$$C_1 = 1 - 0.5 * \left(\frac{\partial' z_D}{q - \partial' z_D}\right) \quad (5a)$$

$$C_2 = 1 + 0.2 \log\left(\frac{t}{0.1}\right) \quad (5b)$$

$$C_3 = 1.03 - 0.03\,(L/B) \quad (5c)$$

where $\partial' z_D$ = effective vertical stress at depth D below the ground surface (kPa); q = bearing pressure (kPa); t = time since application of load (yr); L = foundation length (m); B = foundation width (m).

Method of Burland and Burbidge (1985)

This method establishes an empirical relationship between average (SPT) blow counts, foundation width, and foundation subgrade compressibility. It is based on regression analysis of several case studies. Blow counts are not corrected for overburden pressure, but they are corrected for subgrade layers. Three correction factors are used for calculating settlement. Hence, the equation used for computing settlement is given in Eq. (6) as :

$$S = q_{net} * B^{0.7} * I_c * f_s * f_l * f_t \quad (6)$$

Where: S = settlement of footing (mm); B= footing width (m); Ic = compressibility index = $\frac{1.71}{(N_{60}')\text{^}1.4}$; N_{60}' = is the average value of N_{60} within the influence depth; q_{net} = net bearing pressure (kPa); f_s = shape correction factor; f_l = correction factor for thickness of soil layer; f_t = time factor, used if $t \geq 3$ yrs.
The correction factors can be determined from the following equations:

$$f_s = \left(\frac{1.25\frac{L}{B}}{0.25+\frac{L}{B}}\right)^2 \quad (6a)$$

$$f_l = \frac{H}{Z1} * \left(2 - \frac{H}{Z1}\right) \quad (6b)$$

$$f_t = 1 + R_3 + R_t * \log(t'/3) \quad (6c)$$

Where: L = footing length (m); H= thickness of soil layer (m); z_1 = influence depth (m); R_3 = time dependent settlement during the first three years of loading = (0.3- 0.7); R_t = time-dependent settlement that takes place after the first three years at a slower rate = (0.2 – 0.8); t' = time at the end of construction (yr).

DESCRIPTION AND BACKGROUND INFORMATION OF THE HIGHWAY BRIDGES SELECTED IN THIS STUDY

This section presents the background information for the spread footing sites selected in this study. More information about historical construction summary, subsurface conditions, design characteristics of the bridge structures, and field instrumentation plans, can be found in a recent study by Ahmed A. (2013). Several case studies are selected in this study, and are presented as follows:

Highway Bridges in Northeast United States

In this study, field data based on measured settlements of 20 spread footings are selected from 10 highway bridges in Northeast of USA [Gifford et al. (1987) and Samtani et al. (2010)]. The ten highway bridges were designed as four single-span structures, two double-span, and three 4-span bridges in addition to a single 5-span structure. Nine of the bridges were designed to carry highway traffic, while one instrumented bridge consisted of a 4-span railroad bridge across an interstate highway for which 5 bridges had simple-span and the other 5 had continuous-beam structures. The bridges were selected in Connecticut, Massachusetts, New York, Rhode Island, and Vermont, the division due to bridges numbers, locations, and number of sites are clarified in TABLE 3. During construction, which was approximately three years, 24 sites of foundations were monitored from initial construction until completion of construction to the actual use. Nine of the ten selected highway bridges were provided with initial settlement performance data on the initial through the post construction stages of each of these bridges. Only 20 sites were used due to construction problems with four other sites, so that the actual settlement of each site could be compared with the predicted settlement using the appropriate prediction methods listed in TABLE 1.

TABLE 3. Classification and Location of Bridges Data Field used in this Study

Bridge No.	Bridge Location	Structural Element	Element Designation
001	Highway VT127 Burlington, Vermont	Abutment 1 Abutment 2	S1 S2
002	Dicker Rd. Cheshire, Connecticut	Abutment 1 Abutment 2 Center Pier	S3 S4 S5
003	Branch Avenue Providence, Rhode Island	West Abutment East Abutment Pier 1 North Pier 1 South Pier 2 North Pier 2 South Pier 3 North Pier 3 South	S6 S7 S8 S9 S10 S11 S12* S13*
004	Route 28 Collierville, New York	South Abutment North Abutment	S14 S15
005	Route 146 Uxbridge, Massachusetts	North Abutment South Abutment	S16 S17
006	VT Route 11 Chester, Vermont	Abutment 1 Abutment 2	S18* S19*
007	Conrail over I-86 Manchester, Connecticut	Abutment 2	S20
008	Tolland Turnpike Manchester, Connecticut	Abutment 1 Abutment 2	S21 S22
009	Route 84 Manchester, Connecticut	Abutment 1 Abutment 2	S23 S24

010 **	Route 84 Manchester, Connecticut		NA

Where: * Construction problems at these footings resulted in disturbance to the subgrade soils and short term settlement was increased, so these sites were excluded from the comparison.
** Total settlement was not measured.
NA: Not available.

Highway Bridges Selected in Ohio

The three spread footings at two highway bridge sites, FRA-670-0380 and MOT-70/75, in Ohio (Sargand and Masada, 2006), were instrumented and monitored during different phases of construction for the performance prediction methods of calculating immediate settlement on cohesionless soils.

I- FRA-670-0380 Project

This project was identified by Ohio Department Of Transportation (ODOT). The bridge is a two-span structure in the city of Colmbus, that allows crossing of High Street over I-670 .

The superstructure of the bridge is a composite consisting of a concrete deck supported by steel girder beams. Compiled field data based on measured settlements was available for one footing of this bridge. More details about this bridge, location, and site are shown in Table 4.

II- MOT-70/75 Project

This project was also identified by Ohio Department Of Transportation (ODOT) at the northeast end of Ramp C bridge constructed as part of the massive I-70/I-75 interchange reconstruction project near Dayton, in Montgomery County. The ramp is a continuous bridge with 20 spans of steel girders with reinforced concrete piers and decking. Two locations, pier 18 and pier 19, were investigated to determine how their foundations reacted to the load generated in each construction stage.These locations were considered by using compiled field data based on measured settlements. More details about this bridge, location, and sites are shown in Table 4.

Table 4. Classification and Location of Bridges in Ohio used in this Study

Bridge No.	Bridge Location	Structural Element Evaluated	Element Designation
11	High Street Over I-670 Columbus, Ohio	Central Pier	S25
12	The Interchange I-70/I-75 Montgomery, Ohio	Pier 18 (East) Pier 19 (West)	S26 S27

DATA BASE OF MEASURED SETTLEMENTS COMPARED WITH PREDICTED SETTLEMENTS

The spread of values of measured settlements (δM) for the 23 sites of spread footings are compared with predicted values of settlement (δP), calculated by the six prediction methods, are shown in FIG.1. The figure presents the accuracy of all the six methods such that the more accurate method has more data points closer to the diagonal line 1:1, demonstrating that some methods are more accurate than others are.

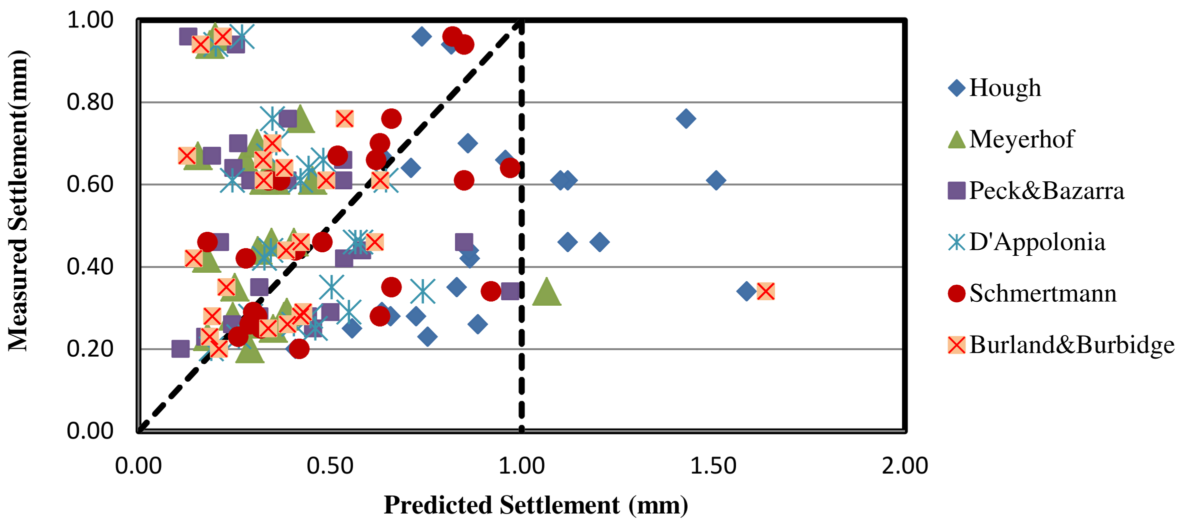


FIG. 1. Comparison of measured and predicted settlements for all six methods based on field data.

In the context of Load and Resistance Factor Design (LRFD), accuracy refers to bias factor which is defined as the ratio of the mean value of the measured settlement to predicted settlement (δM/ δP). Table 5 shows values of bias factor of the six prediction methods. The statistical parameters of the six methods are presented in Table 6.

TABLE 5. Bias Factor for Settlement (δM/δP) of Field Data

Site #	Bias Factor (δM /δP)					
	Hough	Meyerhof	Peck and Bazaraa	D'Appolonia	Schmertmann	Burland and Burbidge
S1	0.42	1.39	1.11	0.69	0.53	1.53
S2	1.06	4.33	3.49	1.97	1.29	5.30
S3	1.15	5.05	3.69	4.65	1.11	5.77
S4	0.53	1.80	1.95	2.17	1.15	1.41
S5	0.54	1.34	2.09	2.49	1.79	0.97
S6	0.49	2.36	0.78	1.28	1.02	2.91
S7	0.40	1.71	1.57	0.94	1.11	1.25
S8	0.39	0.74	0.89	0.62	0.90	0.66
S9	0.29	0.86	1.06	0.64	0.90	0.67
S10	0.46	0.75	0.58	0.53	0.97	0.67
S11	0.45	0.71	0.55	0.54	0.78	0.74
S14	0.41	1.13	0.54	0.81	0.96	1.08

S15	0.21	0.32	0.35	0.46	0.37	0.21
S16	0.30	1.28	1.32	0.88	0.88	1.23
S17	0.51	1.41	0.75	1.27	1.07	1.14
S20	0.90	1.87	2.58	1.44	0.66	1.68
S21	0.38	1.32	2.16	0.79	2.56	0.75
S22	0.69	2.37	1.24	1.37	1.06	2.03
S23	0.55	1.87	1.14	1.44	0.72	1.87
S24	0.43	1.14	0.63	0.95	0.44	1.45
S25	0.49	0.69	1.82	1.05	0.48	0.95
S26	0.81	2.26	2.69	1.94	1.11	2.00
S27	1.30	4.80	7.38	3.56	1.17	4.36

TABLE 6. Statistical Parameters of Bias Factor for Settlement (δM/δP) of the Six Prediction Methods

Statistical Parameters	Hough	Meyerhof	Peck and Bazaraa	D'Appoloina	Schmertmann	Burland and Burbidge
Max	1.30	5.05	7.38	4.65	2.56	5.77
Min	0.21	0.32	0.35	0.46	0.37	0.21
Mean	0.57	1.80	1.76	1.41	1.05	1.77
STDEV	0.28	1.29	1.54	1.03	0.49	1.47
COV	0.50	0.71	0.88	0.73	0.47	0.83

Where, Max = maximum value; Min = minimum value; STDEV = standard deviation; COV = coefficient of variation = STDEV/Mean; Count =23.

Even though AASHTO recommended Hough method (1959) and FHWA (2006, 2010) recommended the use of Schmertman method (1978), other methods are selected in this study to check which method would be the most accurate one for calculating settlement of spread footings on cohesionless soils. It can be concluded from Table 6, which presents the statistical parameters for the six prediction methods that Hough (1959) and Schmertmann (1978) methods gave the lowest values for COV, and Schmertmann method results in a value for bias factor closest to 1.0. Both the Hough and Schmertmann methods seem to produce better results than other methods, but the Schmertmann method appears to be the best for predicting immediate settlement on cohesionless soils, based on bias factors.

FIG.2.shows graphs for each of the prediction methods for calculated settlements versus measured settlements for all the 23. It turns out that the Schmertmann method (1978) has the highest coefficient of correlation (R^2); is a statistical measure of two or more random variables, which by its value indicates how much of a change in one variable is explained by a change in the other. A value of 1.0 indicates perfect correlation between the two variables; the method with the highest correlation coefficient is more accurate among the others for calculating immediate settlement for shallow foundations on cohesionless soils.

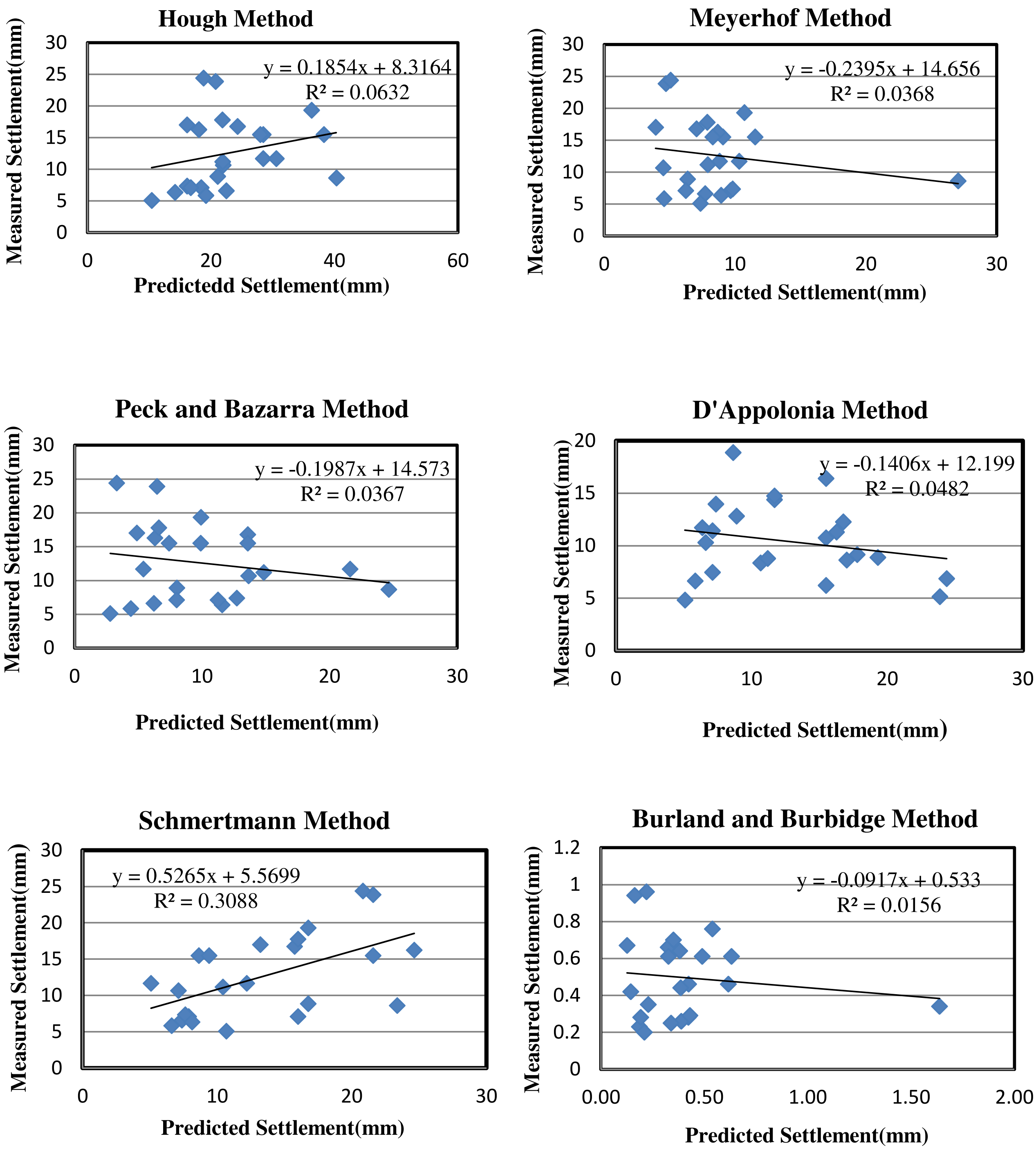
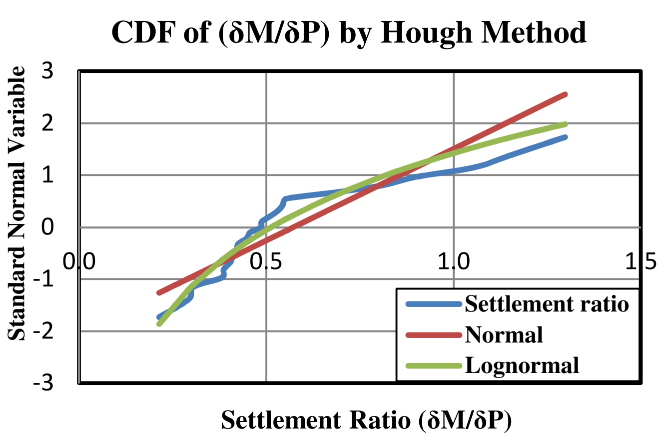


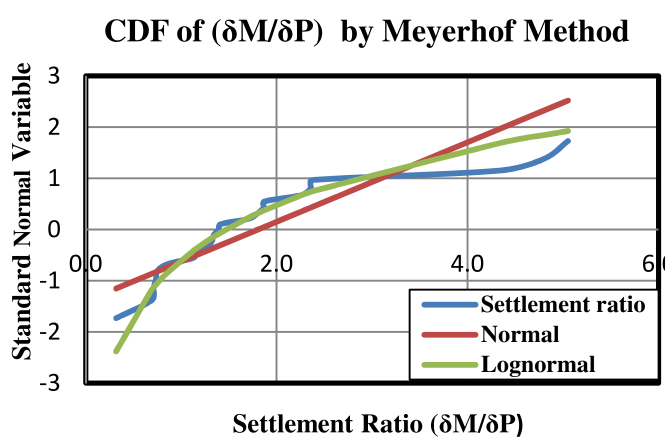
FIG.2 Comparison of predicted values of settlement with measured for the six methods.

DISTRIBUTION OF BIAS FACTOR OF SETTLEMENT (δM/δP)

By considering any settlement prediction method that correlates an in-situ test results with settlements and assuming that the predicted method calculates the settlement perfectly, i.e., (δM /δP) = 1.0, even though the measured settlements would still be different from the predicted settlements due to inherent variability of the soil and the measurement error. The in-situ test results used in predicted settlement are represented in SPT N-values or E_s, which is unlikely to represent the soil conditions of the whole site. The critical situations are when the measured values significantly exceed analytically the predicted values.
The cumulative distribution functions (CDF) of bias factor for each prediction method are plotted on the normal probability paper as shown in FIG.3. The construction and use of the normal probability paper is described in (Nowak and Collins 2013). It is a convenient way to present cumulative distribution functions (CDF), as it allows for an easy evaluation of the most important statistical parameters as well as type of distribution function. The horizontal axis represents the basic variable, in case of considered test data, it is the ratio of the settlement. Vertical axis is the inverse normal probability scale, and it represents the distance from the mean value in terms of standard deviations. The vertical coordinate can also be considered as the probability of exceeding the corresponding value of the variable. For any value of the bias factor (horizontal axis), the vertical coordinate of CDF corresponds to a certain probability of being exceeded. For example, value of 1 on the vertical scale corresponds to 0.159 probability that the value of bias factor will be exceeded.
For the six prediction methods of settlement, the settlement ratio (δM /δP) is plotted on the normal probability paper with its both normal and lognormal distributions, as shown in FIG.3. From inspection of these plots, it can be noticed that the lognormal distribution is a reasonable assumption for the distribution of the bias factor or settlement ratio (δM /δP).

It can be concluded from the figures below for Settlement Ratio (δM/δP) that the Hough, Meyerhof, and Burland and Burbidge methods seem not to have a perfect lognormal distribution, but it fits better than normal distribution. While Peck and Bazaraa, D'Appolonia, and Schmertmann methods seem to fit a lognormal distribution rather than a normal distribution. Therefore, the lognormal distribution would be a reasonable assumption for these methods rather than normal assumption.





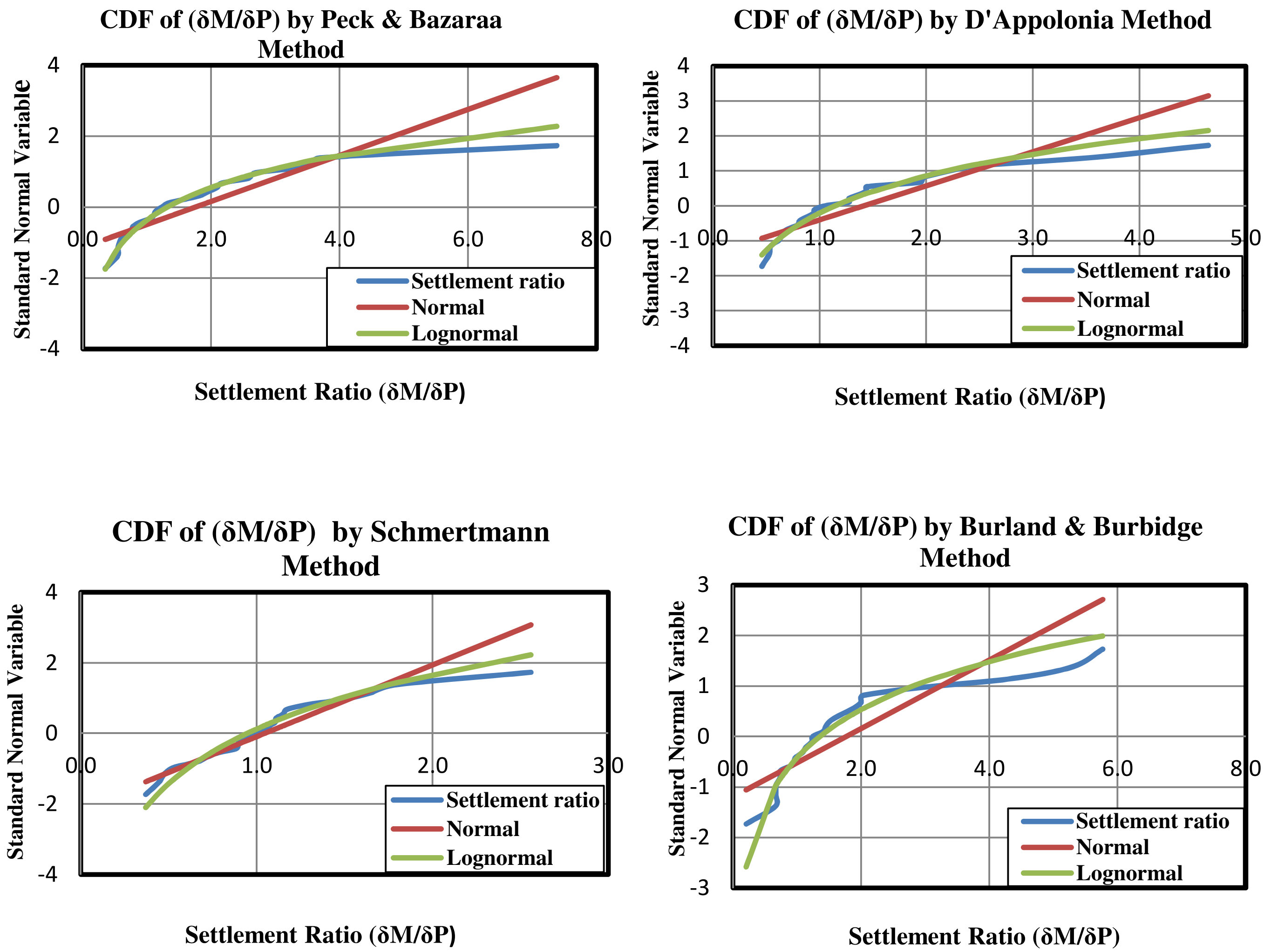


FIG. 3. CDF of Bias Factor for Settlement (δM /δP) for 23 sites.

The CDF's in FIG.4 for the settlement ratio of all the six prediction methods are not normal but rather lognormal. The critical situations are when the measured values significantly exceed analytically predicted values. In minimizing critical situations, the Hough and Schmertmann methods seem to produce better results than other methods. The shape of CDF is an indication of the type of distribution. A straight line means that the distribution is normal. Therefore, it appears that the CDF's indicate that none of them can be considered as a normal distribution.

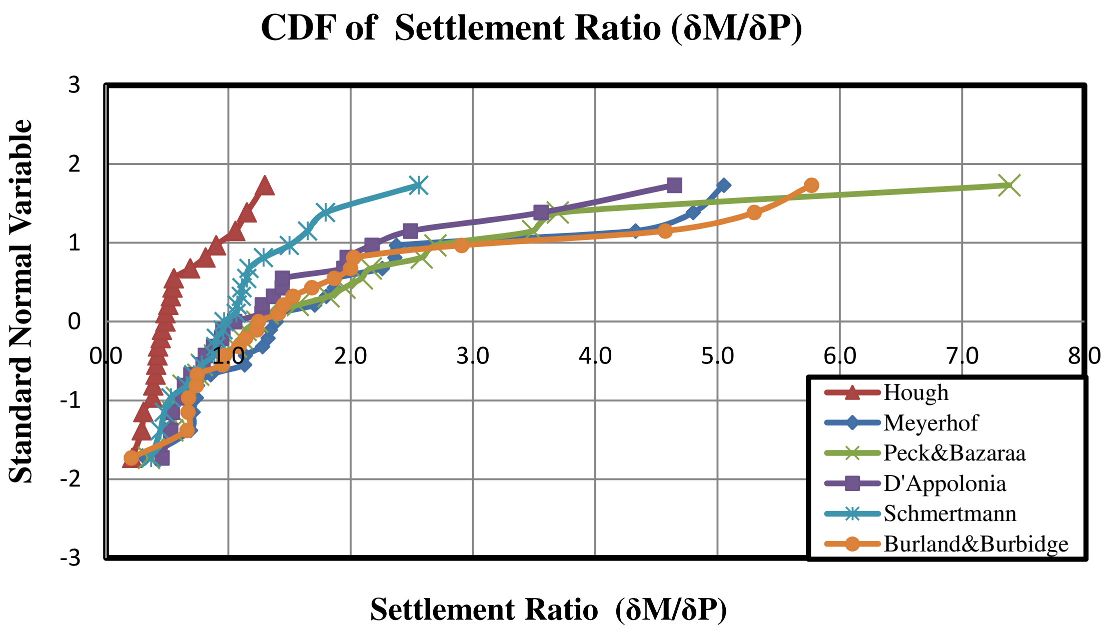


FIG. 4.: CDF of (δM/δP) for 23 sites by all Six Prediction Methods

CONCLUSIONS

Six prediction methods for calculating immediate settlement of shallow foundations on cohesionless soils are considered for 12 highway bridges in the Northeast of US and Ohio. The objective was to examine the accuracy of these methods, which are evaluated by comparing predicted and measured settlements of 23 footings on cohesionless soils. The range of measured settlements was between (5.75-24 mm) that was within the acceptable limits. Statistical parameters for settlement are evaluated for each method. Methods proposed by Hough and Schmertmann indicated the best statistical parameters for settlement. Schmertmann's method resulted in bias factor closer to 1.0 (bias = 1.05), and had the lowest value of coefficient of variation (COV =0.47). In addition, Schmertmann's method had the highest correlation coefficient (R^2) between measured and predicted settlements, which is an indication that this method is more accurate than the others. Even though the Hough method had the lowest value of (COV= 0.5) among the other methods and the bias factor was less than 1.0 (bias = 0.57), most of the predicted settlement values are about twice the actual settlements. Therefore, the recommendation of this study is to use Schmertmann's method for calculating immediate settlement of shallow foundations on cohesionless soils. The Hough method can be recommended, but predictions will be overconsevative. However, the bias factors corresponding to these two methods can be similar if the nominal values of settlement predicted by Hough's method are divided by about 2.0.

Review of the CDF's in FIGS.3 and 4 indicate that none of the methods can be considered as a normal distribution.

ACKNOWLEDGMENT

The writers wish to acknowledge Dr. Naresh Samtani and Dr. Alan Lutenegger for providing measured settlement data described in this paper.

REFERENCES

AASHTO LRFD Bridge Design Specifications (2012). "American Association of State Highway and Transportation Officials", Washington, D.C.

Ahmed A. Y. (2013)."Reliability analysis of settlement for shallow foundations in bridges" Ph.D. Dissertation, University of Nebraska-Lincoln, NE.

Braja M. Das, and Nagaratnam Sivakugan (2007). "Settlement of Shallow Foundations on Granular Soils - an overview". International Journal of Geotechnical Engineering. No. 1, pp. 19-29.

Burland, J.B., and M. C Burbidge (1985). "Settlement of Foundations on Sand and Gravel ". Institution of civil engineers, Glasgow and West of Scotland Association, London, Vol. 78, No. 1, pp. 1325-1381.

Coduto P. Donald (2001). Foundation Design. Principles and Practices. Prentice –Hall New Jersey.

D' Appolonia, D.J., D'Appolonia E. D., and R. F. Brissette (1970). "Closure : Settlement of Spread Footings on Sand". Journal of Soil Mechanics and Foundation Division. Vol. 96, No. 2, pp. 754-762.

D' Appolonia, D.J., and T.W. Lambe (1970). "Method for Predicting Initial Settlement". Journal of Soil Mechanics and Foundation Division. ASCE, Vol. 96, SM2, pp. 523-543.

Douglas D.J. (1986). "State –of-the –art". Ground Engineering. Vol. 19, No. 2, pp. 2-6.

Gifford, D.C., Wheeler, J. R., Kraemer, S. R., and A. F. McKown (1987). "Spread Footings for Highway Bridges". Final report FHWA/ RD-86 /185, US Department of Transportation , Federal Highway Administration.

Hough B. K. (1959)." Compressibility as the Basis for Soil Bearing Value". Journal of Soil Mechanics and Foundation Division. Vol. 85, No. 4, pp. 11-39.

Lutenegger J. Alan and DeGroot J. Dan (1995). "Settlement of Shallow Foundations on Granular Soils". Final Report of research Conducted For Massachusetts Highway Department.

Meyerhof G.G. (1956). "Penetration Tests and Bearing Capacity of Cohesionless Soils". Journal of Soil Mechanics and Foundation Division. ASCE, Vol. 82, No. 1, pp. 1-19.

Meyerhof G.G. (1965). "Shallow Foundations". Journal of Soil Mechanics and Foundation Division. ASCE, Vol. 91, SM2, pp. 21-31.

Nowak, A.S. and Collins, K.R. (2013). "Reliability of Structures", McGraw-Hill, New York.

Peck, R.B., and A.R.S.S. Bazaraa (1969). "Discussion of Settlement of Spread Footings on Sand". Journal of Soil Mechanics and Foundation Division. ASCE, Vol. 95, SM3, pp. 305-309.

Samtani N. C. , Nowatzki E A. , and D. R. Mertz (2010). "Selection of Spread Footings to Support Highway Bridge Structures". Final report FHWA-RC/TD-10-001, US Department of Transportation , Federal Highway Administration.

Schmertmann. J.H (1970). "Static Cone to Compute Static Settlement Over Sand". Journal of Soil Mechanics and Foundation Division. ASCE, Vol. 96, No. 3, pp. 1011-1043.

Schmertmann, J.H., Hartman J. P., and P.R. Brown (1978). "Improved Strain Influence Factor Diagrams". Journal of Soil Mechanics and Foundation Division. ASCE, Vol. 104, No. 8, pp.1131-1135.

Sargand M. Shad and Masada Teruhisa. (2006). " Further Use of Spread Footing Foundation for BridgesFinal Report FHWA-OH-2006/8, Ohio Department of Transportation and US Department of Transportation, Federal Highway Administration.

Tan, C.K. and J.M. Duncan (1991). "Settlement of Footings on Sands: Accuracy and Reliability". Proceedings of Geotechnical Engineering Congress. Colorado, No. 1, pp. 446.