Settlement of Shallow Foundations on Sand – A Database Study

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ABSTRACT: *Generally, the first choice in the selection of a foundation for buildings and other structures is a shallow foundation because it is typically more economical and easier to construct than a deep foundation. However, shallow foundations are usually considered to settle more than deep foundations. This is a fallacy, as well-designed shallow foundations do not settle more than well-designed deep foundations. To calculate the settlement of shallow foundations on sand, the most critical parameter is the soil modulus. This parameter is influenced by a number of factors, the range of values is large, and the selection is difficult. Comparison between observed settlement and measured settlement can help to calibrate the soil modulus, which best matches the settlement measurements. In this article, a probability analysis based on a database of 315 shallow foundation settlement records on sand is presented. The data is organized in a large spreadsheet called TAMU-SHAL-SAND. The foundation widths in the database vary from 0.30 m to 135 m with a mean of 7.76 m and a coefficient of variation of 1.21. The SPT N values are between 2 blows per foot (bpf) and 60 bpf with an average of 23.7 bpf and a coefficient of variation of 0.56. The CPT q_c values range from 0.32 MPa to 19.2 MPa with a mean of 7.92 MPa and a coefficient of variation of 0.60. The PMT E_0 value ranges from 2.4 MPa to 16.6 MPa with an average of 10.5 MPa and a coefficient of variation of 0.40. Using the database, scatter plots of predicted vs. measured settlement are presented. In addition, a probability plot is presented, with the probability that the predicted settlement will be less than the measured settlement on the vertical axis and a prediction multiplier on the horizontal axis. The results can help the practitioner decide at which level of probability to operate. The data show that using E (kPa) = 1000 N (bpf), $E = 4\ q_c$ or $E = 3\ E_0$ in the elastic equation gives a settlement which has a 90% probability of being larger than the measured settlement; N is the uncorrected SPT blowcount, q_c is the CPT point resistance, and E_0 is the first load pressuremeter modulus.*

KEYWORDS: settlement, shallow foundations, sand, probability plot, database, TAMU-SHAL-SAND

SITE LOCATION: Geo-Database

INTRODUCTION

In the design of shallow foundations, two criteria should be satisfied: ultimate limit state (bearing capacity of the soil beneath the foundation) and serviceability limit state (tolerable settlement of the foundation). In sands, generally, the bearing capacity is not a problem, and the settlement criterion controls the design. Thus, settlement calculations for shallow foundations on sand is a key factor in the design of civil engineering structures.

There are several methods to calculate the settlement of shallow foundations on sands. One of the most extensively used methods is the elastic method. In this case, the critical parameter is the soil modulus. This parameter is influenced by several factors, and the range of values is large. A comparison between observed settlement and measured settlement can help calibrate the soil modulus, which best matches the settlement measurements. TAMU-SHAL-SAND is a database of measured settlements of shallow foundations in sand, which was organized in this project. It consists of three sub-databases: the Jeyapalan database, the Burland database, and the Briaud database.

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SHALLOW FOUNDATION DATABASE IN SANDS: TAMU-SHAL-SAND

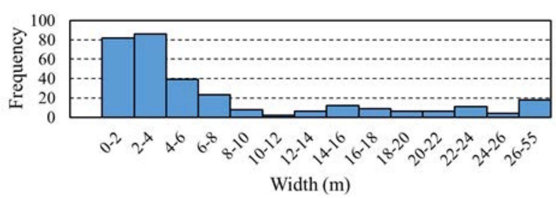
Jeyapalan and Boehm (1986) collected a database of shallow foundation settlements in sands to check the accuracy of different prediction methods. This database contains 71 settlement records together with the applied pressure. The footing shapes include 41 rectangular footings, 27 square footings, and 3 strip footings. The soil type is sand in all cases, but the particle size is not specified. The soil data consists of the Standard Penetration Test (SPT) blowcounts (N) and Cone Penetration Test (CPT) tip resistance.

Burland and Burbidge (1985) collected 170 settlement records of foundations, tanks, and embankments on sands and gravels. They investigated the influence of shape, depth of foundation, depth of water table, grain size, and time on the settlement magnitude. They concluded that for small settlements, the result of conventional settlement calculations is good enough.

Jeanjean & Briaud (1993), Briaud and Gibbens (1994), Gibbens and Briaud (1995), Ballouz et al. (1995), and Nasr and Briaud (1993) produced a series of reports on field tests and full-scale shallow foundation settlement records. The result of those reports was a database of 74 foundation settlement records in sands (SHALDB version no. 4, Nasr, Briaud, 1993).

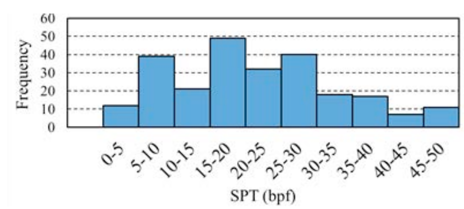
The TAMU-SHAL-SAND database is a large addressable spreadsheet which regroups the 3 databases and consists of 315 settlement records covering a wide range of coarse grain soils (fine sand, medium sand, coarse sand, silty sand, sand-gravel mixture, and gravels). The TAMU-SHAL-SAND spreadsheet is available at no charge. For the Burland database, the time at which the settlement was measured was the end of construction. This time varied from a few days to more than 5 years with a mean of 575 days and a coefficient of variation of 1.05. The measurement time for the Jeyapalan database is not given. The measurement time for the Briaud database (load tests) varied from 1 hour to 1 day. While there is a significant difference in time of observations, a study of each database separately did not lead to a significant difference in the modulus correlations. This may be due to the fact that the settlement of sand, unlike clay, is not significantly affected by time and that other factors introduce sufficient scatter to mask that influence. Also, the soil properties, including the SPT blowcount, the CPT tip resistance, and the PMT first load modulus, were typically obtained within the depth of influence of the foundation.

The TAMU-SHAL-SAND database has been organized in an Excel spreadsheet divided into five main sections: General Characteristics, Foundation Properties, Index Soil Properties, Strength and Deformation Soil Properties, and Observed Settlement Data. Figure 1a-d shows the foundation width, SPT blowcount value N, CPT tip resistance q_c, and PMT first load modulus E_0 distributions for the combined TAMU-SHAL-SAND database. The SPT N values are uncorrected for energy and uncorrected for the testing depth. The CPT q_c values are not corrected for the testing depth. The Pressuremeter modulus E_0 is not corrected for the testing depth. In most cases, these values of N, q_c, and E_0 are quoted in the publications as averages below the foundation. The correction of these parameters for the testing depth (stress level) is not recommended because the test measurement is directly influenced by the stress level at the depth where it is measured, and so is the modulus.



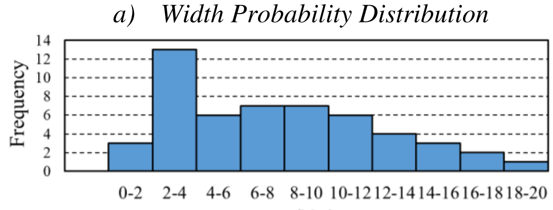
Mean	COV	Min	Max
7.76	1.21	0.30	135

a) Width Probability Distribution



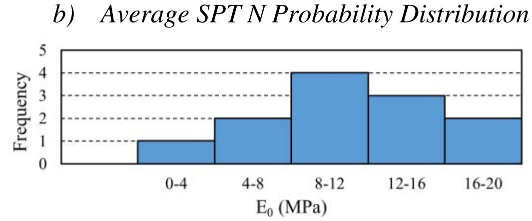
Mean	COV	Min	Max
23.68	0.56	2.00	60

b) Average SPT N Probability Distribution



Mean	COV	Min	Max
7.92	0.6	0.32	19.19

c) Average CPT q_c Probability Distribution



Mean	COV	Min	Max
10.48	0.40	2.4	16.6

d) Average PMT E_0 Probability Distribution

Figure 1. Probability distributions of Width, SPT blowcounts, CPT tip resistance and PMT first load modulus for TAMU-SHAL-SAND database.

CALCULATION OF SETTLEMENT IN SAND

The equation which was selected for the settlement calculations was the elastic settlement equation. Note that the goal is not to calculate the immediate settlement but the settlement after construction. The equation used is:

$$\boldsymbol{s = I(1-\nu^2)pB/E} \quad (1)$$

where I is an influencing factor; ν is the Poisson ratio taken as 0.35 for all calculations (drained conditions); p is the average pressure generated under the foundation; B is the width of the foundation, and E is the soil modulus of deformation. The influence factor I is the combination of three separate factors as follows:

$$\boldsymbol{I = I_s I_e I_h} \quad (2)$$

These three influence factors account for the shape of the footing (I_s), the embedment depth (I_e), and the presence of a hard layer (I_h), respectively (Briaud, 2013). Note that Eq. 1 is linear, and it was the goal of this paper to preserve the simplicity of that equation and optimize the modulus value to be used.

SPT PREDICTED SETTLEMENT VERSUS MEASURED SETTLEMENT AND PROBABILITY ANALYSIS

Different correlations between the SPT blowcount and the soil modulus have been proposed. Most of the correlations are of the form:

$$\boldsymbol{E(kPa) = \alpha_{SPT} N(bpf)} \quad (3)$$

where E is the soil modulus in kPa, α_{SPT} is the correlation factor, and N is the uncorrected SPT blowcounts in blows per foot (bpf). Table 1 is a summary of the relationships between E and N based on the following references: Bowles (1996), FHWA (2010), Briaud and Miran (1992a, 1992b), Briaud (1992), Mayne (2007a, 2007b), and Schmertmann (1970). These correlations aim at giving the modulus for long-term settlement calculations at working loads. The TAMU-SHAL-SAND database was used to narrow down this wide range of correlations and provide a measure of the probability that the predicted settlement would be larger than the measured settlement. Scatter plots of predicted vs. measured settlement for various values of α_{SPT} are shown in Figure 2a-2d. There are a total of 558 data points in the scatter plots, which is larger than the total number of records (315). The reason is that in the case of the Briaud database, all the points on the load settlement curve within the nearly linear region were used individually.

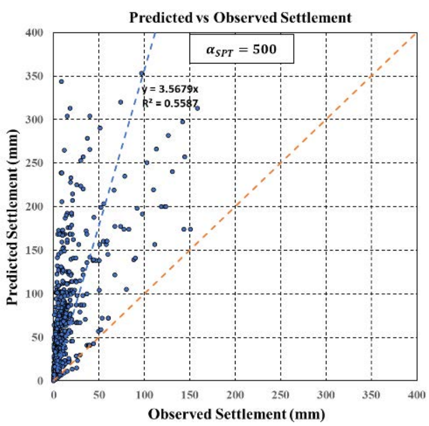
Figure 2a shows the predicted settlement using a modulus in kPa equal to 500 N in bpf. This plot indicates that when a value of E = 500 N is used in Equation 1, 548 out of the 558 predicted settlements are larger than the measured settlements. Therefore, in this case, there is a 548/558 = 98.21% probability that the predicted settlement will be larger than the measured settlement. This gives one point on the probability plot of Figure 3 (98.21% and 500). Figure 2b shows the predicted settlement using a modulus in kPa equal to 1000 N in bpf in Equation 1. In this case, 509 out of the 558 predicted settlements are larger than the measured settlements. Therefore, there is a 509/558 = 91.22% probability that the predicted settlement will be larger than the measured settlement. This gives a second point on the probability plot of Figure 3 (91.22% and 1000). This process was repeated for many values of the correlation factor α_{SPT} and the results are plotted in Figure 3 for the TAMU-SHAL-SAND database. Now the engineer predicting the settlement can choose a probability that the predicted settlement will be larger than the measured settlement and use the corresponding correlation factor. For example, if the predictor is comfortable with a 90% probability of being conservative, a modulus E(kPa) = 1000 N(bpf) can be used.

In Figure 3, the data records are also subdivided into the records for foundation widths smaller than or equal to 10 m and for foundations widths greater than 10 m. Because the majority of the data in the database are for widths smaller than 10 m, the probability plot for the records smaller than 10 m is close to the one for all records. However, for the records greater than 10 m, the shift of the probability plot to the right is noticeable. For the 90% probability of overestimating the settlement, the α_{SPT} value increases from 1000 for all records to 1900 for widths greater than 10 m. This indicates that for widths greater than 10 m, the predicted settlements using the modulus correlated using all data is conservative by a factor of almost 2; this may warrant using a larger modulus for large foundations. Figure 4 shows the predicted over measured settlement values (P/M) versus the foundation width (m) for E(kPa) = 1000N(bpf) (91% overestimation probability) and E(kPa) = 4000N(bpf) (49% overestimation probability). It shows that by increasing the foundation width, the ratio of predicted over measured settlement increases, confirming that for the same probability of overestimation, larger α_{SPT} values may be used for larger foundations. However, further analysis of the data indicates that if one considers the data for foundations larger than 10 m only, the predicted over measured settlement ratio decreases with further increase in foundation width. Therefore it may not be prudent to use higher alpha values for larger foundations. Figure 4 gives the engineer a sense of the degree of conservatism associated with the recommended alpha values.

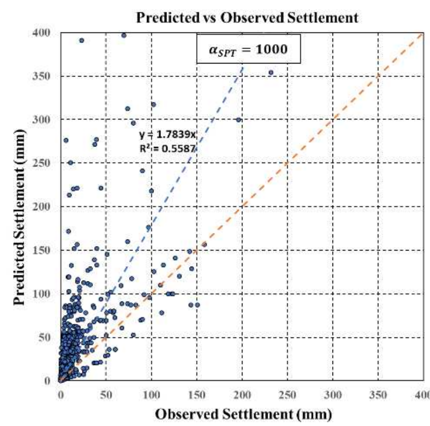
Figure 5 shows the ratio of predicted over measured settlement (P/M) versus the foundation depth normalized by the foundation width (embedment ratio, D_f/B) for $E(kPa) = 1000N(bpf)$ and $E(kPa) = 4000N(bpf)$. It is observed that as the embedment ratio increases, the predicted over measured settlement ratio decreases. This is related to the increasing trend for the foundation width in Figure 4 but is reversed since the parameter on the horizontal axis in Figure 5 is in 1/B.

Table 1. Correlation between soil modulus and soil test results for sands and gravels [Bowles (1996), FHWA (2010), Briaud and Miran (1992a, 1992b), Briaud (1992), Mayne (2007a, 2007b), and Schmertmann (1970)].

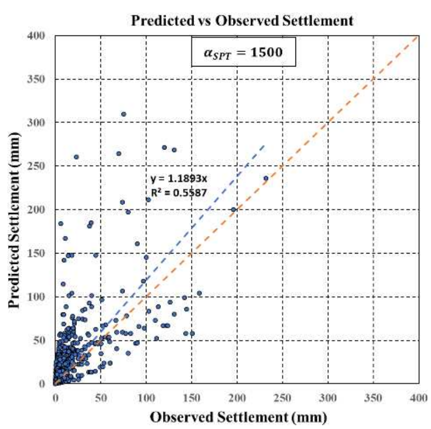
Soil Types	Correlation
Silts, sandy silts, slightly cohesive mixtures	$E\ (kPa) = 400\ N\ (bpf)$
Clean fine to medium sands and slightly silty sands	$E\ (kPa) = 700\ N\ (bpf)$
Coarse sand and sand with little gravel	$E\ (kPa) = 1000\ N\ (bpf)$
Sandy gravels and gravels	$E\ (kPa) = 1200\ N\ (bpf)$ $E\ (kPa) = 7000\ N\ (bpf)$
Sand (normally consolidated)	$E\ (kPa) = (15000\ to\ 22000) \ln (N\ (bpf))$ $E\ (kPa) = 500\ (N\ (bpf) + 15)$
Sand (saturated)	$E\ (kPa) = 250\ (N\ (bpf) + 15)$
Sand (over-consolidated)	$E\ (kPa) = 40000 + 1050\ N\ (bpf)$
Gravelly sand	$E\ (kPa) = 1200\ (N\ (bpf) + 6)$
Sand	$E\ (kPa) = 766\ N\ (bpf)$



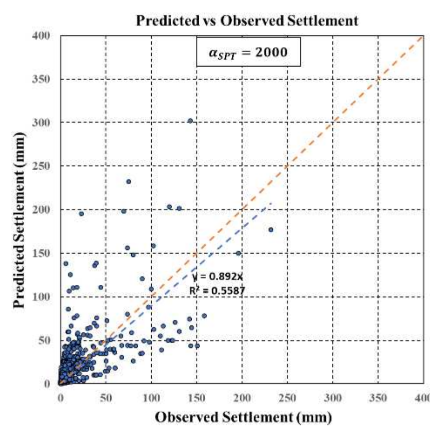
a) α_{SPT} = 500



b) α_{SPT} = 1000



c) α_{SPT} = 1500



d) α_{SPT} = 2000

Figure 2. Predicted versus measured settlement records for TAMU-SHAL-SAND Database.

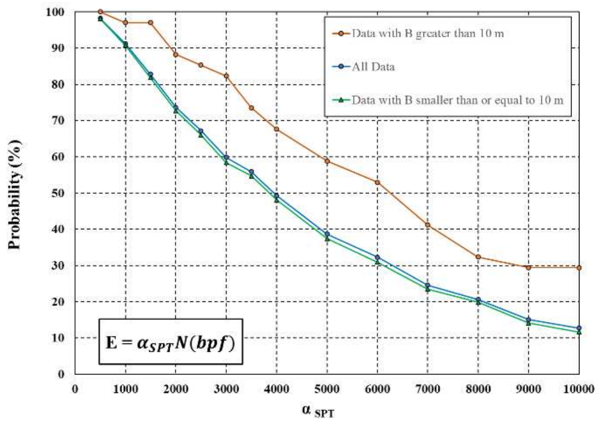
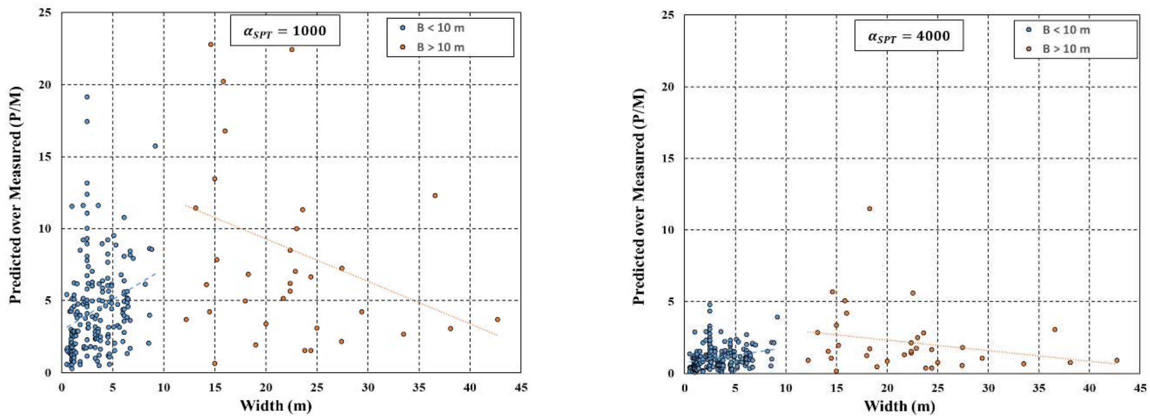
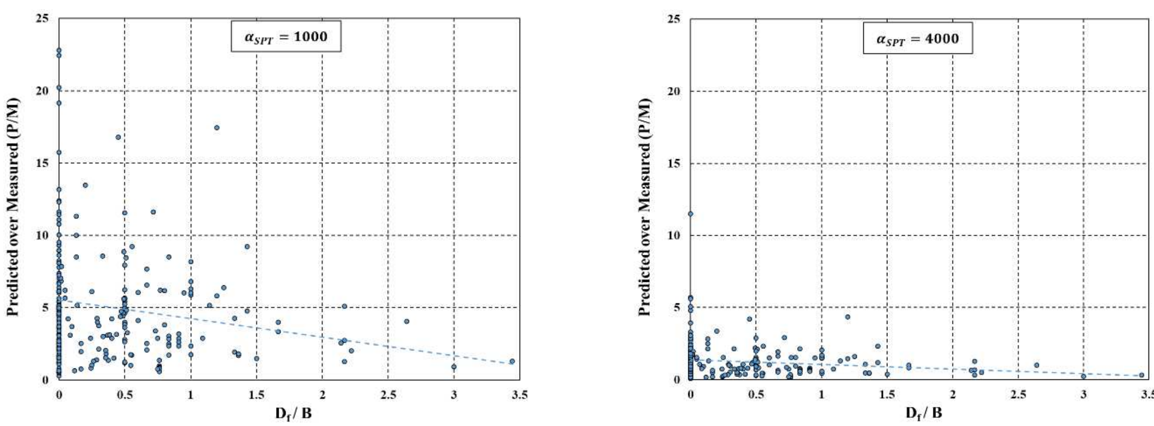


Figure 3. Probability of lower than predicted settlement occurence based on SPT results for all data in TAMU-SHAL-SAND Database, data with foundation widths smaller than 10 m, and data with foundation widths larger than 10 m.



a) α_{SPT} = 1000 b) α_{SPT} = 4000

Figure 4. Predicted over measured settlement records versus width of foundation for TAMU-SHAL-SAND Database when using E (kPa) = 1000 N (91.2% of probability) and E (kPa) = 4000 N (49.3% of probability).



a) α_{SPT} = 1000 b) α_{SPT} = 4000

Figure 5. Predicted over measured settlement records versus depth over width of foundation (D_f/B) for TAMU-SHAL-SAND Database when using E (kPa) = 1000 N (91.2% of probability) and E (kPa) = 4000 N (49.3% of probability).

CPT PREDICTED SETTLEMENT VERSUS MEASURED SETTLEMENT AND PROBABILITY ANALYSIS

The work presented for the SPT in the previous section was repeated for the CPT. The SPT blowcount N is replaced by the CPT point resistance q_c and the modulus equation is:

$$\boldsymbol{E = \alpha_{CPT} q_c} \tag{4}$$

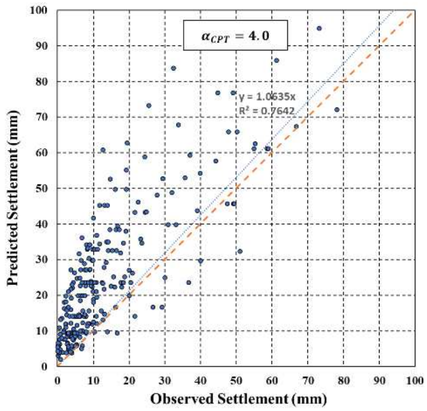
where E is the soil modulus in kPa, α_{CPT} is the correlation factor, and q_c is the CPT tip resistance in kPa. Table 2 is a summary of the relationships between E and N based on the following references: Bowles (1996), FHWA (2010), Briaud and Miran (1992a, 1992b), Briaud (1992), Mayne (2007a, 2007b), and Schmertmann et al. (1978). These correlations aim at giving the modulus to obtain the long term settlement at working loads. The TAMU-SHAL-SAND database was used to narrow down this wide range of correlations and give a measure of the probability that the predicted settlement would be larger than the measured settlement.

Figure 6a-b show predicted settlements versus measured settlements for a modulus E (kPa) = 4 q_c(kPa) and E (kPa) = 8 q_c(kPa) respectively. Figure 7 shows the probability that the predicted settlement will be larger than the measured settlement vs. the cone penetrometer correlation factor α_{CPT} for the TAMU-SHAL-SAND database. To reach a 90% probability that the predicted settlement will be larger than the measured settlement, a CPT correlation factor of 4 is necessary (E = 4q_c). This is quite a bit higher than Schmertmann's recommendation of using E = 2.5q_c.

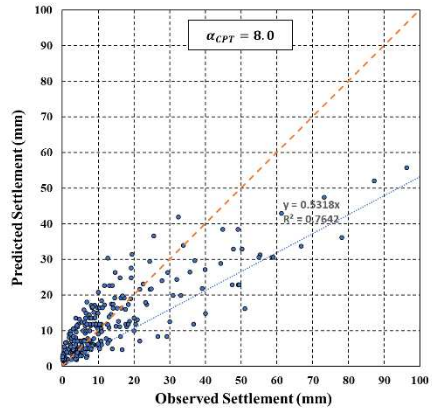
Figure 8 illustrates the predicted over measured settlement ratio (P/M) versus the foundation width (m) for E (kPa) = 4 q_c(kPa) (approximately 90% of probability) and E (kPa) = 8 q_c(kPa) (approximately 55% of probability). The P/M settlement ratio shows an increasing trend as the width B increases. This increasing trend can possibly be explained by the fact that as the foundation width increases, the zone of influence of the foundation also increases, and the representative soil property (q_c) may be too shallow, thus likely too low to be representative of the entire zone of influence. Figure 9 shows the predicted over measured settlement ratio versus the foundation depth over the foundation width (embedment ratio, D_f/B) for E (kPa) = 4 q_c(kPa) and E (kPa) = 8 q_c(kPa). By increasing the values of the embedment ratio, the predicted over measured settlement ratio decreases. This is consistent with the increasing trend observed for the width (Figure 8) since the plot in Figure 9 is vs. 1/B.

Table 2. Correlation between soil modulus and soil test results for sands and gravels [Bowles (1996), FHWA (2010), Briaud and Miran (1992a, 1992b), Briaud (1992), Mayne (2007a, 2007b), and Schmertmann (1970)].

Soil Types	Correlation
Sandy soils (normally consolidated)	$E = 2\,q_c$ $E = (2.5 - 3.5)\,q_c$ recent < 100 years $E = (3.5 - 6)\,q_c$ old > 3000 years
Sand (normally consolidated)	$E = (1 + D_r^2)\,q_c$ D_r is relative density
Sand (over-consolidated)	$E = (6 - 10)\,q_c$
Sand: $q_c < 5$Mpa	$E = 2\,q_c$
Sand: $q_c > 10$Mpa	$E = 1.5\,q_c$
All sands	$E = 2.5\,q_c$ For square and circular foundations
All sands	$E = 3.5\,q_c$ For strip foundations



a) $\alpha_{CPT} = 4$



b) $\alpha_{CPT} = 8$

Figure 6. Predicted versus measured settlement records for TAMU-SHAL-SAND Database when using E (kPa) = 4 q_c(kPa).

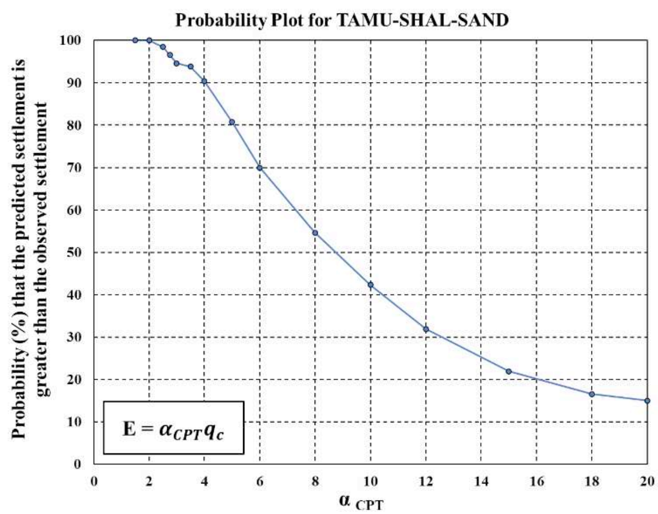
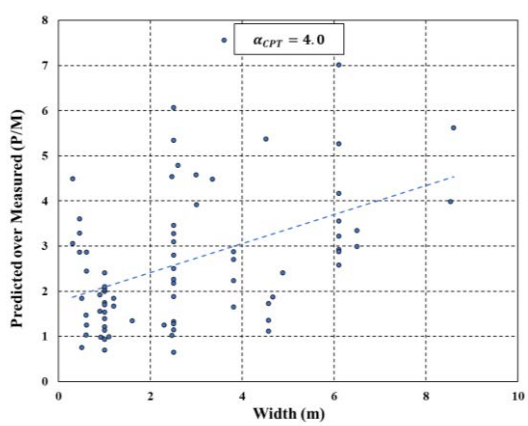
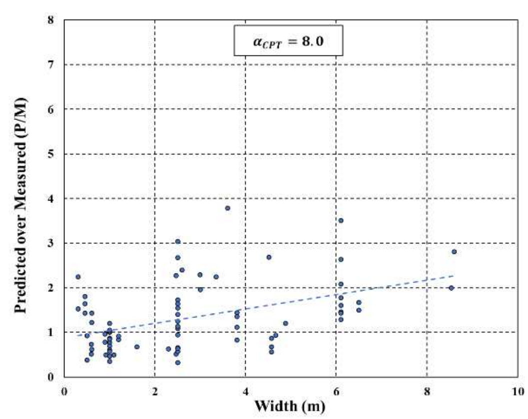


Figure 7. Probability plot based on CPT results for TAMU-SHAL-SAND Database for widths smaller than 10 m.

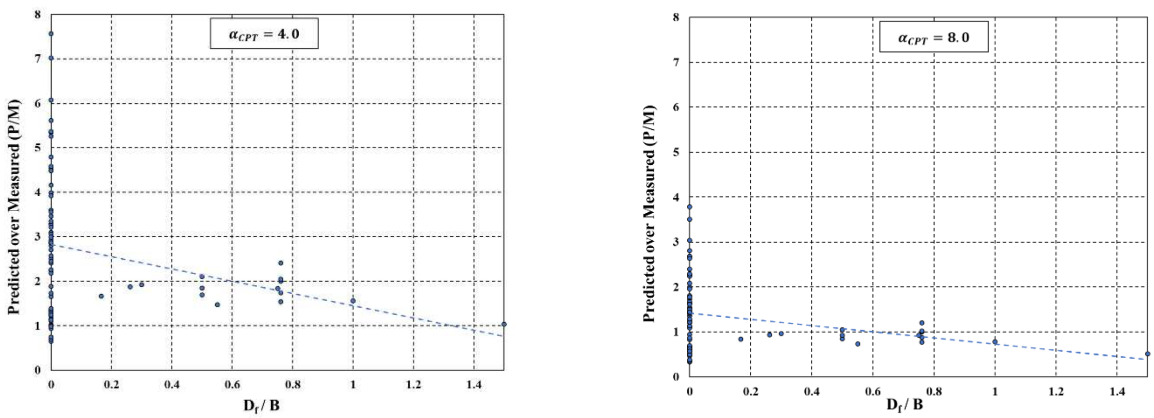


a) $\alpha_{CPT} = 4$



b) $\alpha_{CPT} = 8$

Figure 8. Predicted over measured settlement records versus width of foundation for TAMU-SHAL-SAND Database when using E (kPa) = 4 q_c(kPa) (90.4% of probability) and E (kPa) = 8 q_c(kPa) (54.6% of probability).



a) $\alpha_{CPT} = 4$ *b)* $\alpha_{CPT} = 8$

Figure 9. Predicted over measured settlement records versus depth of foundation over width of foundation (D_f/B) for TAMU-SHAL-SAND Database when using E (kPa) = 4 q_c(kPa) (90.4% of probability) and E (kPa) = 8 q_c(kPa) (54.6% of probability).

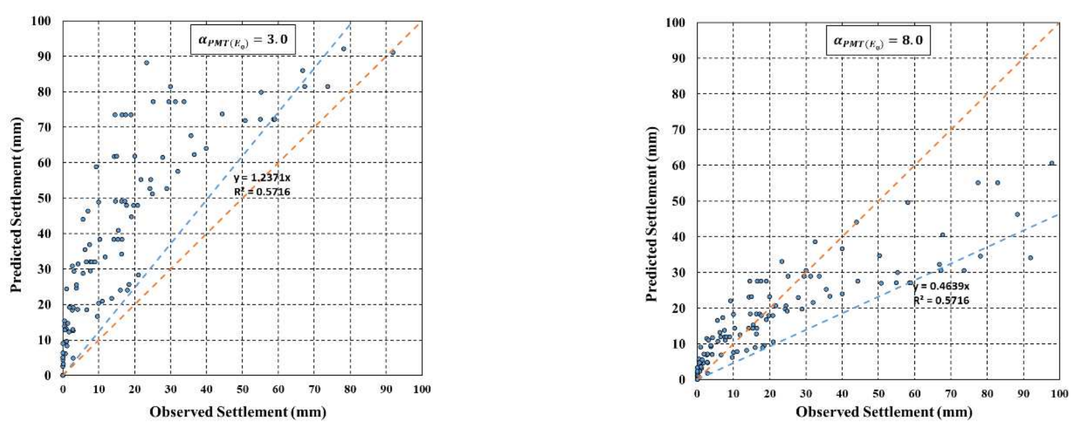
PMT PREDICTED SETTLEMENT VERSUS MEASURED SETTLEMENT AND PROBABILITY ANALYSIS

The soil modulus can be estimated from the PMT first load modulus (E_0) by Equation 5:

$$\boldsymbol{E = \alpha_{PMT(E_0)} E_0} \tag{5}$$

where E is the soil modulus in kPa, $\alpha_{PMT(E_0)}$ is a correlation factor for the PMT first load modulus and E_0 is the PMT first load modulus in kPa. As was done for the SPT and the CPT, the correlation factor for the PMT first load modulus can be varied, leading to different scatter plots of predicted settlement vs. measured settlement; then, the corresponding probability plot is generated. Figure 10a-b shows predicted settlement versus measured settlement for a modulus of E (kPa) = 3.0 E_0 (kPa) and E (kPa) = 8.0 E_0 (kPa) respectively. Figure 11 shows the probability that the settlement predicted using Equation 1 and a modulus equal to $\alpha_{PMT(E_0)}$ E_0 will be larger than the measured settlement vs. the correlation factor $\alpha_{PMT(E_0)}$. A soil modulus equal to three times the PMT first load modulus (E = 3 E_0) leads to a probability that the predicted settlement will be greater than the observed settlement equal to 90%.

Figures 12 and 13 show the P/M settlement ratio versus width B(m) and embedment ratio D_f/B, for E (kPa) = 3 E_0 (kPa) (92% of probability) and E (kPa) = 3 E_0 (kPa) (48% of probability) respectively. By increasing the width of the foundation, the P/M ratios get larger. By increasing the embedment ratio (D_f/B), the predicted values get closer to the observed values. These results for the PMT are consistent with the results for the SPT and the CPT.



a) $\alpha_{PMT} = 3$ *b)* $\alpha_{PMT} = 8$

Figure 10. Predicted versus measured settlement records for TAMU-SHAL-SAND Database.

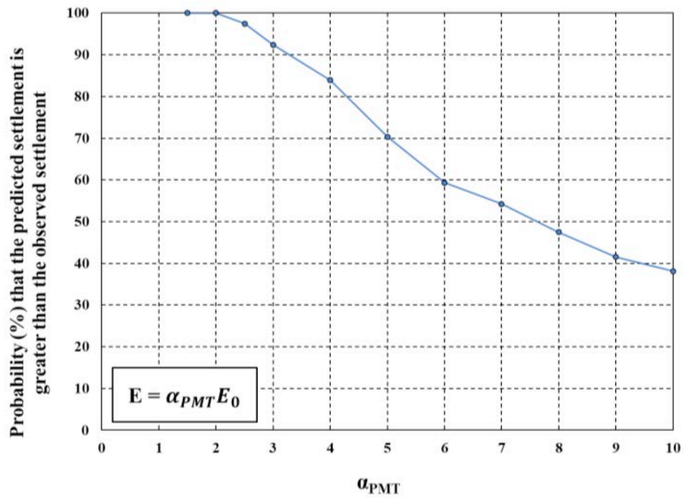
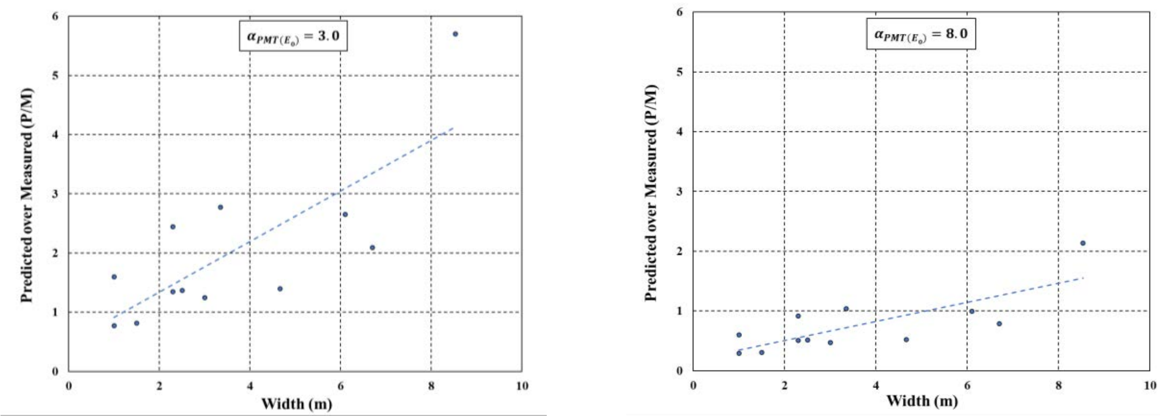
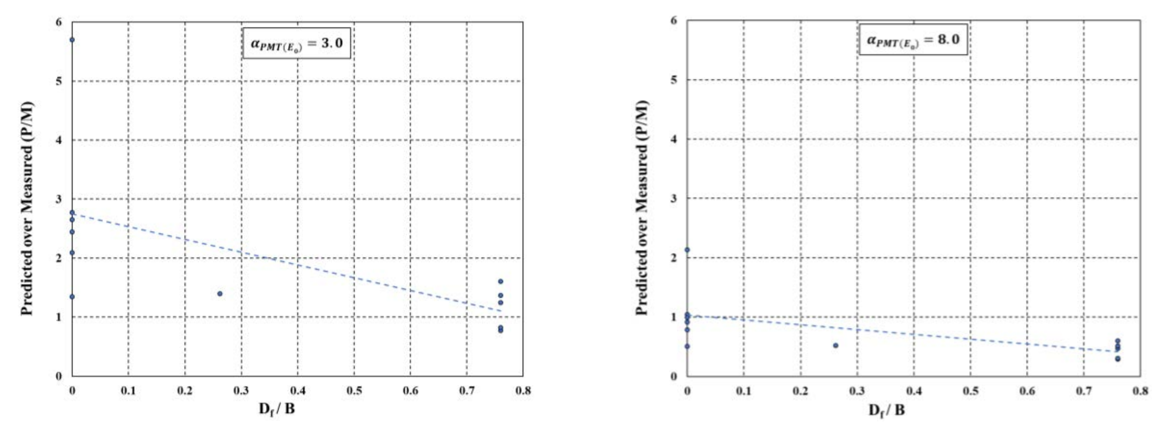


Figure 11. Probability plot based on PMT results for TAMU-SHAL-SAND Database.



a) $\alpha_{PMT} = 3$ b) $\alpha_{PMT} = 8$

Figure 12. Predicted over measured settlement records versus width of foundation for TAMU-SHAL-SAND Database when using E (kPa) = 3 E_0 (kPa) (92.3% of probability) and E (kPa) = 8 E_0 (kPa) (47.5% of probability).



a) $\alpha_{PMT} = 3$ b) $\alpha_{PMT} = 8$

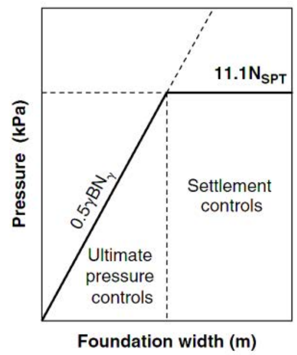
Figure 13. Predicted over measured settlement records versus depth of foundation over width of foundation (D_f/B) for TAMU-SHAL-SAND Database when using E (kPa) = 3 E_0 (kPa) (92.3% of probability) and E (kPa) = 8 E_0 (kPa) (47.5% of probability).

COMPARISON OF MEASURED PRESSURES AND SETTLEMENTS TO PRESSURES AND SETTLEMENTS CALCULATED USING PECK CHART

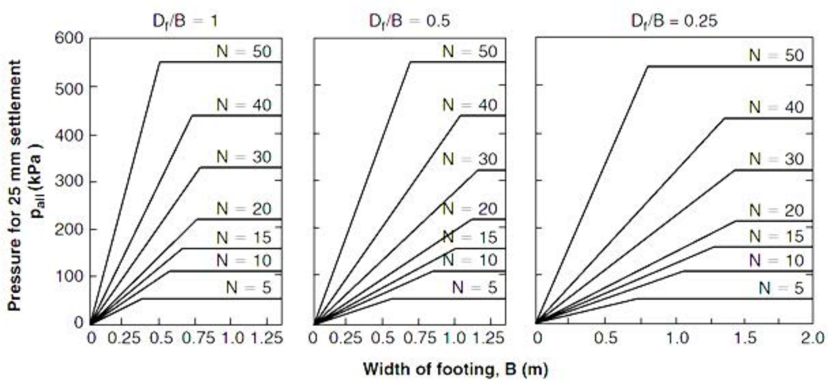
Terzaghi and Peck (1963) developed some simple charts for the design of shallow foundations on sand (Figure 14). These charts give the allowable pressure corresponding to 25 mm of settlement for footings on sand and will be called "the Peck chart" from this point on. For a given footing width, a given depth of embedment, and a given uncorrected SPT blowcount, the charts are read to obtain the allowable pressure ($p_{allowable}$) corresponding to 25 mm settlement while also satisfying the ultimate bearing capacity criterion. The allowable pressure refers to the settlement criterion, while the safe pressure refers to the ultimate bearing capacity criterion. Considering a reasonable factor of safety, safe pressure can be calculated as:

$$\boldsymbol{p_{safe} = p_u/F} \tag{6}$$

where p_{safe} is the safe bearing pressure, p_u the ultimate bearing pressure and F the factor of safety.



(a)



(b)

Figure 14. Peck chart providing the allowable bearing pressure for 25 mm settlement for footings on sand with SPT value (Terzaghi and Peck, 1963).

As shown in Figure 14a for small values of B, the pressure increases linearly with the width of the footing because the ultimate pressure criterion controls the design. This linear increase is explained as follows. Since these charts are proposed only for sand, the cohesion is zero and since the influence of the embedment depth is taken into account separately, the ultimate bearing pressure p_u can be calculated by the following equation:

$$\boldsymbol{p_u = 0.5\gamma B N_\gamma} \tag{7}$$

where γ is the soil unit weight, and $N\gamma$ is a bearing capacity factor depending on the friction angle of the soil. The effect of the embedment depth is included in the charts by proposing three different charts for three values of the relative embedded depth D_f over the width B of the footing. Since p_u increases linearly with the footing width, p_{safe} will also increase linearly with the footing width. The plateau on the charts following the bearing capacity criterion line occurs because at that point, the settlement criterion controls the design. It is inferred from the Peck charts that the settlement s of a footing on sand is proportional to the SPT blowcounts (N) as follows:

$$\boldsymbol{p_{25mm}(kPa) = 11.1N(blows/0.3m)} \tag{8}$$

Indeed, this equation corresponds to the various plateaus in Figure 14. Thus, p_{25mm} is independent of the footing width B; for large footing widths (~1 m or more), the settlement criterion will control the design.

The measured pressure p_m generating 25 mm of settlement can be obtained from the TAMU-SHAL-SAND database as follows. If the settlement is precisely 25 mm, the corresponding measured pressure is used. If the settlement is not exactly 25 mm, the pressure p_m is obtained as follows. First, it is assumed that the relationship between the pressure and the settlement is linear. Therefore a proportionality relationship is used to find the predicted pressure corresponding to 25 mm settlement. The proportionality equation is:

$$\boldsymbol{p_{25mm}/p_m = 25mm/s_m} \tag{9}$$

where p_{25mm} is the pressure predicted according to this extension of the Peck charts approach for 25 mm settlement, p_m is the measured pressure, and s_m is the measured settlement in mm. Equation 8 can then be extended to other settlement values by combining Eqs. 8 and 9 as follows:

$$\boldsymbol{s(mm) = 2.3p_m(kPa)/N(bpf)} \tag{10}$$

where s(mm) is the predicted settlement in mm, p_m is the measured pressure in kPa, and N is the SPT blowcounts in bpk. The values of p_{25mm} predicted, as described above, based on the measured values in the database, were placed directly on the Peck charts. This is done in Figures 15-21. Note that the lines on the figures are the original lines proposed by Peck. Due to a large number of data points, the figures are sorted according to different ranges of N values (N=0 to N=5, N=5 to N=10, N=10 to N=20, N=20 to N=30, N=30 to N=40, and N=40 to N=50). For smaller footing sizes (B less than about 3 m), the pressure corresponding to 25 mm settlement is much higher than the chart recommends, so for smaller footings, the Peck chart is conservative to very conservative. There is a general trend toward the pressure corresponding to 25 mm settlement to decrease as the footing width increases. This is consistent with the elastic equation (Eq. 1) where the pressure for a given settlement varies as 1/B consistent with the trend observed in Figs. 15 to 21. This is a shortcoming of the Peck chart. Note that the lines shown in the charts are the design lines proposed by Peck.

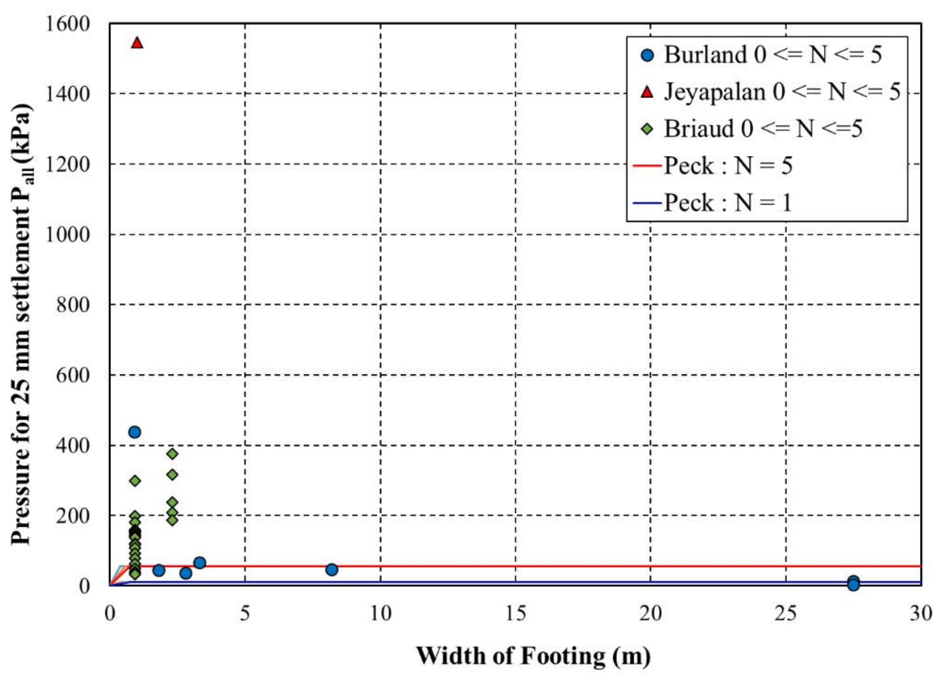


Figure 15. Comparison between pressures computed from three databases and Peck charts for $\boldsymbol{0 \le N \le 5}$.

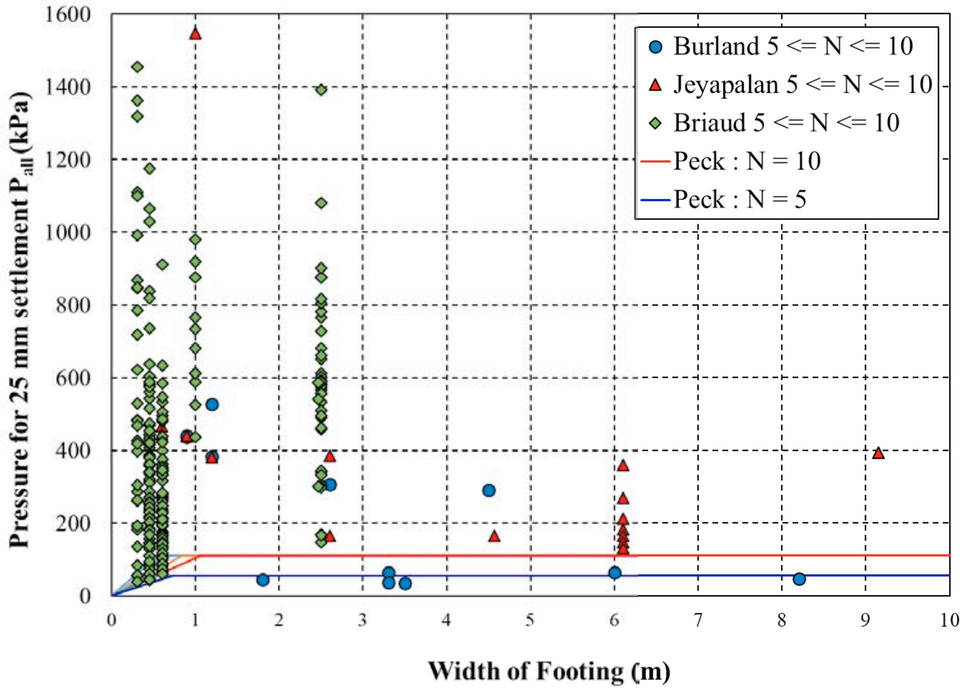


Figure 16. Comparison between pressures computed from three databases and Peck charts for $\mathbf{5 \leq N \leq 10}$.

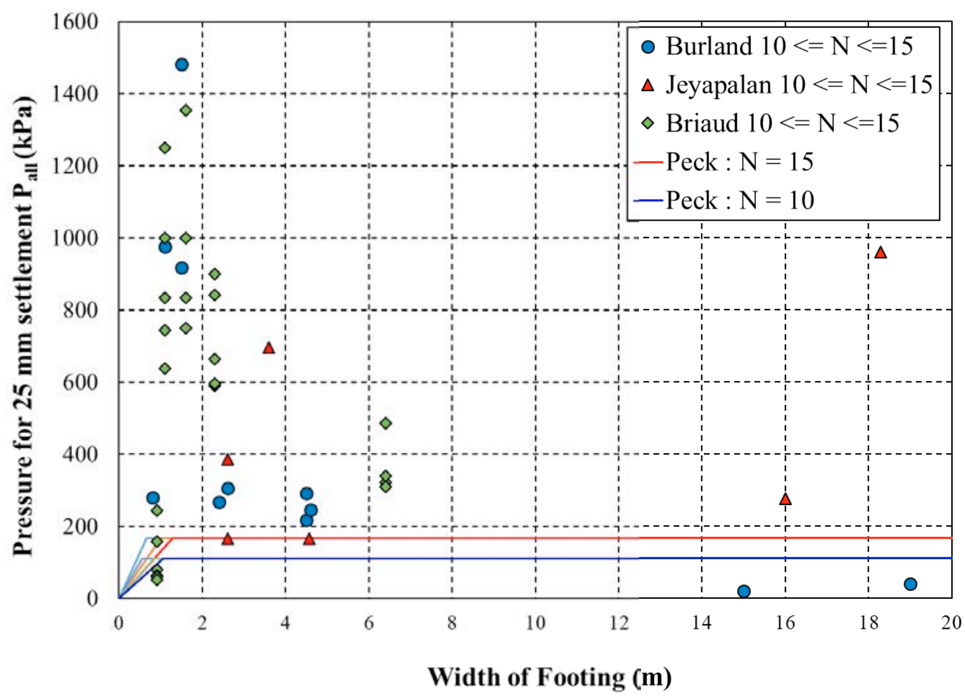


Figure 17. Comparison between pressures computed from three databases and Peck charts for $\mathbf{10 \leq N \leq 15}$.

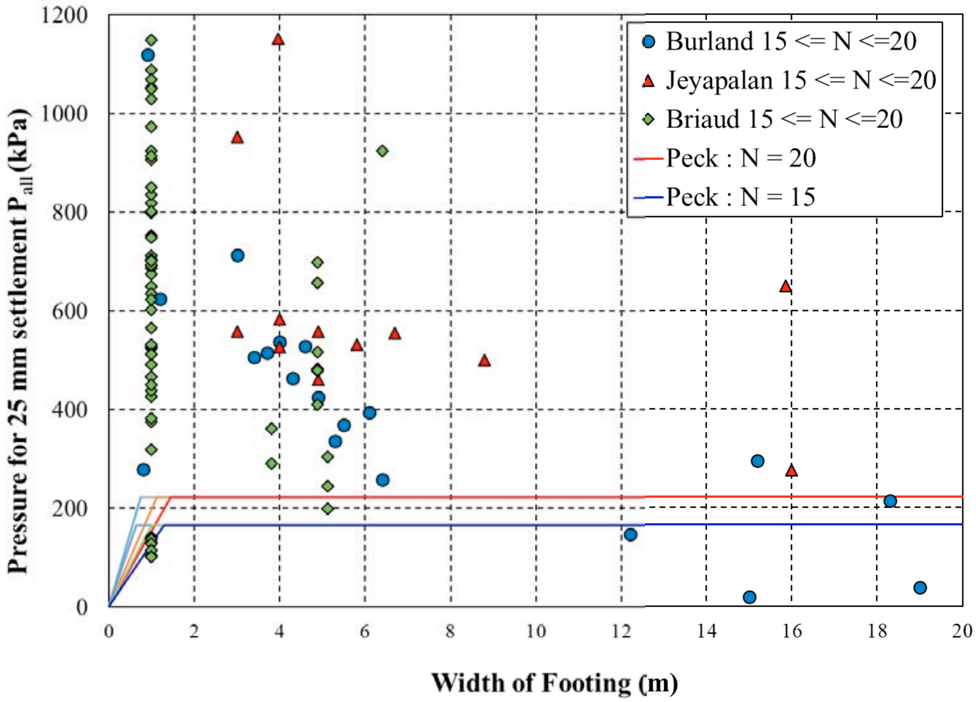


Figure 18. Comparison between pressures computed from three databases and Peck charts for $15 \leq N \leq 20$.

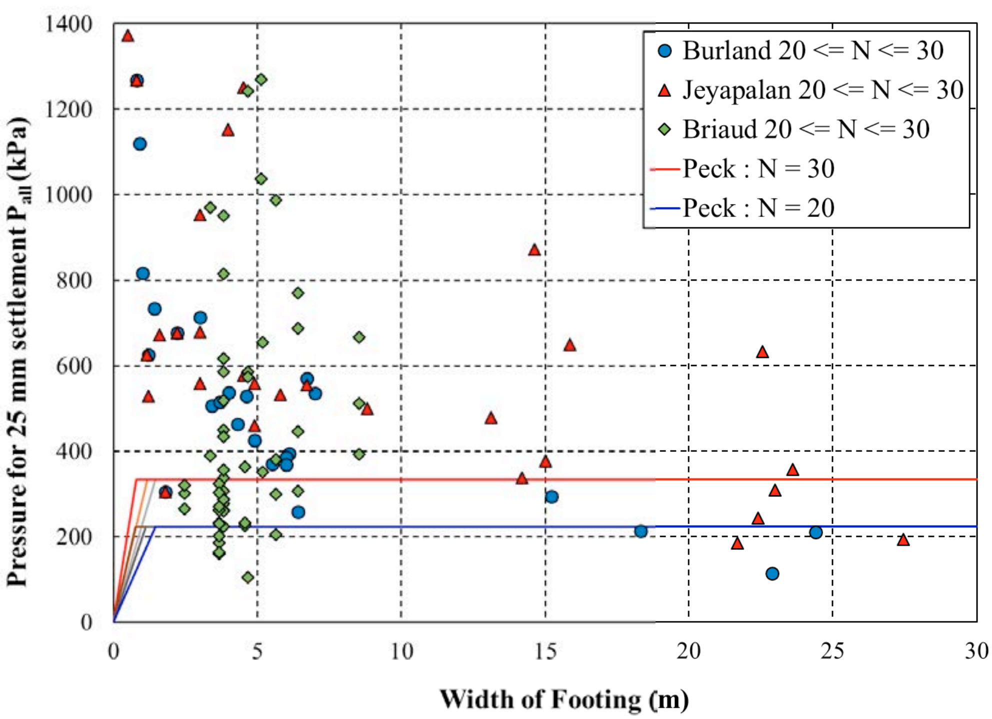


Figure 19. Comparison between pressures computed from three databases and Peck charts for $20 \leq N \leq 30$.

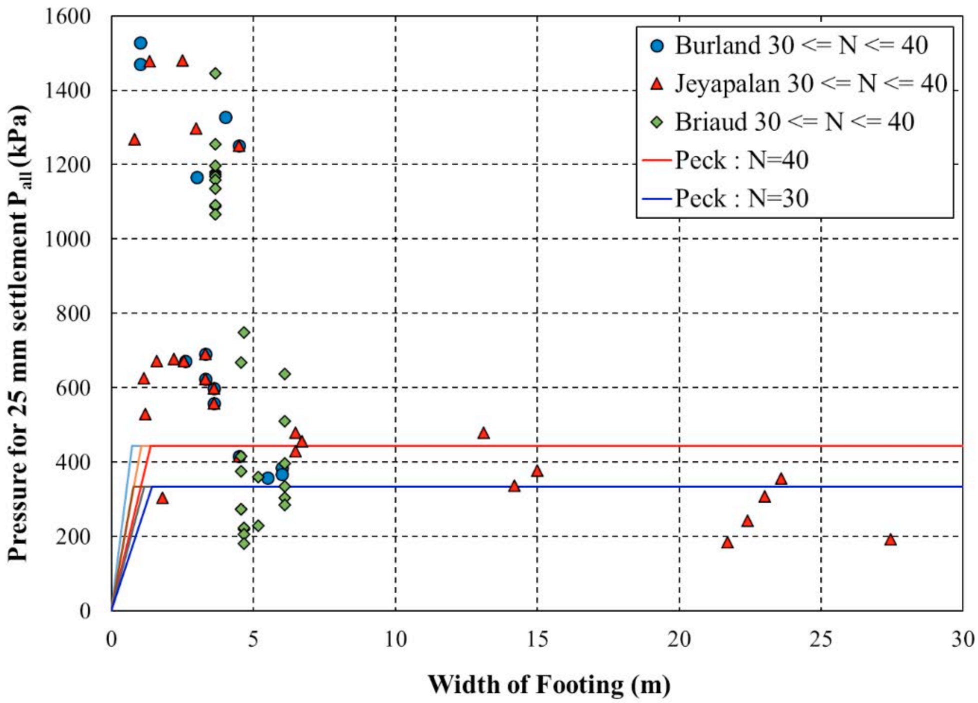
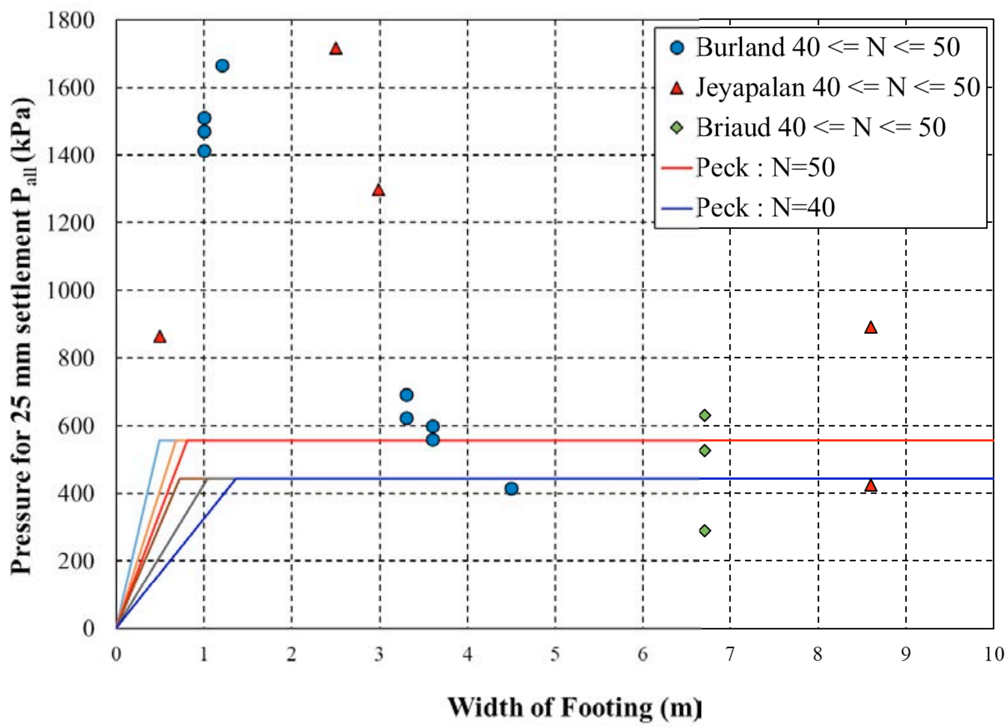


Figure 20. Comparison between pressures computed from three databases and Peck charts for $\mathbf{30 \leq N \leq 40}$.



3

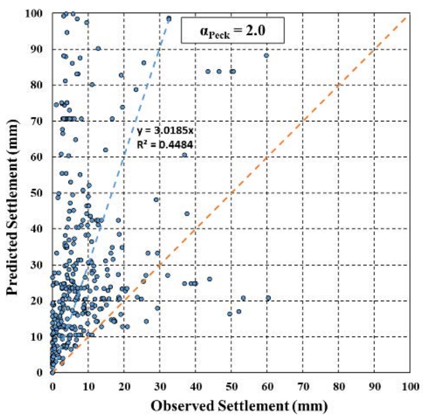
Figure 21. Comparison between pressures computed from three databases and Peck charts for $\mathbf{40 \leq N \leq 50}$.

PECK CHART PREDICTED SETTLEMENTS VERSUS MEASURED SETTLEMENTS FOR TAMU-SHAL-SAND DATABASE

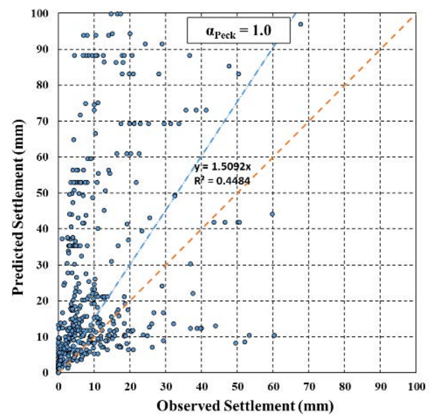
Equation 10 is corrected with a calibration factor by writing it as follows:

$$s(mm) = \alpha_{Peck} \times 2.3p(kPa)/N(bpf) \tag{11}$$

where α_{Peck} is a correction factor to impact the magnitude of the predicted settlements. Figure 22 shows the settlement values predicted by using Equation 11 for two values of the correction factor α_{Peck} compared to the measured values of settlement. For various values of α_{Peck}, a plot of predicted settlement vs. measured settlement was created. For each plot, the number of points where the predicted settlement was larger than the measured settlement was recorded and divided by the total number of points in the plot. This gave the probability P that the predicted settlement would be larger than the measured settlement and led to one point on the probability P vs. α_{Peck} plot. The results of the probability calculations for the TAMU-SHAL-SAND database are presented in Figure 23. This probability plot shows that a correction factor α_{Peck} equal to about 2 in Equation 11 corresponds to a 90% probability that the Peck chart predicted settlement would be larger than the measured settlement.



a. $\alpha_{Peck} = 2.0$



b. $\alpha_{Peck} = 1.0$

Figure 22. Predicted versus measured settlement records for TAMU-SHAL-SAND Database.

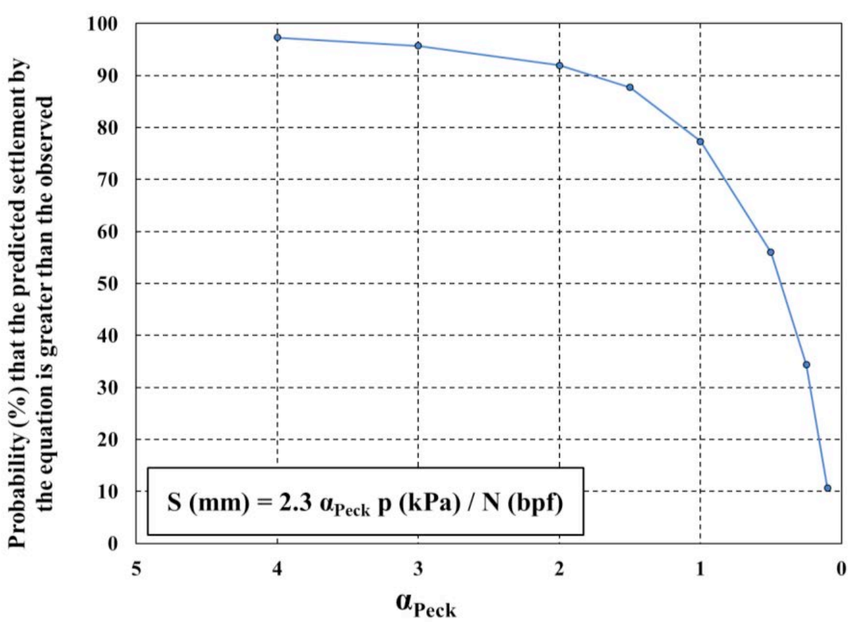


Figure 23. Probability plot based on PMT results for TAMU-SHAL-SAND Database.

CONCLUSION

In this paper, a database of 315 shallow foundations on sands is assembled from three existing databases. The data is organized in a large spreadsheet called TAMU-SHAL-SAND and available at no charge. The widths of the footings vary from 0.3 to 135 m, the SPT blowcount N from 2 to 60 bpf, the CPT point resistance q_c from 0.3 to 19.2 MPa, and the PMT modulus E_0 from 2.4 to 16.2 MPa. These soil parameters are uncorrected. The elasticity equation is selected to predict the settlement and compare it to the measured settlement with a modulus correlated to N, q_c, and E_0:

$$s = I(1-\nu^2)pB/E \tag{12}$$

Scatter plots of predicted vs. measured settlement are presented, and the probability that the predicted settlement will be smaller than the measured settlement is calculated. The results show that the following modulus correlations used in the elastic settlement equation give a settlement which has a 90% probability of being larger than the measured settlement for the TAMU-SHAL-SAND database:

$$E(kPa) = 1000N(bpf) \tag{13}$$

$$E = 4q_c \tag{14}$$

$$E = 3E_{0_{(PMT)}} \tag{15}$$

These correlation factors give predicted versus measured settlement ratios, which increase as the foundation width increases and decreases as the embedment ratio increases. This trend might warrant the use of higher correlation factors for larger foundations. However, the increasing trend is observed for foundation width up to 10 m and is reversed for foundation width larger than 10 m; therefore, higher values of the correlation factors may not be appropriate. In the end, the plots of predicted versus measured settlement ratio can guide the decision of the engineer (Figures 4, 8, and 12).

The Peck chart giving the pressure p_{25} corresponding to 25 mm of settlement is evaluated based on the TAMU-SHAL-SAND database. It is found that for the smaller footing widths, the measured value of p_{25} is larger to much larger than the Peck chart predicted value of p_{25}. The trend is for p_{25} measured to become closer to p_{25} predicted by the Peck chart for larger footing sizes. The following equation gives a settlement which is larger than the measured settlement in the TAMU-SHAL-SAND database 90% of the time:

$$s(mm) = 4.6\, p(kPa)/N(bpf) \tag{16}$$

which is same as Equation 11 with an α_{Peck} of 2.0. This equation is derived from the Peck chart; however, it does not include the width of the foundation, as does the elastic equation above. This is why the data in Figures 15 to 26 show a decreasing trend with increasing foundation width. This is a shortcoming of the Peck chart.

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