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Variability in Settlements of Foundations on Fine Grained Soils

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Abstract. Estimation of settlement is a very significant part in the design of foundations. Standard Penetration Test (SPT) is a commonly adopted method of geotechnical investigations. However, variability of in situ conditions is the most challenging aspect of analysis and design based on settlements. Two methods are considered to estimate the settlements of shallow foundations. One is based on variation of SPT N values with depth and the other is based on tip resistance, q_c which could be highly variable is further converted to SPT N based on mean or average particle size of the soil stratum. Settlements are estimated for three different sizes of footings in both the methods for a site explored by a large number of boreholes. The variability in the estimation of settlements for a given site conditions is determined. Relative advantages and limitations of the two methods of estimation of settlements are listed and presented.

Keywords: Settlement, foundation, Standard penetration test, in situ, tip resistance, variability.

1 Introduction

The basic and essential component of foundation design is estimation of settlements. Permissible settlement is always the controlling criteria for the design of shallow foundation more than the safe bearing capacity. Settlement the vertical downward movement of the ground caused by foundation load is a combination of immediate settlement due to elastic deformation of soil, consolidation settlement resulting from dissipation of excess pore pressure with time and secondary settlement or creep because of plastic adjustment and movement of soil particles under constant effective stress. Elastic or immediate settlement depends upon foundation type, rigid or flexible and type of soil. Generally, the two methodologies adopted to estimate settlements are based on: (1) Laboratory tests, oedometer and triaxial and (2) in-situ tests - SPT, CPT, Dilatometer, Pressuremeter, etc. and settlements need to be validated. Unfortunately, most engineers do not validate their predictions.

This paper presents estimates of settlements using SPT results based on two different approaches. SPT is one of the most versatile and commonly used tests for geotechnical characterization of a site predominantly due to its ease, reliability and economy. SPT N values are far better than considering laboratory determined properties in estimating settlements of foundations. Schmertmann et al. (1978) proposed a simple method based on variation of strain influence factor with depth and static cone tip resistance for estimating settlement. Burland and Burbidge's (1985) procedure estimates settlement based on variation of SPT N values within the depth of influence. In this paper settlements are estimated using the above two methods and variability of settlements at the site are compared. Data required for this study is obtained from the site of Dunkani - Kharaghpur section at NH-06.

2 Literature review

Meyerhof (1956, 1965 and 1974), D'Appolonia et al. (1970), Burland and Burbidge (1985) derived settlements using SPT N. Schmertmann (1970), Schmertmann et al. (1978) derived settlements based on tip resistance from cone penetration test (CPT). Poulos and Davis (1968) developed a three-dimensional approach of predicting settlement and compared them with model footing test results. Bowles (1987) presents a relation for estimating settlement using elastic continuum theory considering both shape and depth factors. Burland and Burbidge (1985) examined settlement variations with reference to depth to width ratio at few site locations. Mayne and Poulos (1999) proposed displacement influence factors for homogenous (modulus constant with depth) and Gibson-type (modulus linearly increasing with depth) and a new solution for Gibson soil of finite thickness. Akpila (2014) investigated bearing capacity and settlements of raft foundations on sandy soil using SPT.

3 Methodology

Borehole data from Six Laning of Dunkani - Kharaghpur section of NH-06 is considered in this paper. Boreholes are drilled at different chainages and corresponding Standard Penetration Test (SPT) N values are given. Fig.1 shows the variations of SPT N with depth. From Figs.1(a) through, (f), and (j) SPT N can be observed to be nearly constant upto depths of 8.0 to 10 m and increases with depth beyond. Figs. 1(d), (g), (h) and (i) show SPT N values increasing and decreasing with depth. Settlements are estimated using these SPT N values for footing widths of 2.0, 4.0 and 10.0 m under uniform pressure of

100 kN/m^2 based on Schmertmann et al. (1978) and Burland and Burbidge (1985) methods. Generally footing width greater than 6 m is considered as raft/mat foundations. Therefore 10 m footing width is considered as raft foundation.

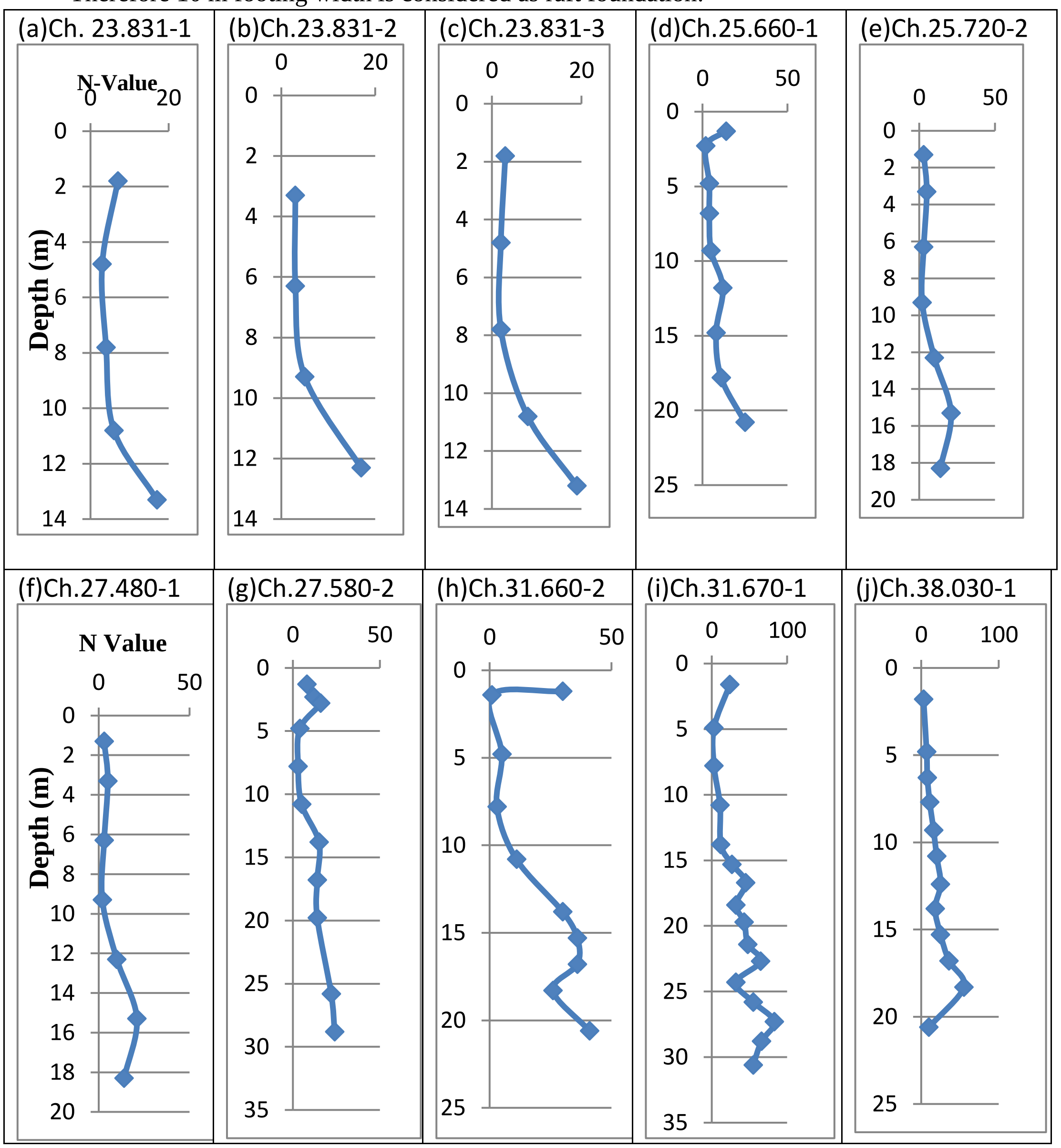


Fig. 1. Depth vs SPT N at various chainages

3.1. Schmertmann et al. (1978) Method

Schmertmann (1970) suggested a method to estimate the settlement of shallow foundations on soils considering a simplified variation of strain influence factor with depth. The compressible soils underneath the footing are divided into different sub-layers based on the variation of static cone resistance, q_c, with depth. The deformation modulus of soil is estimated from static cone resistance, q_c. This method, known as the "2B - 0.6" method, is based on vertical strain distribution with depth underneath the footing to a depth of twice the footing width.

Studies showed that Schmertmann (1970) method needs modification to the strain influence diagram that accounts for different shapes and load intensity. Schmertmann et al. (1978) is an improvement over the previously given method.

The strain influence diagram for axisymmetric footings (square and round) is constructed as:

Strain influence factor I_z is equal to 0.1 and 0 at depths Z=0 and 2B respectively from footing level. Maximum I_z occurs at a depth of B/2 and has a value of:

$$I_{Zp} = 0.5 + 0.1[\frac{\Delta q}{\sigma'_{vp}}]^{0.5} \quad (1)$$

For strip footings (L/B > 10), i.e., plane strain conditions, I_z = 0.2 and 0 at depths 0 and 4B respectively. Maximum l_z at a depth of B has a value of

$$I_{Zp} = 0.5 + 0.1[\frac{\Delta q}{\sigma'_{vp}}]^{0.5} \quad (2)$$

where Δq= net applied footing stress(kN/m^2), σ'_{vp} = initial vertical effective stress (kN/m^2).

The deformation modulus, E_s, for axisymmetric condition is

$$E_s = 2.5\ q_c \quad (3)$$

And for plane strain conditions,

$$E_s = 3.5\ q_c \quad (4)$$

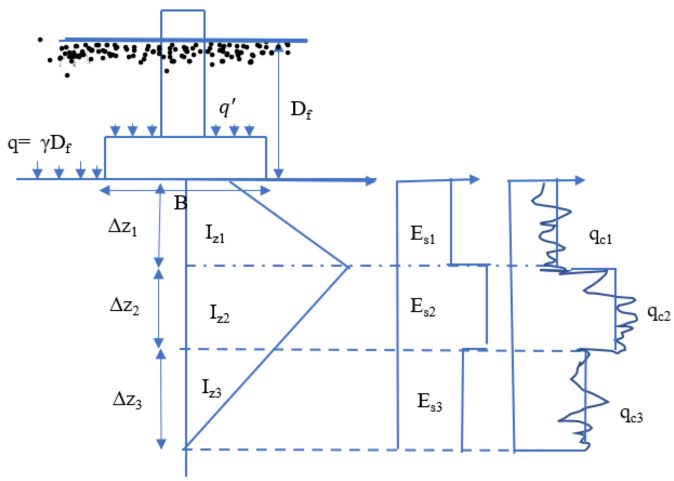


Fig. 2. Strain influence diagram

Settlement, S, is estimated as

$$S = C_1 C_2 (q' - q) \sum_{i=1}^{n} (\frac{I_{zi}}{E_{si}}) \Delta Z_i \quad (5)$$

$$\text{where } C_1 = 1 - 0.5 \left(\frac{q}{q'-q}\right) \text{ =depth correction factor} \quad (6)$$

$$C_2 = 1.0 + 0.2 \log \left(\frac{t}{0.1}\right) = \text{creep correction factor} \quad (7)$$

q'=stress at the level of foundation (kN/m^2); q=initial effective overburden pressure at the foundation level (kN/m^2); I_{zi}=strain influence factor of layer i; E_{si}=deformation modulus of layer i (kN/m^2); Δz_i=thickness of layer i (m); γ=unit weight of soil (kg/m^3); D_f=depth of foundation(m); B=width of footing (m); t=time in years.

Depending upon the variation in deformation modulus, E_s, soil below the footing is divided into a number of layers shown in Fig. 2 up to depth of influence 2B, since axisymmetric condition. Deformation modulus of each layer is taken as E_{s1}, E_{s2}, E_{s3}, etc. Thickness of each layer is taken as Δ_{z1}, Δ_{z2}, Δz_3, etc. and corresponding strain influence factors are I_{z1}, I_{z2}, I_{z3}, etc. Average of the values of influence factors, I_z at top and bottom of each layer is considered for settlement estimation. Schmertmann (1970) suggested that if only SPT N values are available, SPT N is converted in to cone tip resistance, q_c using $\frac{q_c}{N}$ ratio versus mean grain size, d_{50}, plot.

Table 1. Correlation between q_c and SPT N.

Soil type	$\frac{q_c}{N}$(kN/m^2)
Silts, sandy silts, Slightly cohesive silt-sand mixtures	2.0
Clean, fine to medium sands and slightly silty sands	3.5
Coarse sands & sand with little gravel	5.0
Sandy gravels and gravel	8

If the soil mixture consists of sand and large traces of silt, then the ratio of 2 can be used and if large amount of sand is present then ratio of 3.5 is used. If combination of coarse sand with little gravel is present then a ratio of 5.0 is used. If large amount of gravel is present then ratio of 8 is used.

3.2. Burland and Burbidge (1985) Method

Burland and Burbidge (1985) presented an empirical method based on average SPT blow count, foundation width and the zone of influence estimated based on the type of variation of SPT N, (i) constant or increasing and (ii) decreasing with depth.
Case 1: N_{60} is approximately constant or increases with depth,

$$Z' = 1.4(\frac{B}{B_r})^{0.75} B_r \tag{8}$$

where B=footing width (m); B_r=reference footing width=0.3 m; Z'=depth of influence (m).
Case 2: N_{60} decreases with depth, $Z' = 2B$ or $Z''$the depth to bottom of soft layer from footing level. (whichever is less).
Settlement, S_B is estimated as

$$S_B = \alpha_1 \alpha_2\, \alpha_3\, (\frac{1.25\, \frac{L}{B}}{0.25 + \frac{L}{B}})^2 (\frac{B}{B_r})^{0.7} \left(\frac{q'}{p_a}\right) B_r \tag{9}$$

where α_1 =0.14 (constant); $\alpha_2 = \frac{1.71}{{N_{60(a)}}^{1.4}}$ =compressibility index (10)

$\alpha_3 = \frac{z''}{z'}(2 - \frac{z''}{z'}) \le 1$ =correction for depth of influence (11)

and $q' = q_0$ (12)

L= length of footing (m), B = width of footing (m), B_r=reference width=0.3 m, $N_{60(a)}$=average of SPT N within the depth of influence, q_0=net applied stress at the level of the foundation (i.e., the stress at the level of the foundation minus the overburden pressure); p_a=atmospheric pressure=100 kN/m^2.

3.3 Estimation of settlement, S_S, by Schmertmann et al. (1978)

The soils present in the considered site are all silty clay. Hence

$$\frac{q_c}{N} = 2 \quad (13)$$

Cone tip resistance, q_c is calculated from SPT N using Eq.13 from which deformation modulus, E_s, is determined using Eq.3. The strata below the footing is divided into layers based on deformation modulus and values of I_z found at the top and the bottom of each layer. I_z values other than I_{zp} and $I_{z(2B)}$ are obtained by interpolation. Average of I_z of the values at the center of layer is calculated for each layer along with thickness of layer, Δz. Product of each layer thickness with the ratio of influence factor to deformation modulus is summed up for all the layers. The obtained sum is multiplied with correction factors for depth (C_1), and for creep, (C_2) for net stress of 100 kN/m^2 to estimate the total settlement. Strain influence factor diagrams are drawn for footing widths of 2.0, 4.0 & 10.0 m for all chainages and their corresponding settlements estimated. Table 2 presents typical settlement analysis for chainage 23.831-1 for footing width of 2 m.

Table 2. Estimation of settlement for chainage 23.831-1 using Schmertmann et al. (1978) method

B=2 m						
Layer No.	Thickness Δz (m)	SPT N	q_c= 200N (kN/m^2)	Deformation modulus E_s=2.5q_c (kN/m^2)	Strain influence factor (I_z)	(I_z/E_s) * Δz
1	1	5	1000	2500	0.35	0.00015
2	0.5	5	1000	2500	0.56	0.00011
3	1.45	3	600	1500	0.35	0.00035
4	1.05	4	800	2000	0.105	0.00006
						0.00065
Settlement, S_S=53.62 mm						

The stratum is divided into 4 layers based on variation of deformation modulus, E_s with depth (Table 2). Even though deformation modulus, E_s is the same for the first two layers, they are considered as distinct layers because maximum influence factor, I_z at depth of $\frac{B}{2}$ occurs in Layer 1. Δz, is thickness of each layer. Settlements are estimated on similar lines for 4 m footing width and raft foundation (B=10 m) shown in Table 3.

Table 3. Settlements for different width of footings for chainage 23.831-3

Width of footing (m)	Settlement(mm)
2	53.62
4	101.3
10	164.0

Table 3 presents settlements obtained are 54.7 mm, 101.3 mm and 164 mm for 2.0 m, 4.0 m and 10.0 m footing widths respectively.

3.4 Estimation of Settlement, S_B by Burland and Burbidge (1985)

The data from the same chainage 23.831-1(Fig.1 (a)) is analyzed. SPT N values in Fig. 1(a) are considered to be nearly constant upto 10 m depth and to increase with depth for depths beyond 10.0 m. The depth of influence, Z', is determined accordingly using Eq. 8. Average of SPT N are calculated within this depth of influence, Z'. The term α_2 was obtained from Eq.10. The parameters, net bearing stress of 100 kN/m^2 and atmospheric pressure of 100 kN/m^2 are not mentioned in Table 4. Settlements are estimated (Table 4) using Eq.9.
Burland and Burbidge (1985) method is difficult to apply for soil strata whose SPT N values do not follow trends of case I (constant or increasing with depth) or case II (decreasing with depth) such as those depicted in Figs. 1 (d), (g), (h) and (i) For these cases, only the initial variation of SPT N with depth is considered and settlements estimated.

Table 4. Estimation of settlements at chainage 23.831-1 for 2 m, 4 m and 10 m footing widths.

Footing width B (m)	2	4	10
Variation of SPT N with depth	constant	constant	increasing
Depth of influence, Z (m)	1.7	2.9	5.8
Avg N_{60}	5	4.3	4.1
Compressibility index, α_2	0.1	0.21	0.23
Settlement, S_B (mm)	28.3	56.3	112.9

In Table 4, depths of influence, Z are 1.7 m, 2.9 m and 5.8 m for footing widths of 2 m, 4 m and 10 m respectively. Depth of influence (Z=5.8 m) is high for raft foundation (footing width, B=10 m) and the corresponding average N_{60} of 4.1 is less. But depth of influence (Z=1.7 m) is less for 2 m footing width and average N_{60} equal to 5 is high. Greater average N_{60} implies soil is stiff and thus gives less settlement, S_B=28.3 mm whereas smaller average N_{60} implies soil is loose and gives more settlement S_B=112.9 mm.

4 Results and Discussion

Settlements were estimated for all chainages for footing widths of 2.0 m, 4.0 m and 10.0 m using Schmertmann et al. (1978) and Burland and Burbidge (1985) methods and compared in Table 5.

Table 5. Settlements based on Burland & Burbidge (1985) and Schmertmann et al. (1978) methods.

Chainage	Settlements S_s(mm) Schmertmann et al. (1978)			settlements S_B (mm) Burland and Burbidge (1985)			S_s/S_B		
Footing width (m)	2	4	10	2	4	10	2	4	10
23.831-1	53.62	101.3	164.1	28.4	56.4	112.9	1.9	1.8	1.5
23.831-2	63.6	127.7	167.1	57.1	92.7	163.8	1.1	1.4	1.0
23.831-3	106.0	184.2	241.8	75.1	134.7	283.1	1.4	1.4	0.9
25.660-1	61.4	111.5	169.8	75.1	92.7	149.1	0.8	1.2	1.1
25.720-2	39.3	73.6	127.3	20.8	32.7	66.0	1.9	2.2	1.9
27.480-1	49.3	113.4	211.3	34.7	57.9	126.1	1.4	2.0	1.7
27.580-2	35.3	78.5	181.8	7.4	14.9	43.5	4.7	5.3	4.2
31.660-2	30.3	86.4	135.8	8.7	25.2	46.5	3.5	3.4	2.9
31.670-1	57.9	122.5	196.2	38.8	53.6	144.7	1.5	2.3	1.4
38.030-1	34.5	58.8	75.1	28.4	38.8	52.7	1.2	1.5	1.4
38.060-2	37.5	57.1	86.1	31.4	46.1	52.8	1.2	1.2	1.6
41.900-1	88.8	78.0	237.0	102.5	141.3	223.0	0.9	0.6	1.1
41.960-2	37.3	77.9	157.5	9.0	23.9	46.9	4.1	3.3	3.4
44.935-1	143.4	172.4	239.1	271.0	166.6	316.4	0.5	1.0	0.8
44.960-2	44.2	135.5	260.0	11.2	35.8	62.1	4.0	3.8	4.2
44.497-2	75.5	161.9	203.8	44.1	60.5	166.2	1.7	2.7	1.2
48.520-1	22.7	84.6	174.7	8.6	26.0	49.9	2.7	3.3	3.5
50.510-2	90.2	187.3	250.2	75.1	111.7	262.6	1.2	1.7	1.0
50.560-1	88.8	153.5	196.6	82.9	122.0	242.5	1.1	1.3	0.8

64.915-1	29.5	58.5	106.6	13.5	28.1	53.3	2.2	2.1	2.0
64.930-2	15.4	43.2	79.3	3.8	9.4	16.3	4.1	4.6	4.9
69.765-2	24.4	64.1	125.4	8.2	26.6	45.5	3.0	2.4	2.8
69.780-1	32.6	95.7	191.7	15.4	35.8	60.6	2.1	2.7	3.2

Ratios, S_s/S_B, of settlements estimated using Schmertmann et al. (1978) and Burland and Burbidge (1985) are also listed in Table 5. Fig.3 presents the ratios for footing widths of 2.0, 4.0 and 10.0 m given in table 5 in graphical form. Ratio, S_s/S_B varies from 4.7 to 0.5, 5.3 to 0.6 and 4.9 to 0.8 for footing widths of 2.0 m, 4.0 m and 10.0 m respectively. Results shown in Table 5 and Fig. 3 indicate the ratio, S_S/S_B to be greater than 1.0 in most cases implying that Schmertmann et al. (1978) method estimates settlements to be greater than those from Burland and Burbidge (1985) methods for the three sizes of footing widths. In few cases wherein the SPT N value is around 1 and 2 it is vice versa, i.e., Burland and Burbidge (1985) method predicts larger settlements than those from Schmertmann et al. (1978) method.

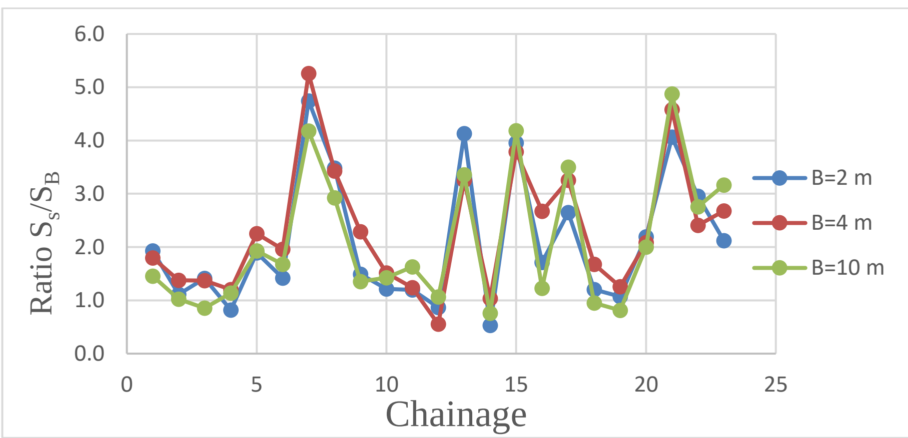
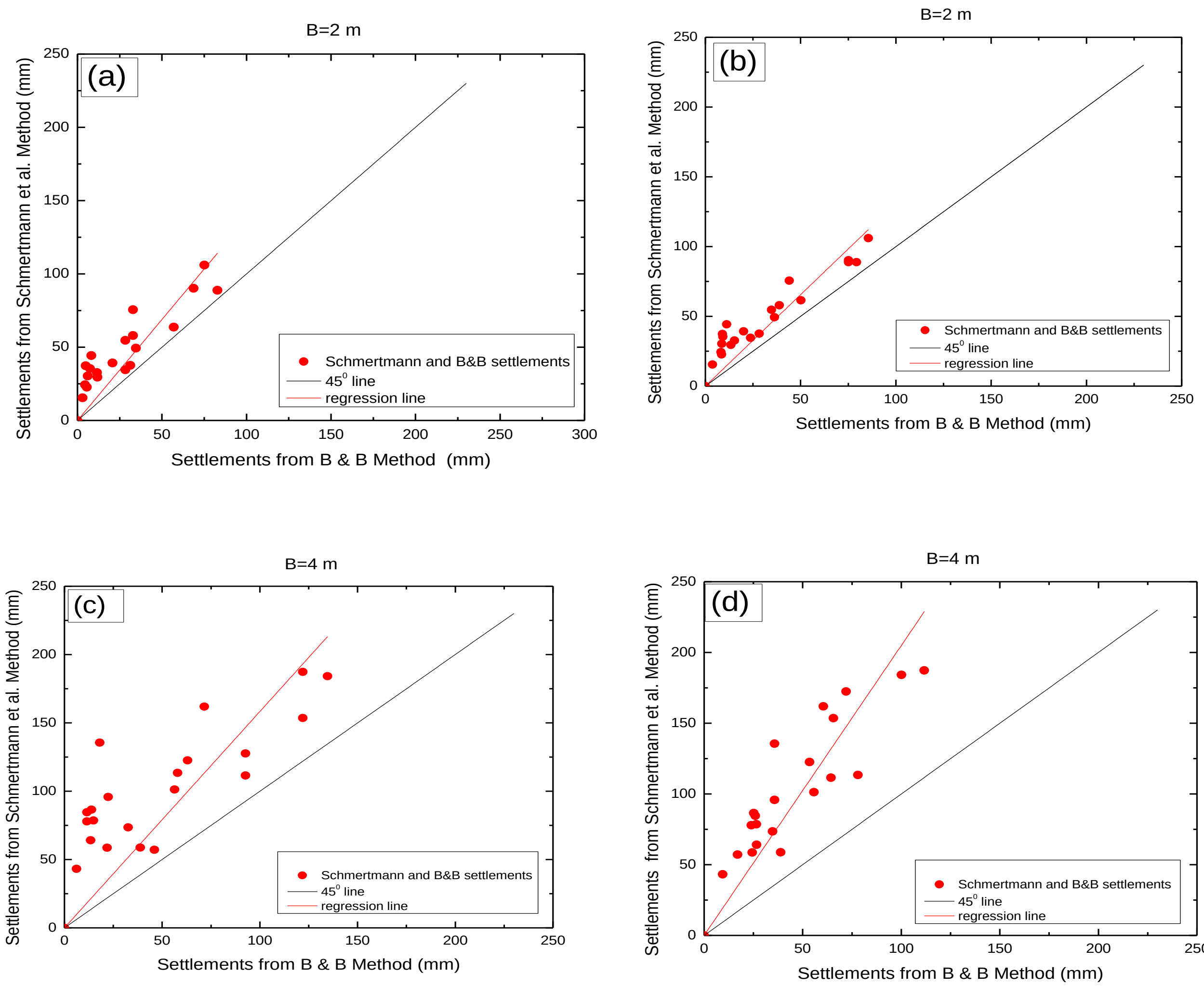


Fig. 3. Ratio, S_s/S_B, between Schmertmann et al. (1978) and Burland and Burbidge (1985) methods for B=2 m, 4 m and 10 m.

The ratio, S_s/S_B is larger than 3.0 (Fig. 3) for chainages who's initial SPT N are greater than 15. It implies that Schmertmann et al. (1978) method accounts for the larger value while Burland and Burbidge (1985) method averages the high value and thus predicts relatively smaller value of settlement. The converse is true if the ratio, S_s/S_B is less than 1 (as at some of the chainages) where in soil is very loose at shallow depths with SPT N value less than 3. The effect of smaller values of N is not felt in Schmertmann et al.

(1978) method possibly because of corresponding smaller strain influence coefficients, I_z, while the average value used in Burland and Burbidge (1985) gets reflected. Estimates of settlements from Schmertmann et al. (1978) and Burland and Burbidge (1985) methods for all the cases, i.e., SPT N is constant/increasing, decreasing or increasing and decreasing with depth are compared in Fig. 4.



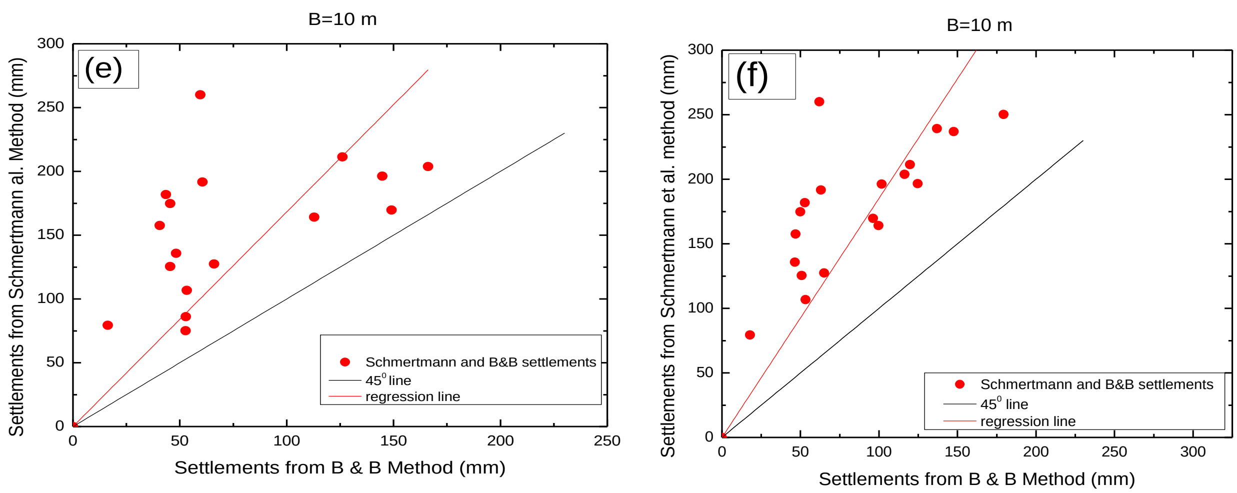


Fig. 4. Settlements from Schmertmann et al. (1978) vs settlements from Burland and Burbidge (1985) methods: (a), (c) and (e) for footing widths 2 m, 4 m and 10 m and SPT N increasing with depth; (b), (d) and (f) for footing widths 2 m, 4 m and 10 m and for SPT N decreasing with depth

Table 6. Angles of deviation of regression lines from 45^{0} for the plots drawn between Schmertmann et al. (1978) and Burland and Burbidge (1985) methods

Footing Width (m)	Angles of deviation of regression lines from 45^{0} Schmertmann et al. (1978) and Burland and Burbidge (1985) methods	
	Increasing SPT N with depth (degrees)	Decreasing SPT N with depth (degrees)
2	8.8	7.64
4	12.6	18.8
10	14.2	16.6

Table 6 shows the angles of deviation for footing width of 2 m are 8.8^{0} and 7.6^{0} which are considered to be relatively close for both SPT N increasing and decreasing with depth. But for 4 m footing width and raft foundation (B=10 m), angles of deviation from 45^{0} are relatively large with 12.6 and 14.2 for SPT N increasing with depth and 18.8 and 16.6 for SPT N decreasing with depth.

4 Conclusions

1. Settlements based on Schmertmann et al. (1978) method are in general larger than those based on Burland and Burbidge method (1985) but if the soil at shallow depth is loose it is vice versa.
2. Burland and Burbidge method (1985) can be used for footing widths less than 4 m for soil profile with SPT N variation with depth is not uniform, i.e., either increasing or decreasing since deviation angle is less.
3. Schmertmann et al. (1978) method is preferable for footing widths greater than 2 m.
4. The settlement ratio, S_S/S_B is greater than 3 for stiff strata at shallow depths. The settlements ratio, S_S/S_B is less than 1 if the soil at shallow depths of footing is soft with SPT N value less than 3.

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