J. Inst. Eng. India Ser. A
DOI 10.1007/s40030-017-0246-7

ORIGINAL CONTRIBUTION

A Comparative Study on Bearing Capacity of Shallow Foundations in Sand from N and ϕ

V. A. Sakleshpur[1] · **C. N. V. Satyanarayana Reddy**[1]

Received: 9 January 2015 / Accepted: 20 October 2017
© The Institution of Engineers (India) 2017

Abstract This work presents a comparative study on the bearing capacity of strip, square, circular footings and raft foundations in sand, estimated from the standard penetration resistance, N, and the angle of shearing resistance, ϕ. The net safe bearing capacity estimated directly from N using Teng's equation is compared with that obtained from ϕ as per IS:6403. Likewise, the net safe settlement pressure determined from IS:8009 (Part 1), based on N, is compared with that attained from the semi-empirical approach of Schmertmann et al. A parametric study quantifies the effects of the standard penetration resistance and the size and depth of foundation on the net safe bearing capacity and the net safe settlement pressure of strip, square, circular footings and raft foundations in sand. Interactive charts are prepared in terms of the standard penetration resistance to highlight the appropriate method for the benefit of civil engineers.

Keywords Bearing capacity · Standard penetration resistance · Angle of shearing resistance · Shallow foundation

Introduction

Over the past two to three decades, in situ tests have gained preference over laboratory tests for delineation of site stratigraphy and estimation of geotechnical design parameters. This has occurred for several reasons. Firstly, in situ tests can be performed relatively faster than costly laboratory tests. Secondly, the quality of disturbed or undisturbed (UD) soil samples, extracted from the field and brought to the laboratory for testing, depends on the tools employed in their retrieval and the expertise of the people chosen for logging the samples. Among the various in situ tests, the Standard Penetration Test (SPT) is widely used in India and in many countries around the world for site exploration and ground characterization. The SPT is a relatively crude test, whose essence is to drive a standard split-spoon sampler, 45 cm into the soil, by the blows of a 63.5 kg hammer falling from a height of 75 cm [1]. The 45-cm penetration is divided into three separate advances of 15 cm each. The standard penetration resistance, N, is obtained by adding the number of blows required for the penetration of the sampler through the final 30 cm into the soil, after discarding the blow count for the initial 15 cm seating drive. The greater the N value, the stronger and stiffer the soil is expected to be. Most soil investigation agencies in India prefer to carry out SPT in sandy soils instead of extracting UD samples for laboratory testing.

The most important shear strength parameter that controls the bearing capacity of shallow foundations in sand is the angle of shearing resistance, ϕ, which can be estimated either directly from laboratory direct shear and drained triaxial compression test results [2–5], or indirectly from correlation with N [6]. Correlations of the net safe bearing capacity, q_{ns}, and the net safe settlement pressure, q_{nssp}, with N are widely used in the design of shallow

---

✉ V. A. Sakleshpur
svabhi.92@gmail.com

[1] Department of Civil Engineering, Andhra University, Visakhapatnam, India

Published online: 02 November 2017

foundations in sand [7–9]. Indian standard code IS:6403 [6] specifies a chart between N and ϕ for different categories of soil compactness (Fig. 1), and recommends the calculation of q_{ns} using the value of ϕ obtained from the chart. However, there exists some confusion among geotechnical engineers and consultants on whether to estimate q_{ns} directly from N [7] or indirectly from ϕ [6] for shallow foundations in sand. Also, no investigation has been reported so far in the literature to address this issue.

This work attempts to fill the above gap in the literature through an analytical parametric study performed to compare q_{ns} estimated directly from N using the empirical equations proposed by the researcher [7], against that computed from ϕ (obtained based on N) as per IS:6403 [6], for strip, square, circular footings and raft foundations in sand. Similarly, q_{nssp} determined from IS:8009 (Part 1) [8], based on N, is compared with that obtained from the well-known semi-empirical approach of [9]. The reason for selecting the methods of IS:6403 [6], and IS:8009 (Part 1) besides several others reported in the literature, is because these methods are commonly used by geotechnical engineers in India for estimation of q_{ns} and q_{nssp} of shallow foundations in sand [7–9]. In this study, the size, shape and depth of foundation are varied for N values ranging from 10 (loose sand) to 40 (dense sand). Interactive charts are prepared in terms of N to highlight the appropriate method for estimation of q_{ns} and q_{nssp} of shallow foundations in sand for the benefit of civil engineers. The lesser of the values of q_{ns} and q_{nssp} is defined as the net allowable bearing capacity, q_{na}, which is eventually used in shallow foundation design.

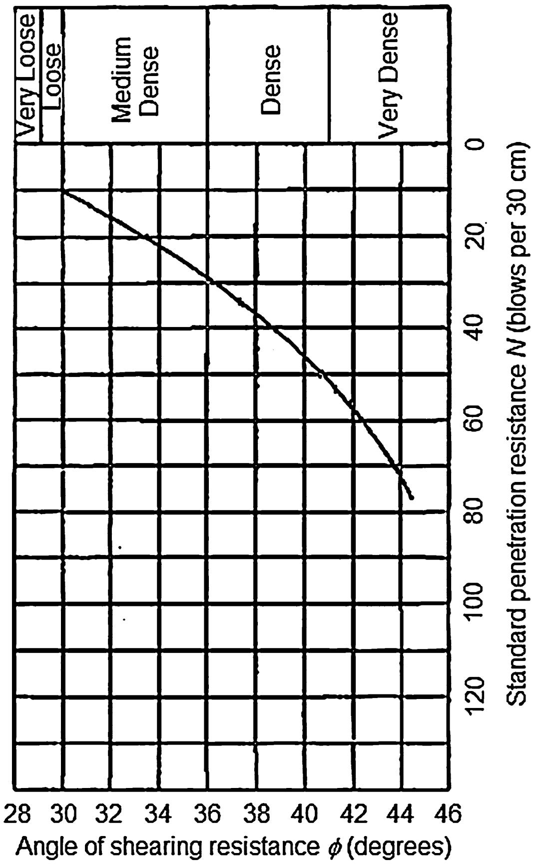


Fig. 1 Standard penetration resistance, N, against the angle of shearing resistance, ϕ. (Modified from [6])

Expressions for Net Safe Bearing Capacity and Net Safe Settlement Pressure

Table 1 summarizes the expressions adopted in this study for estimation of net ultimate bearing capacity, q_{nu}, net safe bearing capacity, q_{ns}, and net safe settlement pressure, q_{nssp}, of isolated footings (strip, square and circular footings) and raft foundations in sand from N and ϕ. It should be noted that the equations proposed by Teng [7] and IS:8009 Part 1 [8] are empirical equations, whereas the equation proposed by Schmertmann et al. [9] is semi-empirical in nature. Referring to Table 1, the expressions for the water table correction factors, R_{w1} and R_{w2}, are given by

$$R_{w1} = 0.5\left(1 + \frac{z_{w1}}{D_f}\right) \leq 1.0 \tag{1}$$

$$R_{w2} = 0.5\left(1 + \frac{z_{w2}}{B}\right) \leq 1.0 \tag{2}$$

where z_{w1} and z_{w2} are the depths (m) of the groundwater table measured from the ground surface and the foundation base, respectively.

In the equation of IS:6403 [6], W' is a water table correction factor, whose value lies between 0.5 and 1.0. $W' = 0.5$ if the groundwater table is located at, or above, the foundation base; whereas $W' = 1.0$ if the groundwater table is located at, or below, a depth of $(D_f + B)$ measured from the ground surface. W' can be linearly interpolated between 0.5 and 1.0 if the groundwater table lies in-between the aforesaid depths. The shape factors, s_c, s_q and s_γ, the depth factors, d_c, d_q and d_γ, and the inclination factors, i_c, i_q and i_γ, are listed in IS:6403 [6]. It should be noted that the depth factors, d_c, d_q and d_γ, and the inclination factor, i_γ, are functions of the angle of shearing resistance, ϕ. The bearing capacity factors, N_c, N_q and N_γ, also depend on ϕ as follows [11]

$$N_q = \tan^2\left(45^\circ + \frac{\phi}{2}\right)\exp(\pi \tan\phi) \tag{3}$$

$$N_c = (N_q - 1)\cot\phi \tag{4}$$

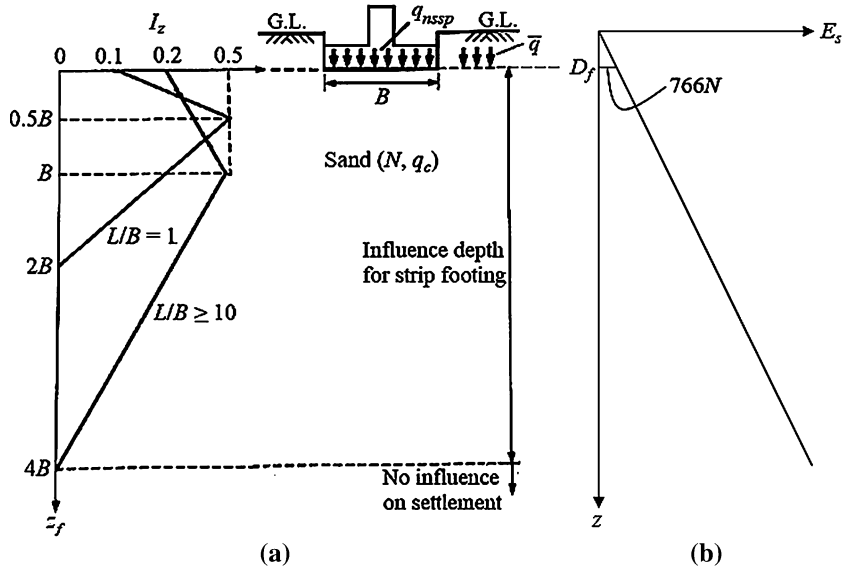
$$N_\gamma = 2(N_q + 1)\tan\phi \tag{5}$$

Table 1 Expressions for net ultimate bearing capacity, q_{nu}, net safe bearing capacity, q_{ns}, and net safe settlement pressure, q_{nssp}, adopted in this study

References	Type of foundation	Equation	Remarks
Teng [7]	a. Isolated footing b. Raft foundation	$q_{nu} = \frac{1}{6}\left[C_1 N^2 B R_{w2} + C_2(100 + N^2) D_f R_{w1}\right]$ $q_{ns} = 0.22N^2 B R_{w2} + 0.67(100 + N^2) D_f R_{w1}$	1. $C_1 = 3$ and $C_2 = 5$ for strip footing 2. $C_1 = 2$ and $C_2 = 6$ for square and circular footings 3. If the value of D_f exceeds the value of B, then it is recommended that D_f be restricted to B
IS:6403 [6]	a. Isolated footing and raft foundation	$q_{nu} = cN_c s_c d_c i_c + \bar{q}(N_q - 1)s_q d_q i_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma W'$ (for GSF) $q_{nu} = \frac{2}{3} cN'_c s_c d_c i_c + \bar{q}(N'_q - 1)s_q d_q i_q + 0.5\gamma B N'_\gamma s_\gamma d_\gamma i_\gamma W'$ (for LSF)	1. GSF = general shear failure ($\phi > 36°$) 2. LSF = local shear failure ($\phi < 29°$) 3. $q_{ns} = q_{nu}$/FS, where FS = factor of safety
IS:8009 Part 1 [8]	a. Isolated footing b. Raft foundation	$q_{nssp} = 1.385(N - 3)\left(\frac{B+0.3}{2B}\right)^2 R_{w2} s_a$ $q_{nssp} = 0.391(N - 3) R_{w2} s_a$	1. Allowable settlement, s_a, is equal to 50 mm for isolated footing and 75 mm for raft foundation in sand [10] 2. Both the q_{nssp} equations are independent of D_f
Schmertmann et al. [9]	a. Isolated footing and raft foundation	$q_{nssp} = \frac{s_a}{T\sum_{i=0}^{2B,4B} \frac{I_{zi}}{E_{si}} \Delta z_i} + 0.5\bar{q}$	1. Time factor, $T = 1 + 0.2\log_{10}(t/0.1)$, where t = time period for settlement analysis (years)

Isolated footing includes strip, square and circular footings; B = width/diameter of footing and least lateral dimension of raft foundation m, D_f = depth of foundation below ground surface (m); R_{w1}, R_{w2}, W' = water table correction factors, c = cohesive intercept kPa, $\bar{q}$ = initial effective overburden pressure at foundation base, kPa, γ = moist unit weight of soil kN/m^3; N_c, N_q, N_γ = bearing capacity factors = $f(\phi)$ [11]; s_c, s_q and s_γ = shape factors [6]; d_c, d_q and d_γ = depth factors [6]; i_c, i_q and i_γ = inclination factors [6]; N_c', N_q' and N_γ' = modified bearing capacity factors for local shear failure = $f(\phi_m)$ [11]; ϕ_m = mobilized angle of shearing resistance = $\text{Tan}^{-1}[(2/3)\tan\phi]$; I_{zi} = strain influence factor for each sublayer, i; Δz_i = thickness of each sublayer, m and E_{si} = representative Young's modulus of each sublayer, kPa

Fig. 2 **a** Strain influence factor diagrams for square/circular footing ($L/B = 1$) and strip footing ($L/B \geq 10$) (modified from [9]), and **b** E_s against depth profile assumed in this study



The modified bearing capacity factors, N_c', N_q' and N_γ', for LSF mode can be obtained by replacing ϕ with the mobilized angle of shearing resistance, ϕ_m. The mobilized angle of shearing resistance is expressed as [6]

$$\phi_m = Tan^{-1}\left(\frac{2}{3}\tan\phi\right) \tag{6}$$

Bearing capacity factors for intermediate values of ϕ between 29° and 36° can be obtained by linear interpolation between LSF and GSF modes. It should be noted that for clean, uncemented sands, $c = 0$ and therefore the first term in the equations of IS:6403 [6] vanishes. With this in mind and normalizing the GSF equation of IS:6403 [6] with γB, the normalized net ultimate bearing capacity, q_{nu}*, of shallow foundations in sand for GSF mode is

$$q_{nu}^{*} = s_q d_q i_q (N_q - 1)\left(\frac{D_f}{B}\right) + 0.5 N_\gamma s_\gamma d_\gamma i_\gamma W' \quad (7)$$

Equation (7) can be extended for LSF mode by replacing N_q and N_γ with $N_q{}'$ and $N_\gamma{}'$, respectively, as discussed before. Furthermore, the values of d_q, d_γ, and i_γ for LSF mode can be obtained by replacing ϕ with ϕ_m in the general expressions of d_q, d_γ, and i_γ [6].

The researchers have [9] postulated that the settlement of shallow foundations in sand is mostly due to deformations or strains occurring within an influence depth measured from the foundation base (Fig. 2a). This depth, z_f, is taken as $2B$ for square and circular footings, and $4B$ for footings with length, L, equal to $10B$ or greater (strip footings). The depth of influence for rectangular footings and raft foundations with $1 < L/B < 10$ can be obtained by linear interpolation. Referring to Fig. 2a, the strain influence factor, I_z, for square and circular footings ($L/B = 1$) increases linearly from a minimum of 0.1 at the foundation base ($z_f = 0$) to a maximum of 0.5 at $z_f = 0.5B$, and then drops to zero at a depth equal to $2B$ below the foundation base. On the other hand, for strip footings with $L/B \geq 10$, I_z increases linearly from a minimum of 0.2 at the foundation base ($z_f = 0$) to a maximum of 0.5 at $z_f = B$, and then drops to zero at a depth equal to $4B$ below the foundation base. The foundation soil is divided into several sublayers based on either the standard penetration resistance, N, profile (obtained from SPT) or the cone penetration resistance, q_c, profile (obtained from Cone Penetration Test (CPT)). The modulus of elasticity, E_{si}, of each sublayer, i, can be estimated from the corresponding N or q_c value of that sublayer. The net safe settlement pressure, q_{nssp}, of the shallow foundation is then calculated by summing up the influences of all the sublayers.

Parametric Study

Interactive charts are developed for q_{ns} and q_{nssp}, in terms of N, for strip, square, circular footings and raft foundations embedded in loose to dense sand. Table 2 summarizes the values of N, B and D_f adopted in this study. The angles of shearing resistance corresponding to the N values adopted in this study are obtained from Fig. 1, and are tabulated in Table 3 along with the modes of failure of foundation soil. It should be noted that the N values reported in Tables 2 and 3 are the corrected N values, which are obtained after applying the overburden and dilatancy corrections to the recorded SPT data [1].

The following are the considerations made in the parametric study:

Table 2 Range of values considered in parametric study

Parameter	Values
Standard penetration resistance, N	10, 15, 20, 25, 30, 35, 40
Width/diameter of isolated footing, B	1.0, 1.5, 2.0 m for strip footing 1.5, 2.0, 2.5, 3.0 m for square and circular footings
Dimensions of raft foundation, $B \times L$	4.0 m × 8.0 m, 5.0 m × 10.0 m, 6.0 m × 12.0 m
Depth of foundation, D_f	1.5, 2.0, 2.5, 3.0 m

Table 3 Angles of shearing resistance corresponding to different N values

Standard penetration resistance, N	Angle of shearing resistance, ϕ (°)[a]	Mode of failure
10	30	Local shear failure[b]
15	32	Transition
20	33	Transition
25	35	Transition
30	36	General shear failure
35	37	General shear failure
40	39	General shear failure

[a] Obtained from Fig. 1

[b] For $N = 10$, sand is considered to exist in a relatively loose state, and therefore local shear failure is likely to occur

1. The groundwater table is located at a depth greater than the width of the foundation, measured below the foundation base. Thus, the water table correction factors, R_{w1}, R_{w2} and W', are equal to 1.
2. The load transferred to the foundation is vertical and uniformly distributed. Thus, the inclination factors, i_c, i_q and i_γ, are equal to 1.
3. The modulus of elasticity, E_s, of sand is equal to zero at the ground surface ($z = 0$) and increases linearly with depth, z, with a value equal to $766N$ [12] at the foundation base ($z = D_f$) (Fig. 2b).
4. The thickness, Δz_i, of each sublayer of sand below the foundation base is equal to 1 m.
5. The moist unit weight, γ, of sand is equal to 18 kN/m^3.
6. The factor of safety (FS) against risk of shear failure in foundation soil is equal to 3.
7. The permissible settlement, s_a, of an isolated footing and a raft foundation in sand are 50 and 75 mm, respectively [10].

8. The time period, t, for settlement analysis is equal to 50 years.

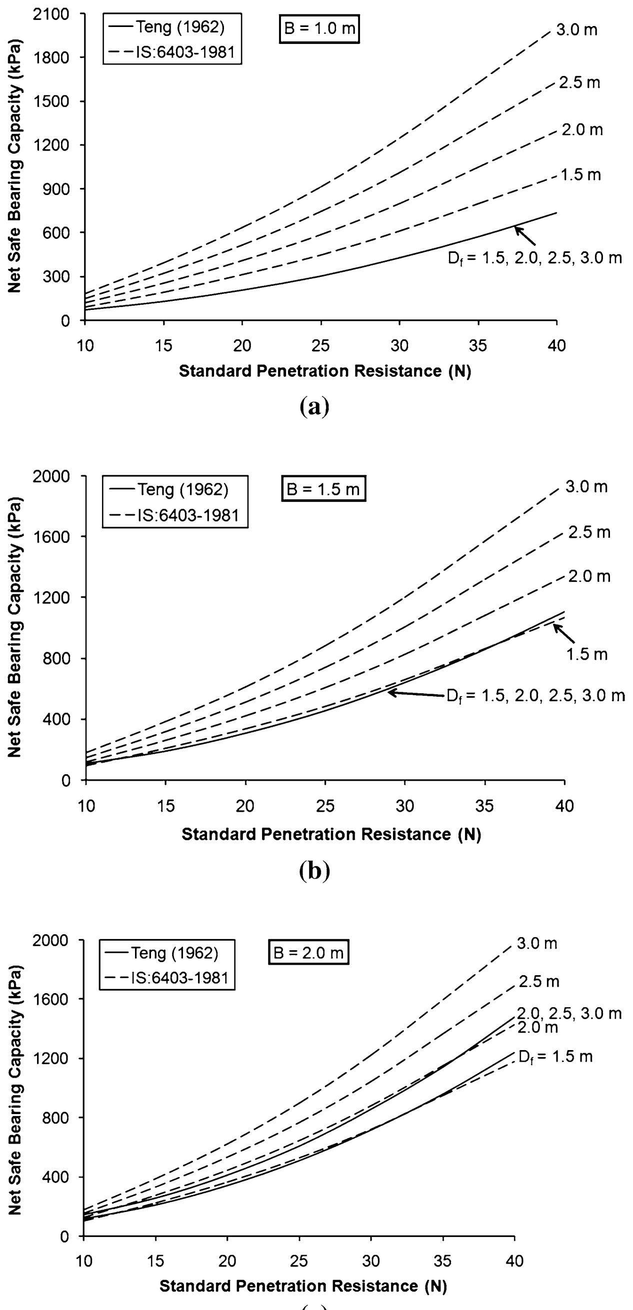
Results and Discussion

Net Safe Bearing Capacity of Strip, Square and Circular Footings

Figures 3, 4 and 5 show the variations of the net safe bearing capacity, q_{ns}, of strip, square and circular footings, respectively, with the standard penetration resistance, N, estimated from IS:6403 and Teng's equation for $B = 1.0$–3.0 m and $D_f = 1.5$–3.0 m. It is observed that q_{ns} increases non-linearly with N, because as N increases, the relative density, D_R, and the angle of shearing resistance, ϕ, of sand also increase. Furthermore, q_{ns} increases with B because wider footings mobilize larger and deeper slip mechanisms, which imply larger effective stresses and thus, greater shear resistance. The net safe bearing capacity of strip and square footings (Figs. 3, 4) estimated from Teng's equation based on N, compares well with that predicted from IS:6403 based on ϕ, for $D_f/B \le 1$. However, for $D_f/B > 1$, Teng's equation gives conservative estimates of q_{ns} due to the restriction of the value of D_f to that of B when D_f exceeds B. In the case of circular footings (Fig. 5), q_{ns} calculated from IS:6403 is in good agreement with that computed from Teng's equation for $D_f/B \le 1$ and $N \le 25$. However, for N values ranging from 25 to 40, IS:6403 gives conservative estimates of q_{ns}, perhaps due to the 25% reduction in shape factor, s_γ, from 0.8 (for square footing) to 0.6 (for circular footing), whereas in Teng's equation, the size and surcharge coefficients, C_1 and C_2, respectively, are the same for both square and circular footings (Table 1).

Net Safe Bearing Capacity of Raft Foundation

Figure 6 presents the variations of the net safe bearing capacity, q_{ns}, of raft foundations with the standard penetration resistance, N, estimated from IS:6403 and Teng's equation for $B \times L = 4.0 \text{ m} \times 8.0 \text{ m}$, $5.0 \text{ m} \times 10.0 \text{ m}$ and $6.0 \text{ m} \times 12.0 \text{ m}$, and $D_f = 1.5$–3.0 m. It is observed that Teng's equation overestimates the net safe bearing capacity of the raft when compared to that of IS:6403. This is because the equation of IS:6403 explicitly accounts for the shape of the raft through the aspect ratio, B/L, whereas Teng's equation does not. The net safe bearing capacity of the raft estimated from Teng's equation is 1.8–2.4 times greater than that computed from IS:6403. Hence, the equation of IS:6403 is more appropriate for estimation of the net safe bearing capacity of the rafts under study, as it is relatively conservative.



(a)

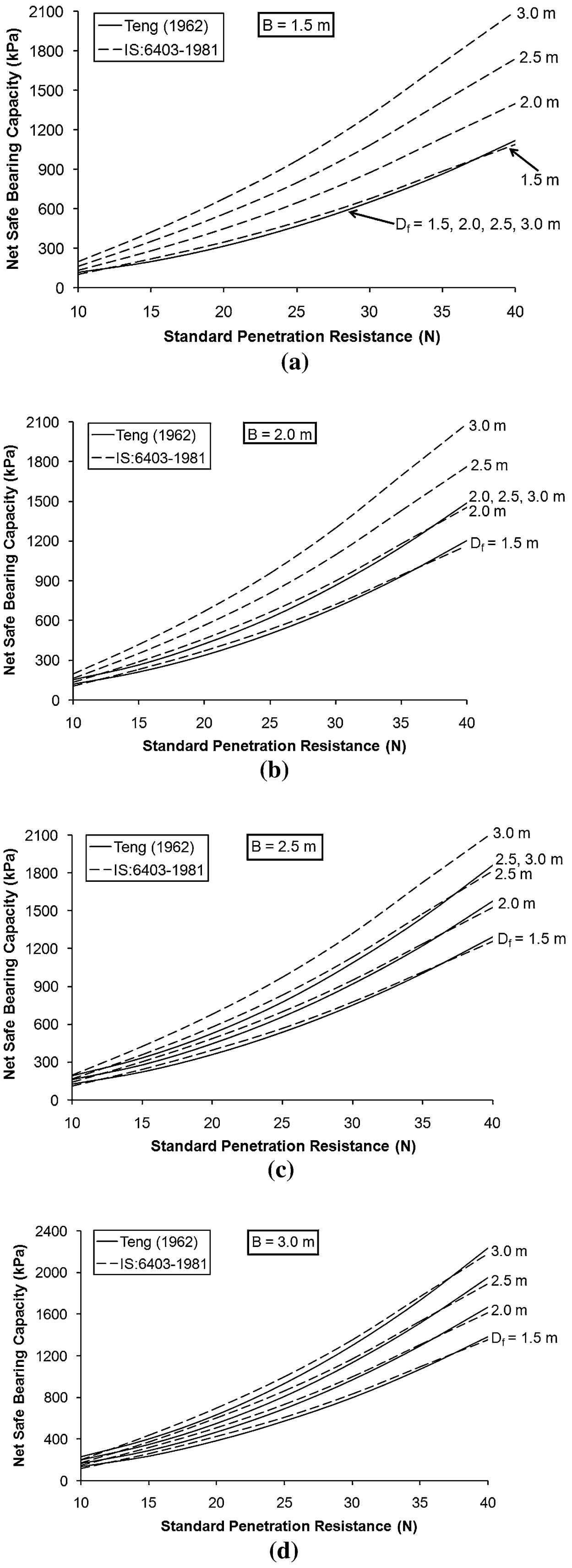
(b)

(c)

Fig. 3 q_{ns} against N for strip footing—effect of D_f for: **a** $B = 1.0$ m, **b** $B = 1.5$ m, and **c** $B = 2.0$ m

Net Safe Settlement Pressure of Strip, Square and Circular Footings

Figures 7 and 8 depict the variations of the net safe settlement pressure, q_{nssp}, of strip and square/circular footings, respectively, with the standard penetration resistance,



(a)

(b)

(c)

(d)

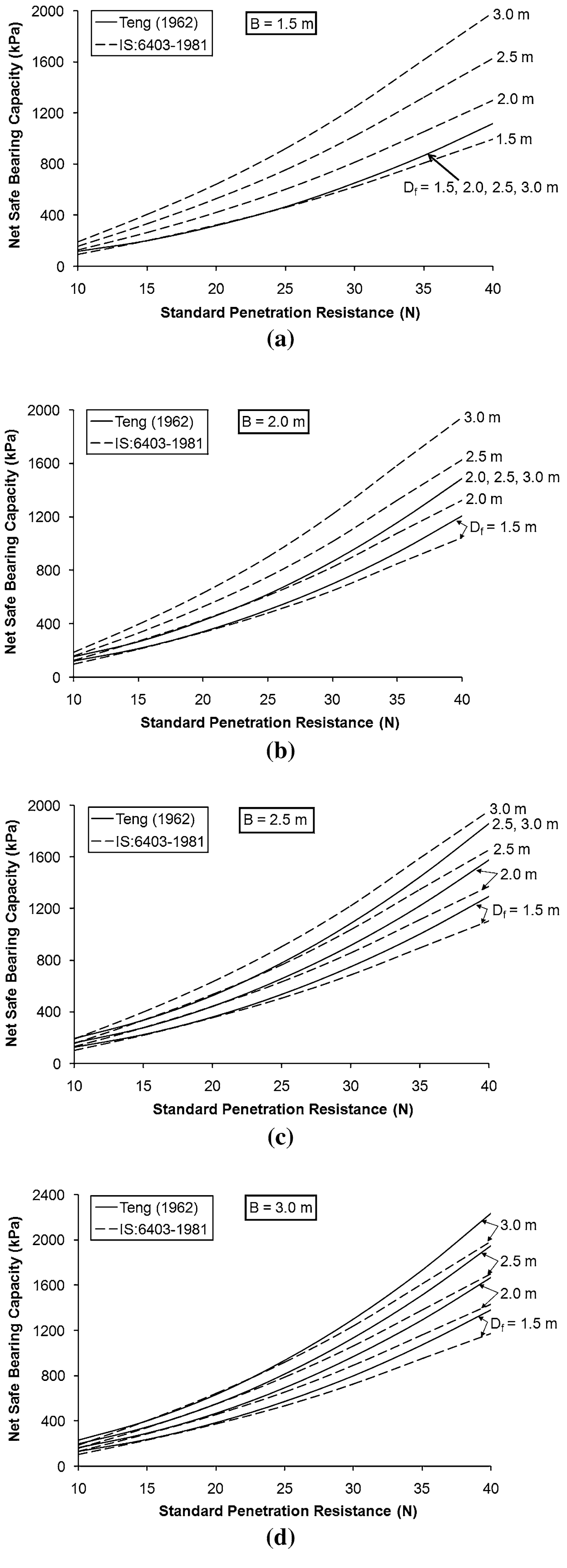
◀**Fig. 4** q_{ns} against N for square footing—effect of D_f for: **a** $B = 1.5$ m, **b** $B = 2.0$ m, **c** $B = 2.5$ m, and **d** $B = 3.0$ m

N, estimated from IS:8009 (Part 1) and Schmertmann et al.'s equation for $B = 1.0$–3.0 m and $D_f = 1.5$–3.0 m. The compressibility of sand decreases with increase in N value and thus, the footing can sustain greater bearing stresses for the same magnitude of settlement. Referring to Figs. 7 and 8, it is observed that q_{nssp} estimated from IS:8009 (Part 1) is independent of D_f. However, q_{nssp} predicted from the semi-empirical approach of Schmertmann et al., decreases with increase in D_f due to the reduction in E_s at any given depth below the base of the footing. The reduction in E_s is attributed to the consideration of a linear E_s versus depth profile with a fixed E_s value of $766N$ at the base of the footing, regardless of where the footing is embedded (Fig. 2b). In other words, for E_s to be always equal to $766N$ at the base of the footing, the slope of the E_s versus depth profile becomes steeper as D_f increases.

The difference between the net safe settlement pressures, estimated from the equations of Schmertmann et al. and IS:8009 (Part 1), is minimum for relatively wide/large diameter footings located at relatively deeper depths in dense sand, but is maximum for relatively narrow/small diameter footings located at relatively shallower depths in loose to medium dense sand. Due to the absence of a depth factor [13], IS:8009 (Part 1) gives very conservative estimates of q_{nssp} for strip and square/circular footings in sand when compared to the approach of Schmertmann et al. If a depth factor of magnitude greater than 1 is incorporated into the equation of IS:8009 (Part 1), then the corresponding net safe settlement pressure of the footing would be closer to that predicted from the approach of Schmertmann et al.

Net Safe Settlement Pressure of Raft Foundation

Figure 9 illustrates the variations of the net safe settlement pressure, q_{nssp}, of raft foundations with the standard penetration resistance, N, estimated from IS:8009 (Part 1) and Schmertmann et al.'s equation for $B \times L = 4.0\ \text{m} \times 8.0\ \text{m}$, $5.0\ \text{m} \times 10.0\ \text{m}$ and $6.0\ \text{m} \times 12.0\ \text{m}$, and $D_f = 1.5$–3.0 m. It is observed that IS:8009 (Part 1) underestimates the net safe settlement pressure of the raft by as much as 44% of that computed from Schmertmann et al.'s approach. Comparing Figs. 6 and 9, it is clearly visible that the net safe bearing capacity of a raft foundation in sand (based on stability criterion) is about 2–3 times greater than the net safe settlement pressure (based on serviceability criterion). This is attributed to the significant contribution from the third term of the bearing capacity



◀**Fig. 5** q_{ns} against N for circular footing—effect of D_f for: **a** $B = 1.5$ m, **b** $B = 2.0$ m, **c** $B = 2.5$ m, and **d** $B = 3.0$ m

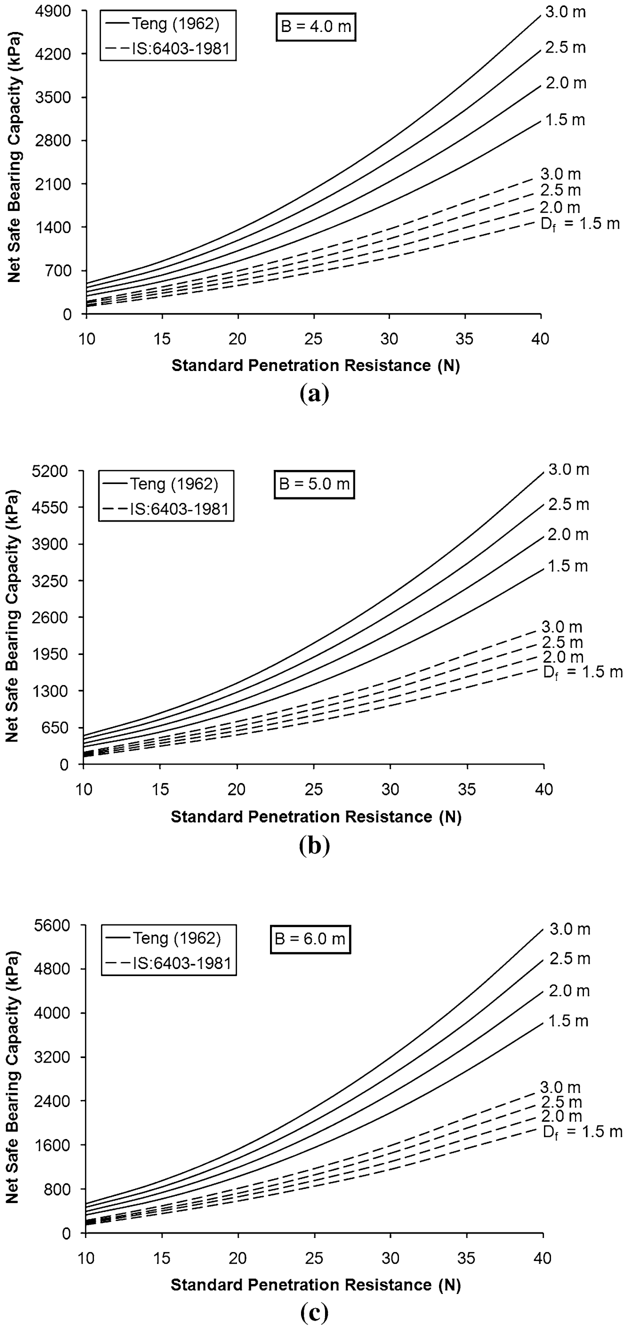
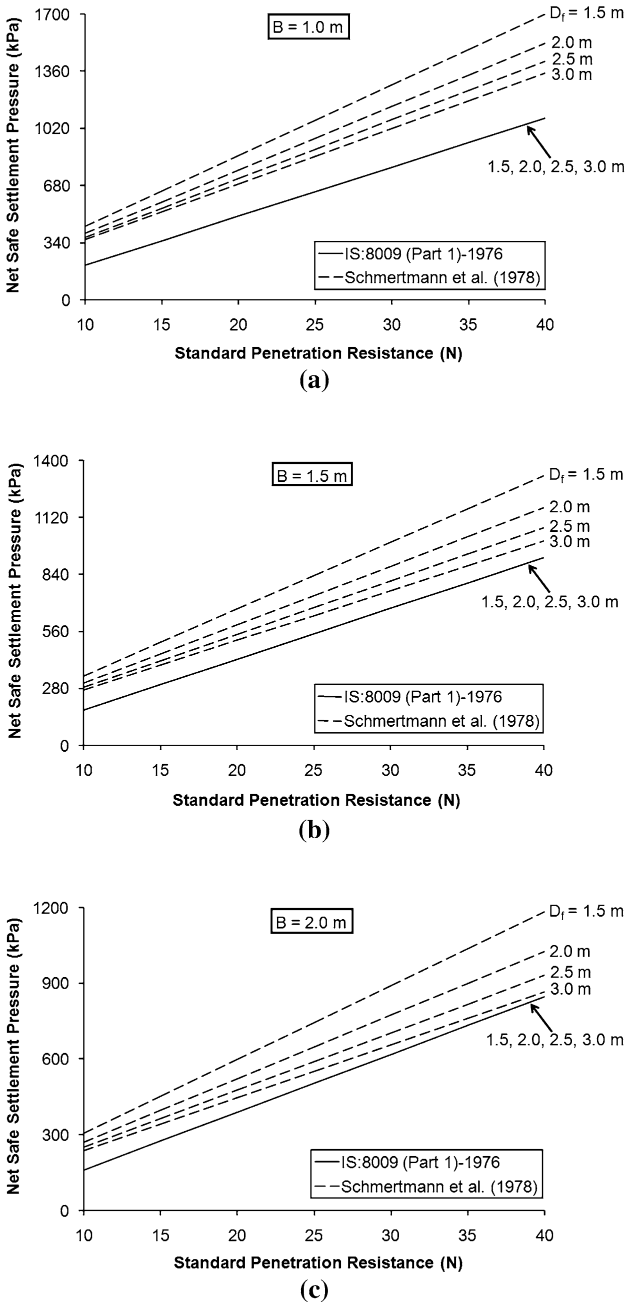


Fig. 6 q_{ns} against N for raft foundation—effect of D_f for: **a** $B = 4.0$ m, **b** $B = 5.0$ m, and **c** $B = 6.0$ m

equation ($0.5\gamma BN_\gamma s_\gamma d_\gamma i_\gamma W'$) owing to the relatively large width of the raft. Therefore, the equation of IS:8009 (Part 1) is to be used for estimation of the net allowable bearing



(a)

(b)

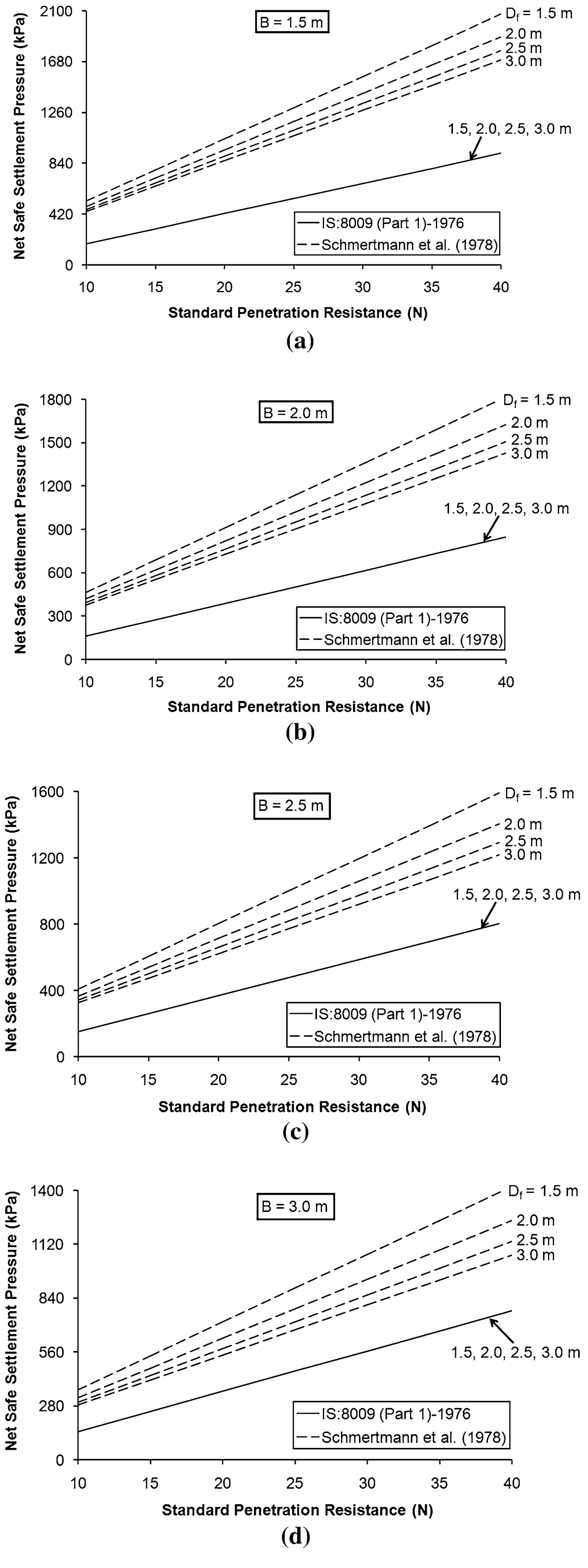
(c)

Fig. 7 q_{nssp} against N for strip footing—effect of D_f for: **a** $B = 1.0$ m, **b** $B = 1.5$ m, and **c** $B = 2.0$ m

capacity of a raft foundation in sand, as it yields relatively conservative values. However, it would be reasonable to revise the equation of IS:8009 (Part 1) and improve its accuracy based on results obtained from plate load tests in sands of different relative densities.

Non-dimensional Charts

The equations proposed by Teng [7], IS:8009 (Part 1) [8] and Schmertmann et al. [9] are either empirical or semi-



(a)

(b)

(c)

(d)

Fig. 8 q_{nssp} against N for square and circular footings—effect of D_f for: **a** $B = 1.5$ m, **b** $B = 2.0$ m, **c** $B = 2.5$ m, and **d** $B = 3.0$ m

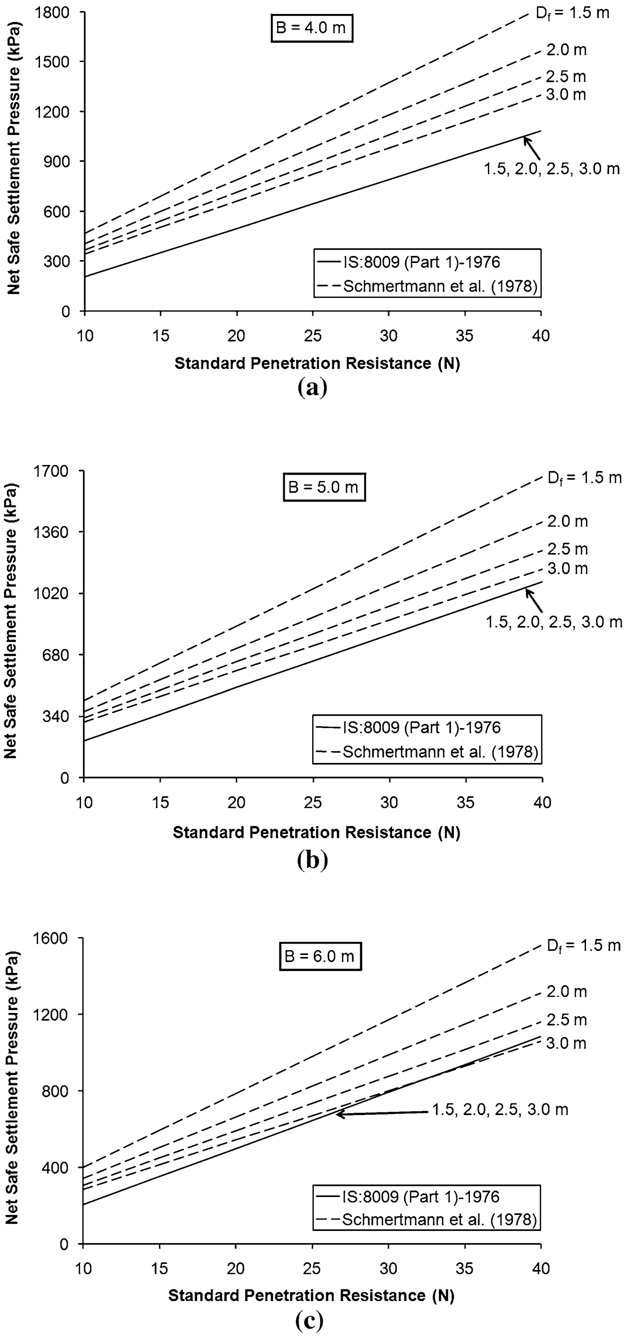


Fig. 9 q_{nssp} against N for raft foundation—effect of D_f for: **a** $B = 4.0$ m, **b** $B = 5.0$ m, and **c** $B = 6.0$ m

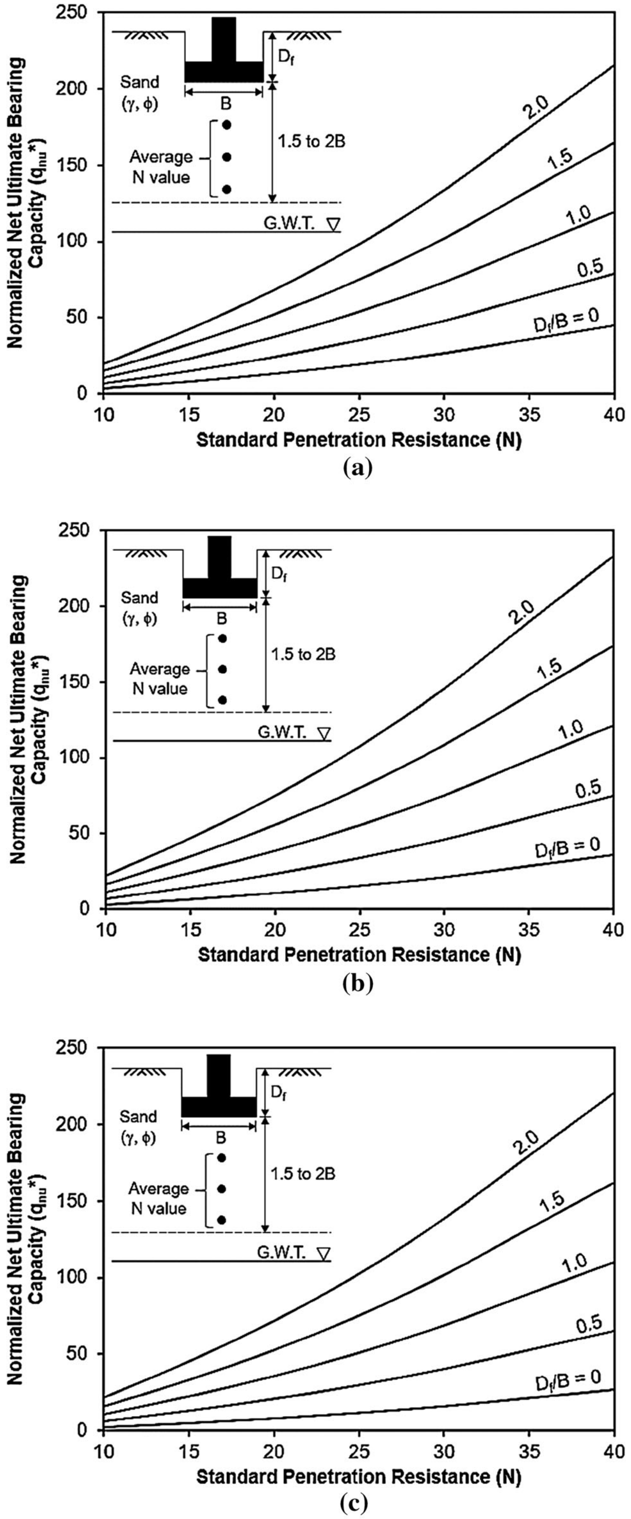


Fig. 10 Non-dimensional charts for q_{nu}* against N—effect of D_f/B for: **a** strip footing, **b** square footing, and **c** circular footing

empirical in nature, and are therefore difficult to normalize. However, the equation of IS:6403 [6] is an extension of Terzaghi's bearing capacity theory [14], which is developed considering the vertical force equilibrium of a rigid/elastic soil wedge beneath the footing, and can therefore be normalized with the parameter γB (Eq. 7). Non-dimensional charts for strip, square, circular footings and raft foundations in sand are developed in terms of normalized net ultimate bearing capacity, q_{nu}*, standard penetration resistance, N, normalized depth of foundation, D_f/B, and aspect ratio, B/L, of foundation for the benefit of civil

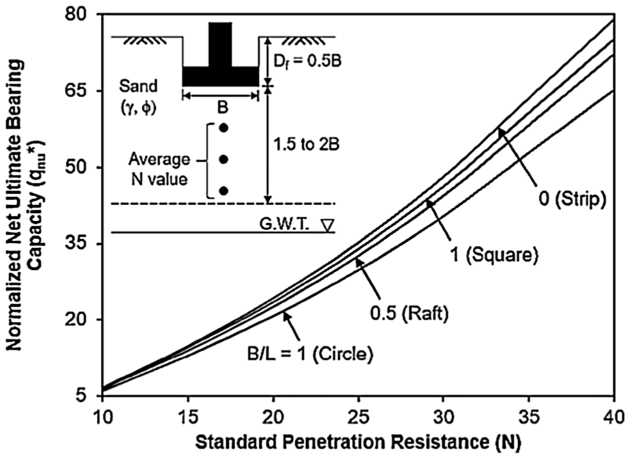


Fig. 11 q_{nu}* versus N—effect of shape of foundation

engineers (Figs. 10, 11). The D_f/B ratio is varied from 0 (surface footing) to 2 while the aspect ratio, B/L, is varied from 0 (strip footing) to 1 (square and circular footings).

Figure 10 can be used to estimate q_{nu}* of strip (Fig. 10a), square (Fig. 10b) and circular (Fig. 10c) footings in sand for any value of γ, any value of N between 10 and 40, and any D_f/B ratio between 0 and 2. It should be noted that the standard penetration resistance, N, must be determined at vertical intervals of 75 cm between the level of the foundation base and a depth equal to 1.5–2 times the width of the foundation [6]. These discrete N values should then be averaged and corrected to obtain a single representative N value for the entire sand layer. The N values plotted along the horizontal axes in Figs. 10 and 11 are representative of the entire sand layer. The net ultimate bearing capacity, q_{nu}, of the shallow foundation can be determined by multiplying q_{nu}* with γB. Thereafter, the net safe bearing capacity, q_{ns}, can be determined by dividing q_{nu} with a suitable factor of safety.

Figure 11 shows the effect of shape of foundation on the normalized net ultimate bearing capacity, q_{nu}*, for $D_f/B = 0.5$. Among the four types of shallow foundations investigated in this study, i.e., strip footing ($B/L = 0$), raft foundation ($B/L = 0.5$), and square and circular footings ($B/L = 1$), it is observed that q_{nu}* is maximum for a strip footing and is minimum for a circular footing. This is mainly due to the way the shape factor, s_γ, is expressed. s_γ is equal to 1.0 for a strip footing, 1–0.4(B/L) for a rectangular footing or raft, 0.8 for a square footing and 0.6 for a circular footing [6]. Therefore, the larger the value of s_γ, the greater the bearing capacity of shallow foundation in sand is expected to be. The influence of the shape of foundation on the magnitude of q_{nu}* is more pronounced for shallow foundations in dense sand when compared to those in loose sand.

Conclusions

Based on the results obtained from the comparative analytical study on bearing capacity of shallow foundations in sand from N and ϕ, the following conclusions are drawn:

1. The net safe bearing capacity of strip and square footings, for $D_f/B \leq 1.0$ and $N = 10$–40, and circular footings, for $D_f/B \leq 1.0$ and $N = 10$–25, in sand, can be estimated directly from N using Teng's equation, without having to do so from ϕ as per IS:6403.
2. Teng's equation and the equation of IS:8009 (Part 1), both based on N, can be used to estimate the net safe bearing capacity and the net safe settlement pressure, respectively, of strip and square footings in sand corresponding to a given D_f/B ratio.
3. For determination of net safe settlement pressure of circular footings in sand, the equation specified by IS:8009 (Part 1) is a conservative option over that of Schmertmann et al.'s approach.
4. The equation of IS:6403 based on ϕ, and the equation of IS:8009 (Part 1) based on N, are suggested for estimation of net safe bearing capacity and net safe settlement pressure, respectively, of the rafts under study.
5. It would be reasonable to revise the equation of IS:8009 (Part 1) for estimation of net safe settlement pressure of isolated footings and raft foundations in sand by performing plate load tests in sands with different relative densities.
6. The framework adopted in this study can be extended to evaluate various methods for estimation of: (a) bearing capacity of shallow foundations from cone penetration resistance, q_c, and (b) limit shaft resistance and ultimate base resistance of pile foundations in sand and clay.

References

1. IS:2131, Method for standard penetration test for soils. Bureau of Indian Standards, New Delhi, India (1981)
2. T. Schanz, P.A. Vermeer, Angles of friction and dilatancy of sand. Geotechnique **46**(1), 145–151 (1996)
3. R. Salgado, P. Bandini, A. Karim, Shear strength and stiffness of silty sand. J. Geotechn. Geoenviron. Eng. ASCE **126**(5), 451–462 (2000)
4. J.A.H. Carraro, M. Prezzi, R. Salgado, Shear strength and stiffness of sands containing plastic or nonplastic fines. J. Geotechn. Geoenviron. Eng. ASCE **135**(9), 1167–1178 (2009)
5. T. Chakraborty, R. Salgado, Dilatancy and shear strength of sand at low confining pressures. J. Geotechn. Geoenviron. Eng. ASCE **136**(3), 527–532 (2010)

6. IS:6403, Code of practice for determination of bearing capacity of shallow foundations. Bureau of Indian Standards, New Delhi, India (1981)
7. W.C. Teng, *Foundation Design* (Wiley, New York, 1962)
8. IS:8009-Part 1, Code of practice for calculation of settlement of foundations: shallow foundations subjected to symmetrical static vertical loads. Bureau of Indian Standards, New Delhi, India (1976)
9. J.H. Schmertmann, J.P. Hartman, P.R. Brown, Improved strain influence factor diagrams. J. Soil Mech. Found. Div. ASCE **104**(8), 1131–1135 (1978)
10. IS:1904, Code of practice for design and construction of foundations in soils: general requirements. Bureau of Indian Standards, New Delhi, India (1986)
11. A.S. Vesic, Analysis of ultimate loads of shallow foundations. J. Soil Mech. Found. Div. ASCE **99**(1), 45–73 (1973)
12. J.H. Schmertmann, Static cone to compute static settlement over sand. J. Soil Mech. Found. Div. ASCE **96**(3), 1011–1043 (1970)
13. K.R. Arora, *Soil Mechanics and Foundation Engineering* (Standard Publishers Distributors, New Delhi, 2004)
14. K. Terzaghi, *Theoretical Soil Mechanics* (Wiley, New York, 1943)