge E. At Bridge D and E, the subsurface included cohesive soils that experienced long-term consolidation settlements; therefore, these bridge projects were not considered as part of this report. The subsurface soils at Bridges A to C were typically cohesionless for which immediate settlements were reported for several different prediction methods by Sargand et al. (1999). ODOT collected additional data from other projects that were included in a report by Sargand and Masada (2006). Usable data from both reports are summarized in Table A.4.1. The ODOT reports by Sargand and co-workers included measured and predicted data for various stages for some sites; these are identified with Stage # in the column titled “Location” in Table A.4.1.

Bridges A, B, and C were one-span, two-span, and one-span, respectively. Ramp C, which constitutes a large portion of the MOT-70/75 Interchange, is a continuous span bridge with 20 spans. Piers 18 and 19 of Ramp C were monitored for settlements. The subsurface conditions for the sites noted in Table A.4.1 were characterized by cohesionless and cohesive glacial till, which were not subject to long-term settlements.

Table A.4.2 shows the measured settlement values along with predicted settlement values based on the Schmertmann and Hough methods from the reports by Sargand and co-workers. All predictions were based on results of the SPTs. Based on the information in Table A.4.2, the following tables were developed:

- Table A.4.3 contains values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.4.2.
- Table A.4.4 contains the lognormal (ln) values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.4.3.
- Table A.4.5 contains statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.4.3.
- Table A.4.6 contains statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.4.4.
- Table A.4.7 contains statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.4.2 and Table A.4.3.
- Table A.4.8 contains statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.4.2 and Table A.4.4.

Figure A.4.1 illustrates the relationship between the measured and predicted values for both the Schmertmann and Hough methods for this data set. If the methods provide a perfect prediction, all the data would be located on the one-to-one correspondence line. In general, the Hough method was unconservative, while the Schmertmann method was conservative. Refer to Appendix B for correlation analysis.

Refer to Sargand et al. (1999) and Sargand and Masada (2006) for detailed information.

Table A.4.1. Site Location Data from Sargand et al. (1999) and Sargand and Masada (2006)

Site	Project	Feature	Location	Element
#1	MOT-70/75 Interchange (I-70/I-75) Montgomery County, OH	Bridge	Ramp C, Pier 18	Footing
#2	MOT-70/75 Interchange (I-70/I-75) Montgomery County, OH	Bridge	Ramp C, Pier 19	Footing
#3	I-670 over Nelson Road, Columbus, OH (“Bridge A”)	Bridge	Rear Abutment Panel A, Stage 2	Footing
#4	I-670 over Nelson Road, Columbus, OH (“Bridge A”)	Bridge	Rear Abutment Panel A, Stage 3	Footing
#5	I-670 over Nelson Road, Columbus, OH (“Bridge A”)	Bridge	Rear Abutment Panel A, Stage 4	Footing
#6	US Route 68 over US Route 35, Xenia, OH (“Bridge B”)	Bridge	Abutment 1, Stage 2	Footing
#7	US Route 68 over US Route 35, Xenia, OH (“Bridge B”)	Bridge	Abutment 1, Stage 3	Footing
#8	US Route 68 over US Route 35, Xenia, OH (“Bridge B”)	Bridge	Abutment 1, Stage 4	Footing
#9	US Route 68 over US Route 35, Xenia, OH (“Bridge B”)	Bridge	Abutment 1, Stage 5	Footing
#10	US Route 39 over Brandywine Creek, Dover, OH (“Bridge C”)	Bridge (Box Culvert)	West Abutment, Stage 2	Footing
#11	US Route 39 over Brandywine Creek, Dover, OH (“Bridge C”)	Bridge (Box Culvert)	West Abutment, Stage 3	Footing
#12	US Route 39 over Brandywine Creek, Dover, OH (“Bridge C”)	Bridge (Box Culvert)	West Abutment, Stage 5	Footing

Table A.4.2. Data for Measured and Predicted Settlements from Sargand et al. (1999) and Sargand and Masada (2006)

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann	Predicted Settlement, S_P, in., Hough (SPT)
#1	0.70	0.79	0.83
#2	0.96	1.14	0.56
#3	0.08	0.29	0.09
#4	0.14	1.08	0.16
#5	0.27	1.46	0.19
#6	0.13	0.02	0.07
#7	0.54	0.07	0.08
#8	0.58	0.57	0.21
#9	0.62	0.79	0.26
#10	0.48	0.59	0.32
#11	0.70	0.90	0.45
#12	1.06	2.09	0.80

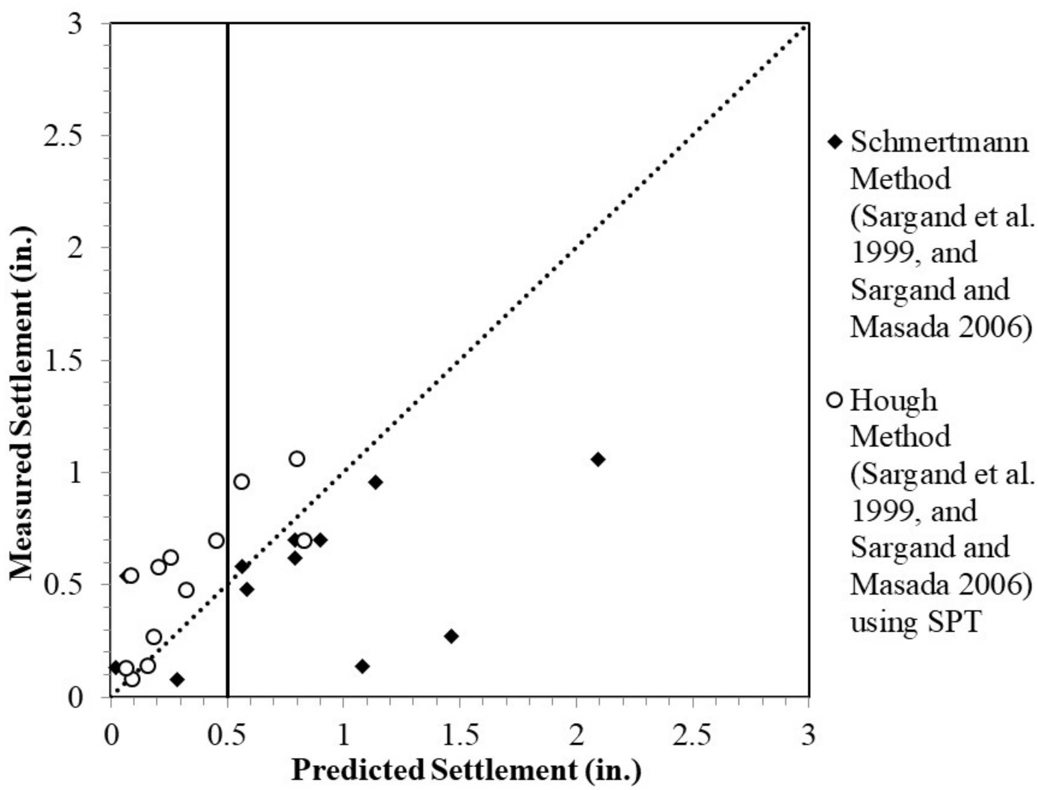

Figure A.4.1. Measured versus predicted settlement for the Schmertmann and Hough methods for data from Sargand et al. (1999) and Sargand and Masada (2006) using SPTs (12 data points for each method).

Table A.4.3. Accuracy (*X*) and Bias (λ) Values Based on Data from Sargand et al. (1999) and Sargand and Masada (2006) in Table A.4.2

Site	Accuracy, *X* Schmertmann	Accuracy, *X* Hough	Bias, λ Schmertmann	Bias, λ Hough
#1	1.1286	1.1857	0.8861	0.8434
#2	1.1875	0.5833	0.8421	1.7143
#3	3.5710	1.1430	0.2800	0.8749
#4	7.7270	1.1290	0.1294	0.8857
#5	5.4170	0.6930	0.1846	1.4430
#6	0.1560	0.5000	6.4103	2.0000
#7	0.1300	0.1560	7.6923	6.4103
#8	0.9770	0.3560	1.0235	2.8090
#9	1.2750	0.4150	0.7843	2.4096
#10	1.2220	0.6740	0.8183	1.4837
#11	1.2870	0.6480	0.7770	1.5432
#12	1.9750	0.7520	0.5063	1.3298

Table A.4.4. Lognormal of Accuracy (*X*) and Bias (λ) Values Based on Data from Sargand et al. (1999) and Sargand and Masada (2006) in Table A.4.3

Site	ln(*X*) Schmertmann	ln(*X*) Hough	ln(λ) Schmertmann	ln(λ) Hough
#1	0.1210	0.1703	-0.1210	-0.1703
#2	0.1719	-0.5390	-0.1719	0.5390
#3	1.2728	0.1337	-1.2728	-0.1337
#4	2.0447	0.1213	-2.0447	-0.1213
#5	1.6895	-0.3667	-1.6895	0.3667
#6	-1.8579	-0.6931	1.8579	0.6931
#7	-2.0402	-1.8579	2.0402	1.8579
#8	-0.0233	-1.0328	0.0233	1.0328
#9	0.2429	-0.8795	-0.2429	0.8795
#10	0.2005	-0.3945	-0.2005	0.3945
#11	0.2523	-0.4339	-0.2523	0.4339
#12	0.6806	-0.2850	-0.6806	0.2850

Table A.4.5. Statistics for X and λ for Sargand et al. (1999) and Sargand and Masada (2006) Database Based on Data in Table A.4.3

Statistic	For X of Schmertmann	For X of Hough	For λ of Schmertmann	For λ of Hough
N	12	12	12	12
Minimum	0.1300	0.1560	0.1294	0.8434
Maximum	7.7270	1.1857	7.6923	6.4103
μ	2.1711	0.6863	1.6945	1.9789
σ	2.2882	0.3260	2.5338	1.5204
COV	1.0539	0.4751	1.4953	0.7683

Table A.4.6. Statistics for ln(X) and ln(λ) for Sargand et al. (1999) and Sargand and Masada (2006) Database Based on Data in Table A.4.4

Statistic	For ln(X) of Schmertmann	For ln(X) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	12	12	12	12
Minimum	-2.0402	-1.8579	-2.0447	-0.1703
Maximum	2.0447	0.1703	2.0402	1.8579
μ_{LNA}	0.2296	-0.5048	-0.2296	0.5048
σ_{LNA}	1.2176	0.5742	1.2176	0.5742
COV_{LNA}	5.3039	-1.1376	-5.3039	1.1376

Table A.4.7. Statistics for X and λ for Predicted Data Larger than 0.5 Inch from Sargand et al. (1999) and Sargand and Masada (2006) Database Based on Data in Table A.4.2 and Table A.4.3

Statistic	For X of Schmertmann	For X of Hough	For λ of Schmertmann	For λ of Hough
N	9	3	9	3
Minimum	0.9770	0.5833	0.1294	0.8434
Maximum	7.7270	1.1857	1.0235	1.7143
μ	2.4662	0.8403	0.6613	1.2958
σ	2.4141	0.3108	0.3166	0.4364
COV	0.9789	0.3698	0.4787	0.3368

Table A.4.8. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from Sargand et al. (1999) and Sargand and Masada (2006) Database Based on Data in Table A.4.2 and Table A.4.4

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	9	3	9	3
Minimum	-0.0233	-0.5390	-2.0447	-0.1703
Maximum	2.0447	0.1703	0.0233	0.5390
μ_{LNA}	0.5978	-0.2179	-0.5978	0.2179
σ_{LNA}	0.7492	0.3594	0.7492	0.3594
COV_{LNA}	1.2532	-1.6495	-1.2532	1.6495

A.5 Data Source: Allen (2018)

Allen (2018) presents results of a monitoring program undertaken by WSDOT to evaluate the performance of embankments, preload fills, and spread footings for tunnels and bridges. Sites at three projects were monitored. Table A.5.1 summarizes these sites.

Data for Sites #1 to #6 were developed from a project that involved construction of a spread footing supported (arch) tunnel to allow the proposed State Route (SR) 395 alignment/fill to pass over the existing Burlington Northern Santa Fe (BNSF) Railroad at the north end of Spokane, Washington. The arch was approximately 51 feet wide at the base, and the footings were designed for a service limit state bearing stress of approximately 7 kips per square foot to keep the footing stress approximately the same as the added overburden stress due to the fill located near the tunnel. The proposed embankment over the existing BNSF tracks varied from 50 to 58 feet in total height. Settlements were predicted and monitored at six sites along the locations of the spread footings for the tunnel structure. The subsurface conditions consisted of loose to dense sands above granitic bedrock at depths of 45 to 110 feet.

Data for Sites #7 and #8 were developed from a project that involved construction of two standard plan geosynthetic retaining walls for highway access from a University of Washington campus located near SR 522 and SR 405 in Bothell, Washington. Wall 10 was 6 feet high, and Wall 9 was 13 feet high. Settlements were predicted and measured at one location for each wall. The subsurface conditions consisted of 7 feet of medium dense sandy elastic or organic silt underlain by very dense sandy silt of silty sand at the Wall 9 site (groundwater was 16 feet below the wall base), and 21 feet of very loose to medium dense sandy organic silt or silty sand underlain by very dense silt or silty sand at the Wall 10 site (groundwater was 8 feet below the wall base).

Data for Sites #9 to #13 were developed from monitoring of settlements under bridge approach fills during the construction of the I-5/SR 432 Talley Way Interchange near Longview, Washington. Subsurface conditions consisted of up to 100 feet of very loose to medium dense elastic or sandy silt (alluvium), underlain by very dense sand, silt, or bedrock.

Table A.5.2 shows the measured settlement values along with predicted settlement values based on the Schmertmann and Hough methods. All predictions for the Hough method were based on results of the SPTs. For Sites #1 to #9, the Schmertmann predictions were based on results of the SPTs. For Sites #10 to #13, the Schmertmann predictions were based on results of the CPTs because the SPT results showed N-values of zero at several depths; therefore, the Schmertmann analyses using SPT results could not be performed. Based on the information in Table A.5.2 and Table A.5.3, the following tables were developed:

- Table A.5.4 contains statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on SPT data in Table A.5.2.
- Table A.5.5 contains the lognormal (ln) values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on SPT data in Table A.5.4.

- Table A.5.6 contains statistics for Accuracy, *X*, and Bias, λ, for the Schmertmann method based on CPT data in Table A.5.3.
- Table A.5.7 contains the lognormal (ln) values of Accuracy, *X*, and Bias, λ, for the Schmertmann method based on CPT data in Table A.5.6.
- Table A.5.8 contains statistics for Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on SPT data in Table A.5.4.
- Table A.5.9 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on SPT data in Table A.5.5.
- Table A.5.10 contains statistics for Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.5.2 and Table A.5.4.
- Table A.5.11 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.5.2 and Table A.5.5.
- Table A.5.12 contains statistics for Accuracy, *X*, and Bias, λ, for the Schmertmann method based on CPT data in Table A.5.6.
- Table A.5.13 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for the Schmertmann method based on CPT data in Table A.5.7.
- Table A.5.14 contains statistics for Accuracy, *X*, and Bias, λ, for the Schmertmann method based on predicted data larger than 0.5 inch in Table A.5.3 and Table A.5.6. Because all predicted values were larger than 0.5 inch, the data in Table A.5.14 are the same as the data in Table A.5.12.
- Table A.5.15 contains statistics for lognormal (ln) values Accuracy, *X*, and Bias, λ, for the Schmertmann method based on predicted data larger than 0.5 inch in Table A.5.3 and Table A.5.7. Because all predicted values were larger than 0.5 inch, the data in Table A.5.15 are the same as the data in Table A.5.13.

Figure A.5.1 illustrates the relationship between the measured and predicted values for both the Schmertmann and Hough methods for this data set using SPTs. Figure A.5.2 illustrates the relationship between the measured and predicted values for the Schmertmann method for this data set using CPTs. If the methods provide a perfect prediction, all the data would be located on the one-to-one correspondence line. In general, the Hough method was more conservative than the Schmertmann method. Refer to Appendix B for correlation analysis.

Refer to Allen (2018) for detailed information.

Table A.5.1. Site Location Data from Allen (2018)

Site	Project	Feature	Location	Element
#1	SR 395 Francis Avenue to US 2, NSLAC-BNSF Railroad Overcrossing Tunnel	Tunnel	Boring RR-3-04, Sta. LR 363+23.5	Embankment
#2	SR 395 Francis Avenue to US 2, NSLAC-BNSF Railroad Overcrossing Tunnel	Tunnel	Boring RR-4-04, Sta. LR 365+39.08	Embankment
#3	SR 395 Francis Avenue to US 2, NSLAC-BNSF Railroad Overcrossing Tunnel	Tunnel	Boring RR-5-04, Sta. LR 367+04.82	Embankment
#4	SR 395 Francis Avenue to US 2, NSLAC-BNSF Railroad Overcrossing Tunnel	Tunnel	Boring RR-6-04, Sta. LR 369+20.01	Embankment
#5	SR 395 Francis Avenue to US 2, NSLAC-BNSF Railroad Overcrossing Tunnel	Tunnel	Boring RR-7-04, Sta. LR 370+96.89	Embankment
#6	SR 395 Francis Avenue to US 2, NSLAC-BNSF Railroad Overcrossing Tunnel	Tunnel	Boring RR-8-04, Sta. LR 372+93.92	Embankment
#7	SR 522 UWB CCC Campus South Access	Embankment	Wall 10	MSE (geosynthetic) Wall
#8	SR 522 UWB CCC Campus South Access	Embankment	Wall 9	MSE (geosynthetic) Wall
#9	I-5/SR 432 Talley Way Interchange-1	Bridge Approach Fill	P-Line Sta. 15+00	Embankment
#10	I-5/SR 432 Talley Way Interchange-2	Bridge Approach Fill	P-Line Ramp	Embankment
#11	I-5/SR 432 Talley Way Interchange-3	Bridge Approach Fill	P-Line Ramp	Embankment
#12	I-5/SR 432 Talley Way Interchange-5	Bridge Approach Fill	R-Line Sta. 20+00	Embankment
#13	I-5/SR 432 Talley Way Interchange-6	Bridge Approach Fill	R-Line Sta. 23+83	Embankment

CCC = Cascadia Community College
MSE = mechanically stabilized earth
NSLAC = North Spokane Limited Access Corridor
UWB = University of Washington Bothell

Table A.5.2. Data for Measured and Predicted Settlements from Allen (2018) Using SPTs

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann	Predicted Settlement, S_P, in., Hough
#1	5.70	3.50	7.20
#2	4.60	5.04	7.90
#3	3.90	5.31	8.00
#4	2.80	2.98	6.30
#5	2.50	2.38	5.00
#6	1.70	0.63	2.10
#7	0.20	0.30	0.80
#8	0.37	0.31	1.10
#9	1.32	4.33	3.10
#10	12.24	–	14.60
#11	11.40	–	14.60
#12	41.00	–	29.80
#13	24.70	–	24.10

Table A.5.3. Data for Measured and Predicted Settlements from Allen (2018) Using CPTs

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann	Predicted Settlement, S_P, in., Hough
#10	12.24	11.28	–
#11	11.40	11.28	–
#12	41.00	33.32	–
#13	24.70	22.26	–

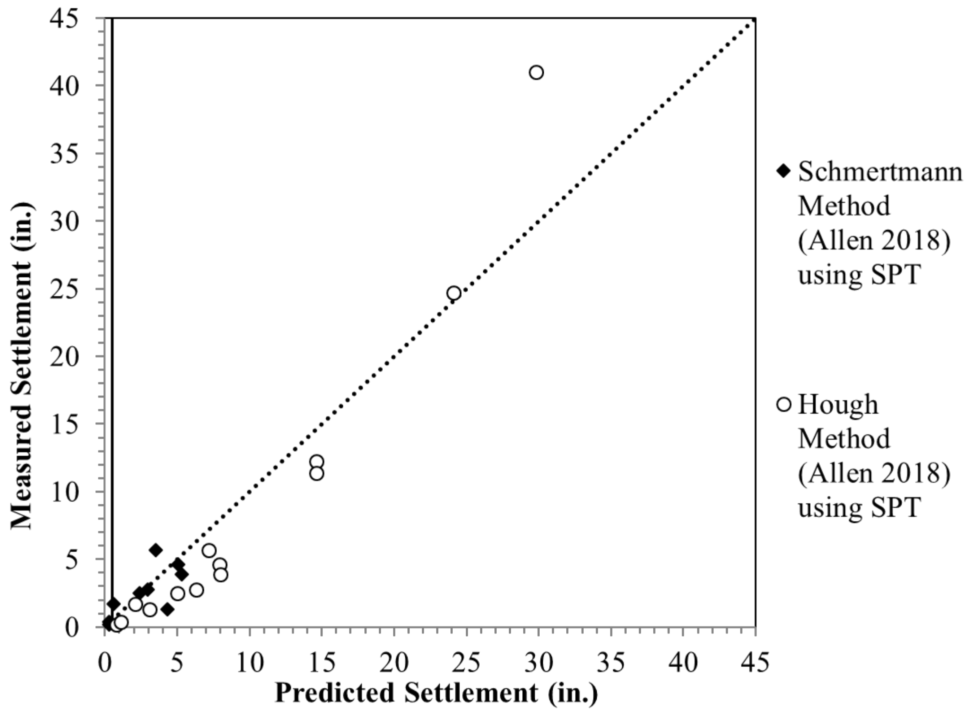

Figure A.5.1. Measured versus predicted settlement for the Schmertmann and Hough methods for data from Allen (2018) using SPTs (9 data points for the Schmertmann method and 13 data points for the Hough method).

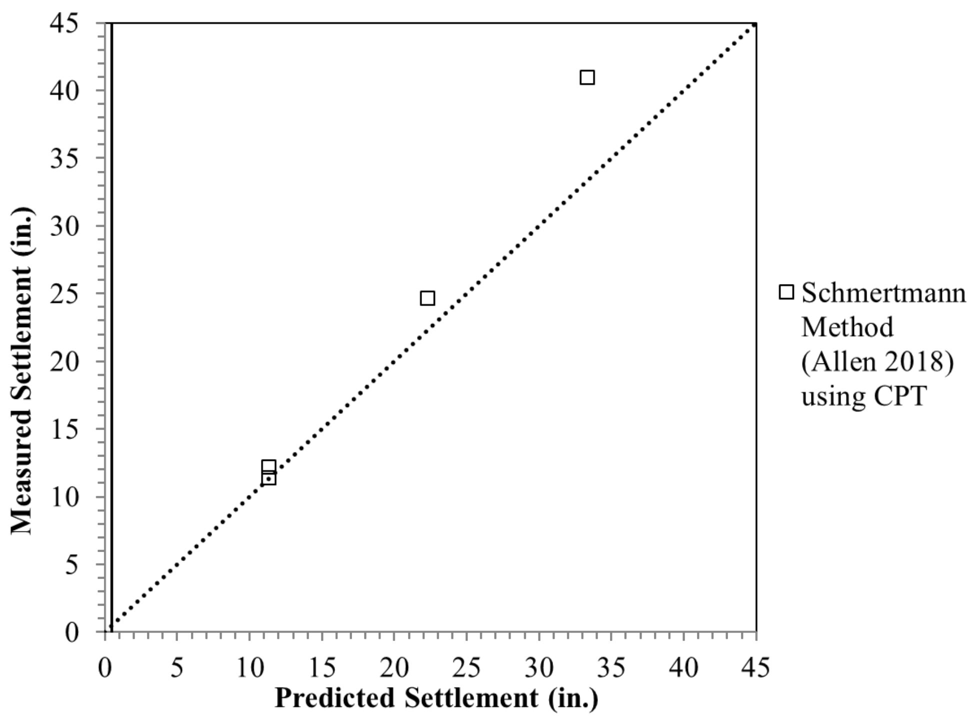

Figure A.5.2. Measured versus predicted settlement for the Schmertmann method for data from Allen (2018) using CPTs (four data points).

Table A.5.4. Accuracy (*X*) and Bias (λ) Values Based on SPT Data from Allen (2018) in Table A.5.2

Site	Accuracy, *X* Schmertmann	Accuracy, *X* Hough	Bias, λ Schmertmann	Bias, λ Hough
#1	0.6140	1.2632	1.6286	0.7917
#2	1.0957	1.7174	0.9127	0.5823
#3	1.3615	2.0513	0.7345	0.4875
#4	1.0643	2.2500	0.9396	0.4444
#5	0.9520	2.0000	1.0504	0.5000
#6	0.3706	1.2353	2.6984	0.8095
#7	1.5000	4.0000	0.6667	0.2500
#8	0.8378	2.9730	1.1935	0.3364
#9	3.2803	2.3485	0.3048	0.4258
#10	–	1.1928	–	0.8384
#11	–	1.2807	–	0.7808
#12	–	0.7268	–	1.3758
#13	–	0.9757	–	1.0249

Table A.5.5. Lognormal of Accuracy (*X*) and Bias (λ) Values Based on SPT Data from Allen (2018) in Table A.5.4

Site	ln(*X*) Schmertmann	ln(*X*) Hough	ln(λ) Schmertmann	ln(λ) Hough
#1	-0.4877	0.2336	0.4877	-0.2336
#2	0.0913	0.5408	-0.0913	-0.5408
#3	0.3086	0.7185	-0.3086	-0.7185
#4	0.0623	0.8109	-0.0623	-0.8109
#5	-0.0492	0.6931	0.0492	-0.6931
#6	-0.9927	0.2113	0.9927	-0.2113
#7	0.4055	1.3863	-0.4055	-1.3863
#8	-0.1769	1.0896	0.1769	-1.0896
#9	1.1879	0.8538	-1.1879	-0.8538
#10	–	0.1763	–	-0.1763
#11	–	0.2474	–	-0.2474
#12	–	-0.3191	–	0.3191
#13	–	-0.0246	–	0.0246

Table A.5.6. Accuracy (X) and Bias (λ) Values Based on CPT Data from Allen (2018) in Table A.5.3

Site	Accuracy, X Schmertmann	Accuracy, X Hough	Bias, λ Schmertmann	Bias, λ Hough
#10	0.9216	–	1.0851	–
#11	0.9895	–	1.0106	–
#12	0.8127	–	1.2305	–
#13	0.9012	–	1.1096	–

Table A.5.7. Lognormal of Accuracy (X) and Bias (λ) Values Based on CPT Data from Allen (2018) in Table A.5.6

Site	ln(X) Schmertmann	ln(X) Hough	ln(λ) Schmertmann	ln(λ) Hough
#10	-0.0817	–	0.0817	–
#11	-0.0106	–	0.0106	–
#12	-0.2074	–	0.2074	–
#13	-0.1040	–	0.1040	–

Table A.5.8. Statistics for X and λ for Allen (2018) Database Using SPTs Based on Data in Table A.5.4

Statistic	For X of Schmertmann	For X of Hough	For λ of Schmertmann	For λ of Hough
N	9	13	9	13
Minimum	0.3706	0.7268	0.3048	0.2500
Maximum	3.2803	4.0000	2.6984	1.3758
μ	1.2307	1.8473	1.1255	0.6652
σ	0.8432	0.9072	0.6941	0.3118
COV	0.6852	0.4911	0.6167	0.4688

Table A.5.9. Statistics for ln(X) and ln(λ) for Allen (2018) Database Using SPTs Based on Data in Table A.5.5

Statistic	For ln(X) of Schmertmann	For ln(X) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	9	13	9	13
Minimum	-0.9927	-0.3191	-1.1879	-1.3863
Maximum	1.1879	1.3863	0.9927	0.3191
μ_{LNA}	0.0388	0.5091	-0.0388	-0.5091
σ_{LNA}	0.6048	0.4752	0.6048	0.4752
COV_{LNA}	15.589	0.9334	-15.589	-0.9334

Table A.5.10. Statistics for *X* and λ for Predicted Data Larger than 0.5 Inch from Allen (2018) Database Using SPTs Based on Data in Table A.5.2 and Table A.5.4

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	7	13	7	13
Minimum	0.3706	0.7268	0.3048	0.2500
Maximum	3.2803	4.0000	2.6984	1.3758
μ	1.2483	1.8473	1.1813	0.6652
σ	0.9539	0.9072	0.7764	0.3118
COV	0.7641	0.4911	0.6573	0.4688

Table A.5.11. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from Allen (2018) Database using SPTs Based on Data in Table A.5.2 and Table A.5.5

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	7	13	7	13
Minimum	-0.9927	-0.3191	-1.1879	-1.3863
Maximum	1.1879	1.3863	0.9927	0.3191
μ_{LNA}	0.0172	0.5091	-0.0172	-0.5091
σ_{LNA}	0.6760	0.4752	0.6760	0.4752
COV_{LNA}	39.224	0.9334	-39.224	-0.9334

Table A.5.12. Statistics for *X* and λ for Allen (2018) Database Using CPTs Based on Data in Table A.5.6

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	4	–	4	–
Minimum	0.8127	–	1.0106	–
Maximum	0.9895	–	1.2305	–
μ	0.9062	–	1.1090	–
σ	0.0729	–	0.0913	–
COV	0.0804	–	0.0823	–

Table A.5.13. Statistics for ln(*X*) and ln(λ) for Allen (2018) Database Using CPTs Based on Data in Table A.5.7

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	4	–	4	–
Minimum	-0.2074	–	0.0106	–
Maximum	-0.0106	–	0.2074	–
μ_{LNA}	-0.1009	–	0.1009	–
σ_{LNA}	0.0814	–	0.0814	–
COV_{LNA}	-0.8066	–	0.8066	–

Table A.5.14. Statistics for *X* and λ for Predicted Data Larger than 0.5 Inch from Allen (2018) Database Using CPTs Based on Data in Table A.5.3 and Table A.5.6

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	4	–	4	–
Minimum	0.8127	–	1.0106	–
Maximum	0.9895	–	1.2305	–
μ	0.9062	–	1.1090	–
σ	0.0729	–	0.0913	–
COV	0.0804	–	0.0823	–

Table A.5.15. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from Allen (2018) Database Using CPTs Based on Data in Table A.5.3 and Table A.5.7

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	4	–	4	–
Minimum	-0.2074	–	0.0106	–
Maximum	-0.0106	–	0.2074	–
μ_{LNA}	-0.1009	–	0.1009	–
σ_{LNA}	0.0814	–	0.0814	–
COV_{LNA}	-0.8066	–	0.8066	–

A.6 Data Source: European Information from Gifford et al. (1987)

Gifford et al. (1987) report the results of five European studies that included a total of 10 footings. Thus, a total of 10 sites were identified. The sites and references from which the data were obtained are identified in Table A.6.1. Information about the structures and the subsurface conditions can be found in the five references listed in Table A.6.1.

Measured and predicted values of settlements for the European data were reported in Gifford et al. (1987) for several settlement predictions. Table A.6.2 contains the measured settlement values along with predicted settlement values based on the Schmertmann method because only CPT results were available. Based on information in Table A.6.2, the following tables were developed:

- Table A.6.3 contains values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.6.2.
- Table A.6.4 contains the lognormal (ln) values of Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.6.3.
- Table A.6.5 contains statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.6.3.
- Table A.6.6 contains statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on data in Table A.6.4.
- Table A.6.7 contains statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.6.2 and Table A.6.3.
- Table A.6.8 contains statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on predicted data larger than 0.5 inch in Table A.6.2 and Table A.6.4.

Figure A.6.1 illustrates the relationship between the measured and predicted values for the Schmertmann method for this data set. If the methods provide a perfect prediction, all the data would be located on the one-to-one correspondence line. In general, the Schmertmann method is conservative for this data source. Refer to Appendix B for correlation analysis.

Refer to Gifford et al. (1987) and each of the five references in Table A.6.1 for detailed information.

Table A.6.1. Site Location European Data from Gifford et al. (1987)

Site	Reference	Project	Feature	Location	Element
#1	Bergdahl and Ottoson (1982)	Alvsbyn Bridge, Sweden	Bridge	Pier	Footing
#2	Wennerstrand (1979)	Support #23 on a bridge in Western Sweden	Bridge	Support #23	Footing
#3	DeBeer and Martens (1956)	Bridge XXIX over the Brussels-Ostend Motor Road, Loppem, Belgium	Bridge	Central pier	Footing
#4	DeBeer (1948)	St. Denys-Westrem, Brussels, Belgium	Bridge	Abutment	Footing
#5	DeBeer and Martens (1956)	St. Denys-Westrem, Brussels, Belgium	Bridge	Central pier	Footing
#6	Levy and Morton (1974)	Twin 12-story buildings, England	Buildings	3 footings	Footing
#7	DeBeer (1948)	Gentbrugge, Belgium	Bridge	Pier A	Footing
#8	DeBeer (1948)	Gentbrugge, Belgium	Bridge	Pier B	Footing
#9	DeBeer (1948)	Gentbrugge, Belgium	Bridge	Abutment	Footing
#10	DeBeer (1948)	Gentbrugge, Belgium	Bridge	Abutment	Footing

Table A.6.2. Data for Measured and Predicted Settlements for European Sites from Gifford et al. (1987)

Site	Measured Settlement, S_M, in.	Predicted Settlement, S_P, in., Schmertmann	Predicted Settlement, S_P, in., Hough (SPT)
#1	0.47	1.57	–
#2	1.46	3.03	–
#3	0.83	0.94	–
#4	0.47	0.67	–
#5	1.30	2.05	–
#6	0.47	0.91	–
#7	0.31	0.31	–
#8	0.16	0.24	–
#9	0.47	0.52	–
#10	0.39	0.31	–

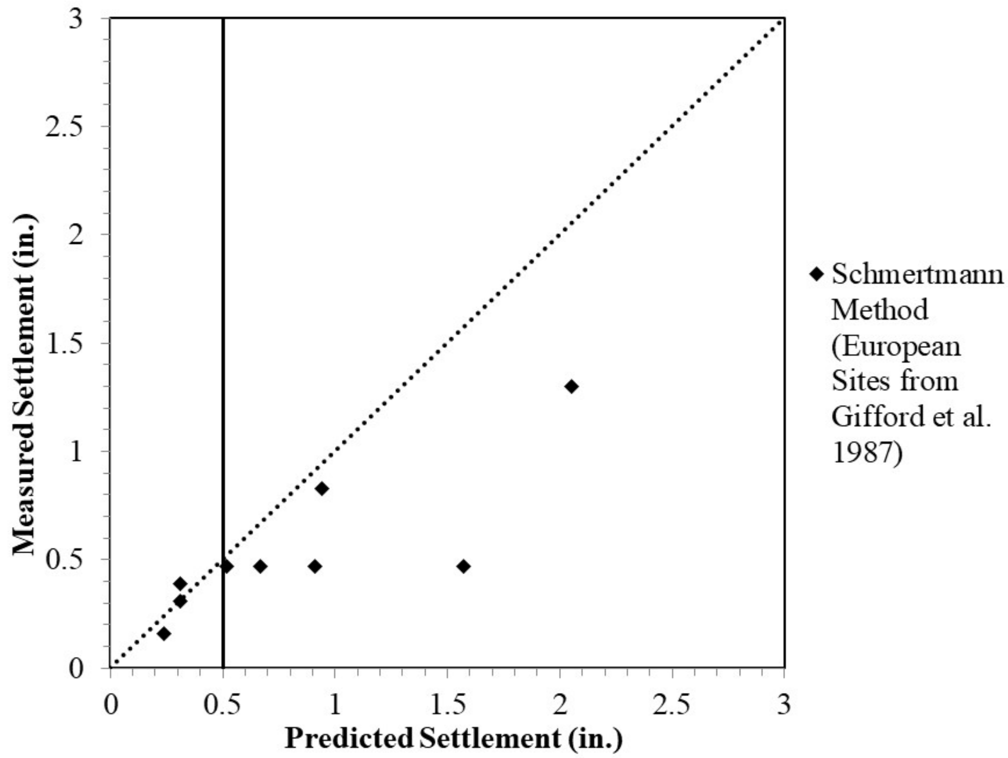

Figure A.6.1. Measured versus predicted settlement for the Schmertmann method for European data sites from Gifford et al. (1987) using CPTs (10 data points).

Table A.6.3. Accuracy (*X*) and Bias (λ) Values Based on European Data from Gifford et al. (1987) in Table A.6.2

Site	Accuracy, *X* Schmertmann	Accuracy, *X* Hough	Bias, λ Schmertmann	Bias, λ Hough
#1	3.3404	–	0.2994	–
#2	2.0753	–	0.4818	–
#3	1.1325	–	0.8830	–
#4	1.4255	–	0.7015	–
#5	1.5769	–	0.6341	–
#6	1.9362	–	0.5165	–
#7	1.0000	–	1.0000	–
#8	1.5000	–	0.6667	–
#9	1.1064	–	0.9038	–
#10	0.7949	–	1.2581	–

Table A.6.4. Lognormal of Accuracy (*X*) and Bias (λ) Values Based on European Data from Gifford et al. (1987) in Table A.6.3

Site	ln(*X*) Schmertmann	ln(*X*) Hough	ln(λ) Schmertmann	ln(λ) Hough
#1	1.2061	–	-1.2061	–
#2	0.7301	–	-0.7301	–
#3	0.1245	–	-0.1245	–
#4	0.3545	–	-0.3545	–
#5	0.4555	–	-0.4555	–
#6	0.6607	–	-0.6607	–
#7	0.0000	–	0.0000	–
#8	0.4055	–	-0.4055	–
#9	0.1011	–	-0.1011	–
#10	-0.2296	–	0.2296	–

Table A.6.5. Statistics for *X* and λ for European Data from Gifford et al. (1997) Based on Data in Table A.6.3

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	10	–	10	–
Minimum	0.7949	–	0.2994	–
Maximum	3.3404	–	1.2581	–
μ	1.5888	–	0.7345	–
σ	0.7362	–	0.2812	–
COV	0.4634	–	0.3829	–

Table A.6.6. Statistics for ln(*X*) and ln(λ) for European Data from Gifford et al. (1997) Based on Data in Table A.6.4

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	10	–	10	–
Minimum	-0.2296	–	-1.2061	–
Maximum	1.2061	–	0.2296	–
μ_{LNA}	0.3808	–	-0.3808	–
σ_{LNA}	0.4150	–	0.4150	–
COV_{LNA}	1.0896	–	-1.0896	–

Table A.6.7. Statistics for *X* and λ for Predicted Data Larger than 0.5 Inch from European Data from Gifford et al. (1997) Based on Data in Table A.6.2 and Table A.6.3

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	7	–	7	–
Minimum	1.1064	–	0.2994	–
Maximum	3.3404	–	0.9038	–
μ	1.7990	–	0.6315	–
σ	0.7729	–	0.2192	–
COV	0.4296	–	0.3471	–

Table A.6.8. Statistics for ln(*X*) and ln(λ) for Predicted Data Larger than 0.5 Inch from European Data from Gifford et al. (1997) Based on Data in Table A.6.2 and Table A.6.4

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	7	–	7	–
Minimum	0.1011	–	-1.2061	–
Maximum	1.2061	–	-0.1011	–
μ_{LNA}	0.5189	–	-0.5189	–
σ_{LNA}	0.3869	–	0.3869	–
COV_{LNA}	0.7456	–	-0.7456	–

A.7 Statistics for Combined Data Sets

Because *AASHTO LRFD Bridge Design Specifications* (2017) are applicable at the national level, a single load factor will need to be chosen for both the Schmertmann and Hough methods (that is, two values). Thus, data from all sources were combined in different ways to generate the following data sets:

- Combined data based on SPTs from U.S. sources only
- Combined data based on SPTs and CPTs from all U.S. sources (that is, excluding European data)
- Combined data based on SPTs and CPTs from all sources (that is, including U.S. and European data)
- Combined data based on CPTs for the Schmertmann method

Data set 1 was used in Chapters 5, 6, and 7. Data sets 2 and 3 were used for correlation analysis in Appendix B. Data set 4 isolates the CPT data for use in Appendix C.

For each of the above combined data sets, a pair of tables to report statistics was prepared as follows:

- Statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on combined data sets
- Statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on combined data sets

Tables A.7.1 to A.7.8 present four pairs of tables corresponding to each combined data set noted above.

Table A.7.1. Statistics for *X* and λ for Data Based on SPT from All U.S. Sources

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	57	61	57	61
Minimum	0.1300	0.1560	0.1294	0.2329
Maximum	7.7270	4.2941	7.6923	6.4103
μ	1.5626	1.6231	1.2052	0.9001
σ	1.3119	0.8565	1.3565	0.8778
COV	0.8396	0.5277	1.1255	0.9752

Table A.7.2. Statistics for ln(*X*) and ln(λ) for Data Based on SPT from All U.S. Sources

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	57	61	57	61
Minimum	-2.0402	-1.8579	-2.0447	-1.4572
Maximum	2.0447	1.4572	2.0402	1.8579
μ_{LNA}	0.1644	0.3298	-0.1644	-0.3298
σ_{LNA}	0.7901	0.6067	0.7901	0.6067
COV_{LNA}	4.8058	1.8397	-4.8058	-1.8397

Table A.7.3. Statistics for *X* and λ for Data Based on SPTs and CPTs from All U.S. Sources

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	70	61	70	61
Minimum	0.1300	0.1560	0.1294	0.2329
Maximum	7.7270	4.2941	7.6923	6.4103
μ	1.5896	1.6231	1.1372	0.9001
σ	1.2615	0.8565	1.2473	0.8778
COV	0.7936	0.5277	1.0968	0.9752

Table A.7.4. Statistics for ln(*X*) and ln(λ) for Data Based on SPTs and CPTs from All U.S. Sources

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	70	61	70	61
Minimum	-2.0402	-1.8579	-2.0447	-1.4572
Maximum	2.0447	1.4572	2.0402	1.8579
μ_{LNA}	0.1993	0.3298	-0.1993	-0.3298
σ_{LNA}	0.7634	0.6067	0.7634	0.6067
COV_{LNA}	3.8314	1.8397	-3.8314	-1.8397

Table A.7.5. Statistics for *X* and λ for Data Based on SPTs and CPTs from All Sources (U.S. and European)

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	80	61	80	61
Minimum	0.1300	0.1560	0.1294	0.2329
Maximum	7.7270	4.2941	7.6923	6.4103
M	1.5895	1.6231	1.0869	0.9001
Σ	1.2049	0.8565	1.1772	0.8778
COV	0.7580	0.5277	1.0831	0.9752

Table A.7.6. Statistics for ln(*X*) and ln(λ) for Data Based on SPTs and CPTs from All Sources (U.S. and European)

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	80	61	80	61
Minimum	-2.0402	-1.8579	-2.0447	-1.4572
Maximum	2.0447	1.4572	2.0402	1.8579
μ_{LNA}	0.2220	0.3298	-0.2220	-0.3298
σ_{LNA}	0.7296	0.6067	0.7296	0.6067
COV_{LNA}	3.2872	1.8397	-3.2872	-1.8397

Table A.7.7. Statistics for *X* and λ for Data Based on CPTs from All Sources (U.S. and European)

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	23	–	23	–
Minimum	0.5890	–	0.2713	–
Maximum	3.6863	–	1.6977	–
μ	1.6561	–	0.7936	–
σ	0.9085	–	0.4080	–
COV	0.5486	–	0.5141	–

Table A.7.8. Statistics for ln(*X*) and ln(λ) for Data Based on CPTs from All Sources (U.S. and European)

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	23	–	23	–
Minimum	-0.5293	–	-1.3046	–
Maximum	1.3046	–	0.5293	–
μ_{LNA}	0.3646	–	-0.3646	–
σ_{LNA}	0.5411	–	0.5411	–
COV_{LNA}	1.4840	–	-1.4840	–

A.8 Statistics for Combined Data Sets After Filtering out Predicted Settlements Smaller than 0.5 Inch

As noted in Chapter 5, settlement data corresponding to predicted settlements smaller than 0.5 inch show large scatter. In this section, the combined data sets from Section A.7 were processed to filter out the data points corresponding to predicted settlement data smaller than 0.5 inch. These are as follows:

- Combined data based on SPTs from U.S. sources only after filtering out data with predicted settlements smaller than 0.5 inch
- Combined data based on SPTs and CPTs from all U.S. sources (that is, excluding European data) after filtering out data with predicted settlements smaller than 0.5 inch
- Combined data based on SPTs and CPTs from all sources (that is, including U.S. and European data), after filtering out data with predicted settlements smaller than 0.5 inch
- Combined data based on CPTs for the Schmertmann method after filtering out data with predicted settlements smaller than 0.5 inch

Data set 1 was used in Chapters 5, 6, and 7. Data sets 2 and 3 were used for correlation analysis in Appendix B. Data set 4 isolates the CPT data for use in Appendix C.

For each of the above combined data sets, a pair of tables to report statistics was developed. Each pair is prepared as follows

- Statistics for Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on combined data sets
- Statistics for lognormal (ln) values Accuracy, X, and Bias, λ, for both the Schmertmann and Hough methods based on combined data sets

Tables A.8.1 to A.8.8 present four pairs of tables corresponding to each combined data set noted above

Table A.8.1. Statistics for X and λ for Predicted Settlements Larger than 0.5 Inch Based on SPT from All U.S. Sources

Statistic	For X of Schmertmann	For X of Hough	For λ of Schmertmann	For λ of Hough
N	40	49	40	49
Minimum	0.2837	0.5833	0.1294	0.2329
Maximum	7.7270	4.2941	3.5246	1.7143
μ	1.8275	1.8241	0.8748	0.6585
σ	1.4065	0.8076	0.7481	0.2983
COV	0.7696	0.4427	0.8552	0.4529

Table A.8.2. Statistics for ln(*X*) and ln(λ) for Predicted Settlements Larger than 0.5 Inch Based on SPT from All U.S. Sources

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	40	49	40	49
Minimum	-1.2598	-0.5390	-2.0447	-1.4572
Maximum	2.0447	1.4572	1.2598	0.5390
μ_{LNA}	0.3792	0.5100	-0.3792	-0.5100
σ_{LNA}	0.6853	0.4333	0.6853	0.4333
COV_{LNA}	1.8073	0.8497	-1.8073	-0.8497

Table A.8.3. Statistics for *X* and λ for Predicted Settlements Larger than 0.5 Inch Based on SPTs and CPTs from All U.S. Sources

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	52	49	52	49
Minimum	0.2837	0.5833	0.1294	0.2329
Maximum	7.7270	4.2941	3.5246	1.7143
μ	1.8214	1.8241	0.8500	0.6585
σ	1.3210	0.8076	0.6863	0.2983
COV	0.7253	0.4427	0.8074	0.4529

Table A.8.4. Statistics for ln(*X*) and ln(λ) for Predicted Settlements Larger than 0.5 Inch Based on SPTs and CPTs from All U.S. Sources

Statistic	For ln(X) of Schmertmann	For ln(X) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	52	49	52	49
Minimum	-1.2598	-0.5390	-2.0447	-1.4572
Maximum	2.0447	1.4572	1.2598	0.5390
μ_{LNA}	0.3899	0.5100	-0.3899	-0.5100
σ_{LNA}	0.6624	0.4333	0.6624	0.4333
COV_{LNA}	1.6990	0.8497	-1.6990	-0.8497

Table A.8.5. Statistics for *X* and λ for Predicted Settlements Larger than 0.5 Inch Based on SPTs and CPTs from All Sources (U.S. and European)

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	59	49	59	49
Minimum	0.2837	0.5833	0.1294	0.2329
Maximum	7.7270	4.2941	3.5246	1.7143
Μ	1.8188	1.8241	0.8241	0.6585
Σ	1.2635	0.8076	0.6513	0.2983
COV	0.6947	0.4427	0.7903	0.4529

Table A.8.6. Statistics for ln(*X*) and ln(λ) for Predicted Settlements Larger than 0.5 Inch Based on SPTs and CPTs from All Sources (U.S. and European)

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	59	49	59	49
Minimum	-1.2598	-0.5390	-2.0447	-1.4572
Maximum	2.0447	1.4572	1.2598	0.5390
μ_{LNA}	0.4052	0.5100	-0.4052	-0.5100
σ_{LNA}	0.6349	0.4333	0.6349	0.4333
COV_{LNA}	1.5669	0.8497	-1.5669	-0.8497

Table A.8.7. Statistics for *X* and λ for Predicted Settlements Larger than 0.5 Inch Based on CPT from All Sources (U.S. and European)

Statistic	For *X* of Schmertmann	For *X* of Hough	For λ of Schmertmann	For λ of Hough
N	19	–	19	–
Minimum	0.6250	–	0.2713	–
Maximum	3.6863	–	1.6000	–
μ	1.8003	–	0.7174	–
σ	0.9258	–	0.3697	–
COV	0.5142	–	0.5153	–

Table A.8.8. Statistics for ln(*X*) and ln(λ) for Predicted Settlements Larger than 0.5 Inch Based on CPT from All Sources (U.S. and European)

Statistic	For ln(*X*) of Schmertmann	For ln(*X*) of Hough	For ln(λ) of Schmertmann	For ln(λ) of Hough
N	19	–	19	–
Minimum	-0.4700	–	-1.3046	–
Maximum	1.3046	–	0.4700	–
μ_{LNA}	0.4600	–	-0.4600	–
σ_{LNA}	0.5261	–	0.5261	–
COV_{LNA}	1.1437	–	-1.1437	–

Appendix B
Correlation Analysis and Importance of Adequate Number of Data Points for Calibration

Appendix B. Correlation Analysis and Importance of Adequate Number of Data Points for Calibration

As indicated in Chapter 4, for calibration of the *SE* load factor, the settlement data are analyzed in terms of normalized ratios such as accuracy, *X*, or bias, λ. Such a ratio represents a random variable. As shown on Figure 5-2 in Chapter 5, the spread of bias is explored against another variable, namely, predicted settlement. While performing calibrations, it is important to evaluate whether the variables involved are statistically correlated. In this case, the two variables are bias and predicted settlement. If changes in the predicted settlement cause the value of bias to significantly increase or decrease in direct proportion, then the variables may be correlated and the value of the *SE* load factor may be affected (smaller or larger) depending on the degree of correlation. This appendix evaluates the strengths of potential correlations for various data sets based on correlation analysis.

B.1 Correlation Analysis Through Correlation Coefficient (r)

One common way to perform correlation analysis is by means of a single number called a correlation coefficient, r, which is also known as Pearson coefficient. The formula for correlation coefficient can be found in most textbooks that deal with statistics and probability (for example, Benjamin and Cornell [1970], Haldar and Mahadevan [2000], Nowak and Collins [2000]). The correlation coefficient provides a measure of the strength of linear relationship between two variables. The correlation coefficient, r, is always between -1 and +1 with negative values representing a negative correlation and positive values representing a positive correlation. In the case of bias versus predicted settlement, a negative correlation is indicated when the value of bias decreases as the predicted value increases, and a positive correlation is indicated when the value of bias increases as the predicted value increases. A value of zero implies statistically independent (that is, uncorrelated) variables, which is desirable in this case. In contrast, a value of -1 or +1 indicates “perfect” negative or positive correlations, respectively.

Practically, for a sample data set, a value of 0 or ±1 for correlation coefficient is not possible. This is particularly true in the field of geotechnical engineering where spatial and temporal uncertainties are prevalent. There is no universally accepted guideline for interpretation of the value of correlation coefficient, and the interpretation often varies based on the application. For example, the interpretation of correlation between variables related to a closely controlled manufacturing environment (for example, automobile industry) is different than when evaluating data based on natural phenomena (for example, floods). A useful and practical guideline is presented by Haldar and Mahadeven (2000), who recommend that two random variables can be considered to be statistically independent if $r < \pm0.30$ and to be perfectly correlated if the $r > \pm0.90$. Between these limits, the following general guidance may be considered to evaluate the strength of correlation:

- Weak: If r is between 0.30 and 0.50, or -0.30 and -0.50
- Moderate: If r is between 0.50 and 0.70, or -0.50 and -0.70
- Strong: If r is between 0.70 and 0.90, or -0.70 and -0.90

B.2 Correlation Coefficient (r) in Contrast to Slope of Linear Regression Line

The value of correlation coefficient, r, should not be confused with the slope of a linear regression line. The correlation coefficient is a normalized (that is, unitless) measure, which means the x and y variables can be interchanged without affecting the value of the correlation coefficient. The correlation coefficient provides an indication of the positive or negative trend in an x-y (Cartesian) scatterplot of two variables. In other words, the positive or negative value of correlation coefficient provides an idea about the uphill trend or downhill trend, respectively, in scatter of the data but not the magnitude of the slope itself. The steepness of the linear regression line fitted to the x-y scatterplot is not related to the correlation coefficient. The strength of correlation is judged based on the value of the correlation coefficient and the practical guidance provided earlier.

B.3 Correlation Coefficients for the Schmertmann and Hough Methods

An expedient way to determine the correlation coefficient is through use of the CORREL (or PEARSON) function in Microsoft Excel. Using the CORREL function, the correlation coefficients for all data sets in Appendix A were evaluated for both the Schmertmann and Hough methods. This process was performed for both unfiltered data and data that were filtered to exclude predicted settlements smaller than 0.5 inch. Tables B.1 and B.2 present the correlation coefficients for both unfiltered and filtered data for a total of 12 cases for both the Schmertmann and Hough methods.

Using the guidance noted earlier for evaluation of the strength of correlation based on the value of the correlation coefficient, the data in Tables B.1 and B.2 indicate uncorrelated to perfectly correlated variables. However, as with any statistical data, it is important to temper interpretations by looking beyond the numbers, particularly when variables appear to be perfectly or strongly correlated. This is especially true for geotechnical variables because of the inherent natural (spatial and temporal) variations that can affect one or both variables being evaluated. Following are some important observations related to interpretation of correlation coefficients in Tables B.1 and B.2:

- The correlation coefficient, r, reduces as the number of data points increases. For example, consider Case 9 in Table B.1 that is based on SPTs only. Figure 5-2 shows the plot of bias versus predicted settlement values for Case 9. As discussed in Chapters 5, 6, and 7, this data set formed the basis for development of the *SE* load factors. The correlation coefficient for the Schmertmann method and the Hough method is -0.29 and -0.03. These values are smaller than ±0.30; hence, the bias and predicted settlement can be considered to be uncorrelated.
- When data are filtered to exclude points corresponding to predicted settlements smaller than 0.5 inch, the correlation coefficient for the Schmertmann method and the Hough method is -0.17 and 0.36, respectively, for Case 9 in Table B.2. While these correlation coefficients still

indicate no to weak (borderline) correlations for the Schmertmann method and the Hough method, respectively, the process of filtering reduces the number of data points and starts affecting the values of the correlation coefficients. It is important to realize that the values of correlation coefficients in data sets after using an arbitrary criterion for filtering data can lead to misleading interpretations. This is because the filtering criterion is largely based on judgment using factors such as generally accepted practices within a given industry (for example, manufacturing, engineering, etc.) while the data scatter in the base data set is still there. Thus, correlation coefficients should be evaluated and interpreted based on data sets before filtering.

Table B.1. Correlation (Pearson) Coefficients for Unfiltered Data Using Method Bias

Case	Data Set (see note)	Data Points for Schmertmann	Data Points for Hough	Table No. for Arithmetic Statistics	Correlation Coefficient, r, for Schmertmann	Correlation Coefficient, r, for Hough
1	Gifford et al. (1987)	20	20	A.1.5	-0.60	-0.39
2	Baus (1992) using CPTs for Schmertmann	9	–	A.2.8	-0.79	–
3	Baus (1992) using SPTs	11	11	A.2.10	-0.63	0.38
4	Briaud and Gibbens (1997)	5	5	A.3.5	-1.00	-1.00
5	Sargand et al. (1999); Sargand and Masada (2006)	12	12	A.4.6	-0.63	-0.37
6	Allen (2018) using SPTs	9	13	A.5.8	-0.44	0.88
7	Allen (2018) using CPTs for Schmertmann	4	–	A.5.12	0.93	–
8	European data from Gifford et al. (1987)	10	–	A.6.5	-0.62	–
9	All sources using SPTs only	57	61	A.7.1	-0.29	-0.03
10	All U.S. sources (both SPTs and CPTs)	70	61	A.7.3	-0.06	-0.03
11	All sources (both SPTs and CPTs)	80	61	A.7.5	-0.05	-0.03
12	All sources using CPTs only	23	–	A.7.7	0.31	–

Notes: See Table 3-1, Table 3-2, and Appendix A for more information on each data set. Cases 1 to 8 apply to specific geographical regions.
CPT = cone penetration test
SPT = standard penetration test

Table B.2. Correlation (Pearson) Coefficients for Data Filtered to Exclude Predicted Settlements Smaller than 0.5 Inch Using Method Bias

Case	Data Set (see note)	Data Points for Schmertmann	Data Points for Hough	Table No. for Arithmetic Statistics	Correlation Coefficient, r, for Schmertmann	Correlation Coefficient, r, for Hough
1	Gifford et al. (1987)	9	17	A.1.7	-0.63	-0.13
2	Baus (1992) using CPTs for Schmertmann	8	–	A.2.12	-0.70	–
3	Baus (1992) using SPTs	10	11	A.2.14	-0.67	0.38
4	Briaud and Gibbens (1997)	5	5	A.3.7	-1.00	-1.00
5	Sargand et al. (1999); Sargand and Masada (2006)	9	3	A.4.7	-0.58	-0.89
6	Allen (2018) using SPTs	7	13	A.5.10	-0.79	0.88
7	Allen (2018) using CPTs for Schmertmann	4	–	A.5.14	0.93	–
8	European data from Gifford et al. (1987)	7	–	A.6.7	-0.55	–
9	All sources using SPTs only	40	49	A.8.1	-0.17	0.36
10	All U.S. sources (both SPTs and CPTs)	52	49	A.8.3	0.08	0.36
11	All sources (both SPTs and CPTs)	59	49	A.8.5	0.08	0.36
12	All sources using CPTs only	19	–	A.8.7	0.51	–

Note: See Table 3-1, Table 3-2, and Appendix A for more information on each data set. Cases 1 to 8 apply to specific geographical regions.

- As the number of data points reduces, the values of correlation coefficients appear to increase based on the data in Table B.1. Increasing, positive or negative, correlation coefficients beyond ±0.30 indicates dependency between bias and predicted settlements. For Cases 1 to 8 and 12, it is clearly seen that the limited number of data points has an effect on the correlation coefficient.
- For Cases 9, 10, and 11, where the number of data points is large (that is, larger than 30 to 40), the correlation coefficients are drastically smaller and within approximately ±0.30, which indicates no correlation as discussed earlier.

B.4 Spurious Correlations and Unwarranted Interpretations

Several authors (for example, Benjamin and Cornell, 1970) have warned about spurious correlations and associated unwarranted interpretations that lead to false assertions. Two reasons for misinterpretations are presence of confounding variables and cause-and-effect relationship. Both features are present in the various data sets in Tables B.1 and B.2, particularly for Cases 1 to 8 where the number of data points is relatively small compared to Cases 9, 10, and 11. These features are discussed below.

B.4.1 Confounding Variables

A confounding variable is one that affects both (independent and dependent) random variables that were considered in computing the correlation coefficient. A confounding variable is sometimes referred to as a lurking variable. Examples of confounding variables for measured and predicted immediate settlements are soil stiffness within the depth of significant influence below the footing, type of soil (cohesive or cohesionless), particle size distribution, variation in moisture content, cleanliness of base of excavation before placement of concrete for spread footing, etc. Immediate settlements are routinely computed for both cohesionless soils as well as cohesive soils where long-term settlements are not anticipated. However, even in these cases, there is always a limited time-dependent settlement that may not be accounted for by a prediction method. Soils with the same designation, say SP (poorly graded sands) or CL (lean clays), as per the Unified Soil Classification System in different regions of the country, may have very different responses to application of stress because a soil classification system does not account for variables such as induration or past geological overburden effects. Further, confounding variables may be related to the use of prediction methods to evaluate settlements under footings or fills. These concerns may be exacerbated for the case of problem soils as defined in ASCE (1994); for example, landslide deposits, interbedded soils, collapse-susceptible soils, soils subject to vibrations, etc. Changes in any of these underlying confounding variables can have different effects on both random variables that are being evaluated for correlation.

The above observations are reflected in the correlation coefficients for Cases 3, 5 and 6 in Table B.1. All three cases have approximately a similar number of data points (9 to 13). Case 3 is related to a data set based on three projects in South Carolina, Case 5 is related to a data set based on four projects in Ohio, and Case 6 is related to a data set based on three projects in Washington state. Although the number of data points, and in some instances the coefficient correlation, is approximately similar, the underlying data are based on different geologies prevalent at each of the projects in these states and the type of application; for example, data from Ohio and South Carolina were obtained from footings only, while data from Washington state were obtained from footings as well as fills. Thus, any interpretations of correlations in these data sets based just on a comparison of correlation coefficients would be misleading.

B.4.2 Cause-and-Effect Relationship

A cause-and-effect relationship is one where a change in one variable (say, x) causes a change in another variable (say, y). While this relationship may appear to be similar to the relationship based on correlation coefficient, the two concepts are quite different and important to understand. For instance, a "strong" correlation based on a large positive or negative correlation coefficient does not necessarily mean that a cause-and-effect relationship exists between the two variables.

An excellent example of misinterpretation of correlation coefficient in terms of relationship between variables is Case 4 in Table B.1 or Table B.2. A correlation coefficient of -1.00 is found for both the Schmertmann method and the Hough method. These coefficients would appear to indicate a "perfect" negative correlation, which would mean that the bias value decreases as the predicted settlement value increases. However, a careful examination of the underlying data described in Section A.3 of Appendix A reveals that predicted settlements for all five data points were compared against a measured settlement of 1.0 inch (also see Figure A.3.1). Bias is defined as measured settlement divided by predicted settlement. Thus, bias in this case would be 1.0 divided by the value of predicted settlement. Based on this, it is obvious that any increase in predicted settlement would result in a corresponding decrease in the bias value (that is, a perfect negative correlation). Clearly, in this case, the value of the correlation coefficient is misleading and an artifact of the underlying data. Similar misinterpretation would result if a correlation were to be evaluated based solely on the assumption of a linear relationship, which is the basis of correlation coefficient, while a nonlinear relationship may exist and copulas instead of correlation coefficients ought to have been considered.

B.5 Key Points Related to Calibration of *SE* Load Factors

The key points related to evaluation of settlement data for calibration of *SE* load factors are as follows:

- The number of data points has a major influence on the correlation coefficient. In general, based on the data in Tables B.1 and B.2, it is observed that the more data points, the smaller the correlation coefficient (that is, less the strength of the correlation).
- In addition to the number of data points, it is important that the settlement data include points that extend to large settlements (for example, larger than 2.0 to 3.0 inches). This would help reduce scatter in the data and provide more realistic and smaller correlation coefficients.

- Even with the same number of data points, the correlation coefficients can be different for data sets from different geologies. This emphasizes the importance of considering local methods and geologies in the statistical evaluations.
- An entity desiring to develop its own calibrated *SE* load factor should collect an adequate number of high-quality data points. Practically, based on the data in Tables B.1 and B.2, it would appear that a data set containing a minimum of 30 to 40 data points would be preferable. As noted above, this data set should include data for large settlements.
- Finally, the entity performing calibrations must carefully evaluate the underlying data to prevent misinterpretations of the results of the correlation analysis.

Appendix C
Preliminary Evaluation of Schmertmann Method Based on the Use of SPT and CPT Data

Appendix C. Preliminary Evaluation of Schmertmann Method Based on the Use of SPT and CPT Data

For the Schmertmann method, the analysis can be performed using either standard penetration test (SPT) or cone penetration test (CPT) data. A detailed discussion on the advantages and disadvantages of each method of subsurface investigation and use of the Schmertmann method can be found in the Federal Highway Administration Soils and Foundations manual (Samtani and Nowatzki, 2006).

Tables C.1 and C.2 present results of four cases. Comparison of Case 1 with Case 2, and Case 3 with Case 4, allows a limited first-order level evaluation of the effect of data from CPTs and SPTs on the *SE* load factors when using the Schmertmann method. Figure C.1 shows the measured and predicted settlements for cases using SPTs and CPTs.

The following observations are based on the four cases:

- In Case 1 and Case 2, the predicted values for the Schmertmann method were based on CPTs and SPTs, respectively, based only on information in Baus (1992). It is noteworthy that these analyses were based on side-by-side CPTs and SPTs as discussed in Chapter 3 and Appendix A. Therefore, even though the number of data points is limited (between 8 and 11 points), it does offer the opportunity to make a direct comparison of *SE* load factors based on CPTs and SPTs for the Schmertmann method. From Table C.1, the *SE* load factors are 1.13 and 2.05 for Case 1 (CPT) and Case 2 (SPT), respectively. From Table C.2, the *SE* load factors are 0.90 and 1.98 for Case 1 and Case 2, respectively. These comparisons indicate that the *SE* load factor based on CPTs is smaller and closer to 1.00 compared to the load factor based on SPTs. This observation is consistent with larger uncertainty in investigations based on SPTs compared with CPTs (Samtani and Nowatzki, 2006). Other than acknowledging the trends in the *SE* load factors based on SPTs and CPTs, no further inferences should be attempted, nor should these values of load factors be considered for designs because the data sets for both Cases 1 and 2 are limited, leading to larger correlation coefficients between the bias and predicted settlements for corresponding Cases 2 and 3 in Tables B.1 and B.2 in Appendix B.
- Cases 3 and 4 allow comparison of *SE* load factors based on CPTs and SPTs, respectively, from different data sources. Unlike the side-by-side comparisons for Cases 1 and 2, the number of data points in these cases is significantly larger. Further, there are more data points for the SPT based on Schmertmann method predictions than for the CPT-based predictions. In Table C.1, there are 57 data points for SPTs compared to 23 data points for CPTs (including those from the European database). In Table C.2, there are 40 data points for SPTs compared to 19 data points for CPTs (including those from the European database). Nevertheless, the trend of a smaller *SE* load factor based on predictions for the Schmertmann method using CPTs versus SPTs is still observed. From Table C.1, the *SE* load factors are 1.87 and 1.19 for Cases 3 and 4, respectively.

From Table C.2, the *SE* load factors are 1.36 and 1.07 for Cases 3 and 4, respectively. These trends are similar to those observed from comparing Cases 1 and 2. Again, as with Case 1 and Case 2, other than acknowledging the trends in the *SE* load factors based on SPTs and CPTs, no further inferences should be attempted, nor should these values of load factors be considered for designs because the data sets for both Cases 3 and 4 are limited, leading to larger correlation coefficients for corresponding Cases 8 and 11 in Tables B.1 and B.2 in Appendix B.

In summary, the preliminary evaluation suggests that the *SE* load factors for the Schmertmann method can be significantly smaller when using CPT data in contrast to SPT data. Larger side-by-side databases similar to those from Baus (1992) are needed to further develop recommended *SE* load factors for the Schmertmann method based on SPTs versus CPTs.

Table C.1. *SE* Load Factors for Reliability Index β=1.00 for Unfiltered Data

Case	Data Set (see note)	Case No. in Table B.1	Data Points for Schmertmann	Table No. for Lognormal (ln) Statistics	*SE* Load Factor for Schmertmann
1	Baus (1992) using CPTs for Schmertmann	2	9	A.2.9	1.13
2	Baus (1992) using SPTs for Schmertmann	3	11	A.2.9	2.05
3	All sources (Schmertmann method) using CPTs only	11	23	A.7.8	1.19
4	All sources (Schmertmann method) using SPTs only	10	57	A.7.2	1.87

Note: See Table 3-1, Table 3-2, and Appendix A for more information on each data set.

Table C.2. *SE* Load Factors for Reliability Index β=1.00 for Data Filtered to Exclude Predicted Settlements Smaller than 0.5 Inch

Case	Data Set (see note)	Case No. in Table B.2	Data Points for Schmertmann	Table No. for Lognormal (ln) Statistics	*SE* Load Factor for Schmertmann
1	Baus (1992) using CPTs for Schmertmann	2	8	A.2.13	0.90
2	Baus (1992) using SPTs for Schmertmann	3	10	A.2.13	1.98
3	All sources (Schmertmann method) using CPTs only	11	19	A.8.8	1.07
4	All sources (Schmertmann method) using SPTs only	10	40	A.8.2	1.36

Note: See Table 3-1, Table 3-2, and Appendix A for more information on each data set.

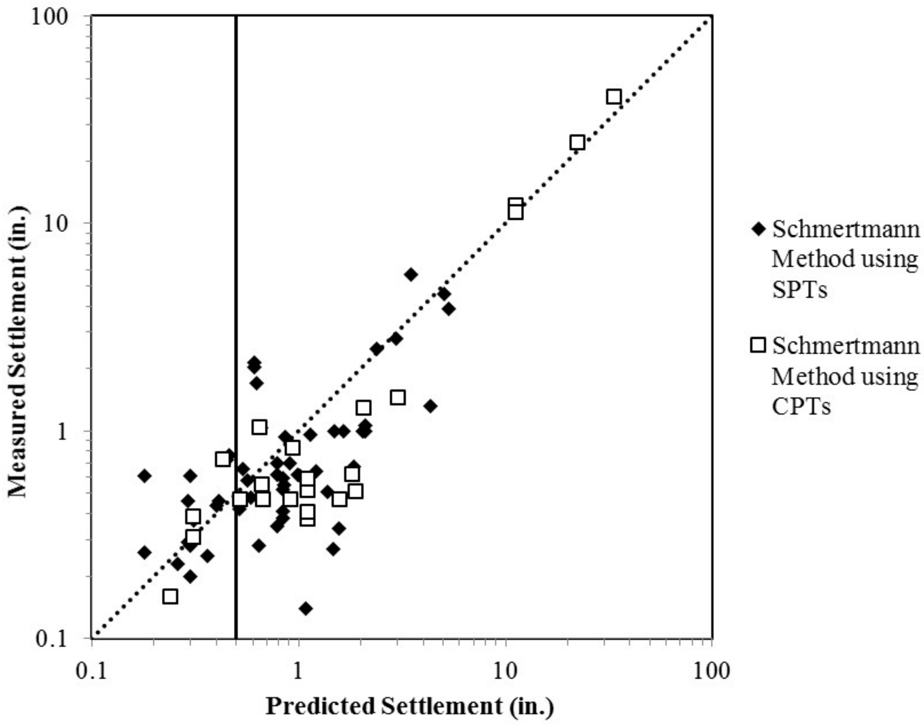

Figure C.1. Measured versus predicted settlement for the Schmertmann method for all SPT-based predictions and all CPT-based predictions (57 data points for SPT-based, and 23 data points for CPT-based).

Appendix D
Evaluation of Effect of *SE* Load Factors Values on Bridge Design

Appendix D. Evaluation of Effect of *SE* Load Factors Values on Bridge Design

This appendix presents a synopsis of the comprehensive parametric analyses that were performed to evaluate the effect of calibrated *SE* load factors on bridge design. Details of the parametric analyses are included in Samtani and Kulicki (2018). The values of the *SE* load factors used in this appendix are for illustration purposes. The final *SE* load factors may differ, but as described below, the range of *SE* load factors that was evaluated encompasses the recommended *SE* load factors in Chapter 7.

Due to the various reasons noted in Chapter 1, the database used in the R19B report (Kulicki et al. 2015) and Samtani and Kulicki (2018) was limited to the work reported by Gifford et al. (1987). This database included 20 points. For the Schmertmann method, an *SE* load factor of 1.25 was proposed corresponding to reliability index, β, of 0.50 based on the concept of reversible-irreversible limit state wherein an owner commits to reversing the detrimental effects of settlement by jacking and shimming a bridge structure, if needed.

When the *SE* load factor of 1.25 was introduced in presentations at American Association of State Highway and Transportation Officials (AASHTO) meetings, a concern was expressed that it will increase the total moments and shears by 25 percent and thereby force a modification to bridge design in the form of additional superstructure elements such as girders. The AASHTO T-5 and T-15 committees requested an evaluation of the effect of the proposed *SE* load factor through example problems based on actual bridges. To address this request, three bridges (a two-span, a four-span, and a five-span) were selected for evaluation. These bridges were subjected to a range of uneven settlements ranging up to approximately 5.0 inches. The results of these evaluations are included in Samtani and Kulicki (2018), and the following observations were made:

- An *SE* load factor of 1.25 will not lead to 25 percent more total force effects (for example, moments). This is because settlement is just one of the many factored force effects in each of the various limit state load combinations within the overall *AASHTO LRFD* framework (see *AASHTO LRFD* Table 3.4.1-1).
- The additional force effects due to the settlement are dependent on the stiffness of the bridge and the angular distortion and are typically much smaller compared to the force effects due to primary dead loads and live loads.
- The use of the construction-point concept greatly reduces the additional force effects.

In 2017, the AASHTO T-15 committee expressed concern that a load factor of 1.25 is predicated on the owner committing to intervention in the form of shimming or jacking a bridge to offset the detrimental effects of settlement. This requirement of intervention could be removed if a larger reliability index, β, of 1.00 was used for estimation of *SE* load factor. For this larger reliability index, a load factor of 1.70 was estimated for the Schmertmann method based on the Gifford et al. (1987) data.

Based on the proposed value of 1.70 for the *SE* load factor, the AASHTO T-15 committee expressed concern that an increase in *SE* load factor from 1.25 to 1.70 may lead to large increases in additional force effects (moments and shears). Therefore, the AASHTO T-15 committee requested reevaluation of the three example bridges based on a larger *SE* load factor of 1.75. In comparison with the previously proposed load factor of 1.25, a load factor of 1.75 indicates a 40 percent increase in this one component of a design load combination.

Additional analyses were performed using the three example bridges and are included in Samtani and Kulicki (2018). It was found that the additional force effects (moments and shears) increased by less than 2 percent when the settlements are smaller than approximately 1.0 inch and the construction-point concept is used. For the case of large settlements such as 4.0 to 5.0 inches, the increase in additional force effects (moments and shears) was less than 6 percent.

Thus, while the selection of a proposed *SE* load factor has been based on theoretical calculations tempered by practical concerns of owners, the range of values (1.25 to 1.75) considered does not result in significantly different structural demands, especially when the construction-point concept is also used. Details of the computations for the three example bridges are included in Samtani and Kulicki (2018).

Based on these observations and the desire to not complicate the load factor selection based on the reversible-irreversible concept, the T-15 committee decided to proceed with a larger reliability index, β, of 1.00 as was used in Chapter 6.