Research Article

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Improved correlation of soil modulus with SPT *N* values

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Abstract: Determining soil "*E*" (modulus of deformation) value has been a persistent challenge in geotechnical engineering. Existing correlations between "*E*" and SPT (standard penetration test) "*N*" values for granular soils yield a notably broad spectrum of "*E*" values, leading to uncertainty and subjectivity in design. A comprehensive review of these correlations reveals significant limitations, such as limited data, small-scale or indirect tests, and other constraints. The present study highlights the deficiencies inherent in existing correlations and proposes a reliable correlation for granular soils. The present study utilizes the results of numerous large-scale load tests conducted on RCC (reinforced cement concrete) foundations resting on granular soils, at various locations in India and at a refinery site in Nigeria. These tests totalling 85 in number serve as a basis for developing an improved and reliable *E*–*N* correlation for granular soils. Soil "*E*" values (secant) were back-calculated for each footing load test result and correlated with SPT "*N*" values. The correlation presented in this article is based on a sound large database and yields higher "*E*" values than those predicted by most available correlations. This advancement will lead to substantial cost savings and enhanced reliability in the design of foundations and substructures.

Keywords: modulus (*E*), SPT, *N* values, design of foundations, large-scale footing, *E*–*N* correlation

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List of notations

B	Footing width (m)
C	Clay content (%)
D	Footing depth below the original ground (m)
E	Soil modulus of deformation (kN/m^2)
E_M	Constrained modulus (kN/m^2)
G	Gravel content (%)
G.W.T	Depth to the groundwater table (m)
I_f	Depth factor
I_s	Steinbrenner influence factor
LL	Liquid limit (%)
M	Silt content (%)
N	Field SPT N value
PL	Plastic limit (%)
q_0	Footing pressure (kN/m^2)
S	Sand content (%)
μ	Poisson's ratio

1 Introduction

In geotechnical engineering, accurately determining soil parameters from field tests is vital for the design process. Standard penetration test (SPT) is one of the most widely employed field tests for assessing the engineering properties of soil. In this test, a standard size sampler is driven into the ground by the impact of a standard hammer, and the number of blows required to drive the sampler into the ground to a depth of 30 cm is known as the SPT *N* value. This value is then used to estimate the engineering properties of soil, including the crucial soil modulus (*E*), using correlations available in the literature. The "*E*" value is the slope of the stress–strain graph and is a measure of soil's compressibility (strain) under the application of a load. It plays a pivotal role in predicting soil/ground deformation.

Numerous correlations exist in the literature for determining "*E*" from "*N*." However, these correlations present a significantly wide range of "*E*" values, lacking guidance on which correlation to use in design. Consequently, practitioners adopt different correlations resulting in wide variations in outcomes and often overly conservative designs. A detailed review of available correlations reveals that these correlations have been derived from limited data, indirect tests, and small-scale tests or are afflicted by other limitations. The deficiencies of these correlations are summarized in Table 1 and discussed in Section 2 (past studies) of this article.

It is imperative to develop a new, reliable correlation based on representative tests and ample data. This study utilizes a large database of load tests conducted on reinforced cement concrete (RCC) footings resting on granular soils to establish a reliable correlation between "*E*" and "*N*" values. The proposed correlation offers the potential for significant cost reductions in the design of foundations and substructures.

2 Past studies

A number of *E* and SPT *N* correlations (>40) for granular soils have been published over the past 60 years. Figure 1 provides a graphical presentation of currently available correlations of *E*–*N* values for granular soils. The limitations of these correlations are summarized in Table 1, revealing that these correlations are either based on non-representative indirect tests, small-scale tests, and limited data or possess other constraints.

Most of these correlations are best-fit lines with data exhibiting notable scatter. As noted by Kulhawy and Mayne [1], all existing *E*–*N* correlations exhibit considerable scatter. Furthermore, Table 1 reveals that several correlations (correlations 1, 3, 4, 18, 23, and 32) rely on laboratory experiments, which can potentially yield inaccurate outcomes in granular soils due to the relatively small size of specimens (<100 mm) and inherent disturbances during sampling and testing. Schultze and Melzer [2] affirmed that the *E* values acquired from the earlier *E*–*N* correlation (Correlation 1) by Schultze and Menzenbak [3], derived from laboratory tests, suffer from deficiencies due to sample disturbance. Nonetheless, the subsequent correlation (Correlation 4) introduced by Schultze and Melzer [2] relied on indirect methods using isotopic soundings and other correlations based on laboratory test data. Moreover, the *N* value of these correlations (Correlations 1 and 4) was obtained from the Dynamic Cone Penetration Test and not from the SPT. Chaplin [4] introduced a correlation (Correlation 3) using the fine sand and silt data from Schultze and Menzenbak [3], with all the limitations of Correlation 1 also implicitly applicable to this correlation.

A number of correlations presented in Table 1 are based on relatively small-scale tests or limited data. Correlations 5, 17, and 20 are based on screw plate tests with a screw diameter of 0.15–0.76 m. Correlations 7b and 16 are based on plate load tests with plate sizes of 0.3–0.76 m. Correlations 7a, 11, 15, 20, 22, 25, and 26 are based on a pressure meter test. Correlation 36 is based on a flat plate dilatometer test with a 0.06 m expandable membrane. One of the widely used correlations (Correlation 6), presented by D'Appolonia *et al.* [5], is based on foundation settlement data of compacted soil fill from a solitary site in USA. Rocha Filho's [6] correlation (Correlation 30) is based on three footing load tests conducted at a site in Brazil. Correlation 34, developed by Davie and Lewis [7], is based on foundation settlement records of only one chimney structure in England.

Two correlations (Correlations 29 and 33) rely on vertical load tests conducted on relatively long bored piles, which inherently involve various assumptions/approximations during analysis. A few correlations (Correlations 14, 19, 33, 35, and 41) are derived from the load test on driven piles, which are known to alter ground conditions during pile driving. In several correlations (Correlations 1, 3, 4, 6, 23, and 32), the constrained modulus "E_M" is designated as *E*, which is typically 20% lower than E_M.

The most noteworthy attempt to establish a reliable correlation (Correlation 31) was undertaken by Stroud [8]. This correlation is based on historical case records of foundation settlement along with SPT *N* values, documented by Burland and Burbridge [9]. The stress dependency was emphasized by plotting *E*–*N* values against q/q_{ult} in this correlation. However, as per the CIRIA report by CIRIA report 143 [10], the development of this correlation necessitated several assumptions. Further limitations of the basis of this correlation are mentioned against this correlation in Table 1.

A few correlations (Correlations 12, 13, and 21), which yield notably high *E* values, were developed by measuring the shear wave velocity in a cross-hole seismic test. Nonetheless, these correlations are only suitable for the assessment and design of sub-structures subjected to low-strain dynamic loads. According to Bowles [11], the dynamic *E* values are typically 2.5–4 times higher than the static *E* values, as indicated in graphs presented by Arango *et al.* [12]. The source or basis of some correlations (Correlations 8, 31, 38, 40, 42 to 48) was either unmentioned or could not be found in the literature.

Correlation 2, which is presented by Farrent [13], relies on load–settlement curves of Terzaghi and Peck (1948) [14]. Several authors, including the CIRIA report 143 [10], Anagnostopoulos and Papadopoulos [15], and Bowles [11], have stated these curves as being conservative.

Table 1: Existing previously published correlations of SPT N and E values for granular soil

Sr. no.		Soil type	Correlation (E in kN/m^2)	Basis/Limitations/Remarks	Contributors
1	1a	Fine sand	$E = 490(N + 14.5)$	(i) E is constrained tangent modulus (E_M).	Schultze and Menzenback [3]
	1b	Fine sand above the ground water table (G.W.T.)	$E = 5{,}200 + 330\,N$	(ii) E value is determined from laboratory oedometer tests. (iii) Schultze and Melzer (1965) noted that E values in this correlation are poor owing to sample disturbance.	
	1c	Fine sand below G.W.T.	$E = 7{,}100 + 490\,N$		
	1d	Sand	$E = 3{,}900 + 450\,N$	(iv) SPT (N) value was obtained from a standard dynamic cone penetrometer (blows per foot).	
	1e	Gravelly sand	$E = 4{,}300 + 1{,}180\,N$		
	1f	Sand and gravel	$E = 3{,}800 + 1{,}050\,N$	(v) Correlations are best-fit lines with scatter increasing for finer soils.	
	1g	Silty sand	$E = 2{,}400 + 530\,N$		
	1h	Silt (PI < 15%)	$E = 1{,}200 + 580\,N$		
	1i	Silt (PI > 15%)	$E = 400 + 1{,}150\,N$		
2	—	Sand	$E = 720\,(1 - \mu^2)\,N$	(i) Based on load–settlement curves proposed by Terzaghi and Peck (1948) [14]. Many contributors, including those in CIRIA report 143 [10] and Bowles [11], have referred to these curves as conservative.	Farrent [13]
3	—	Sand	$E^{\frac{4}{3}} = 44\,N$	(i) Correlation is developed based on data from Schultze–Menzenbak (Correlation 1) for fine sand and silt (PI < 15 %). (ii) All limitations outlined for Correlation 1 also pertain to this correlation.	Chaplin [4]
4	—	Dry sand	$E = (264.2 \log(N) - 263.4\,(q) + 375.6)\,\sigma^{\,0.522}$	(i) E is tangent-constrained modulus (E_M). (ii) N denotes blows from dynamic cone penetrometer tests. (iii) E determined in indirect manner from equations of Moussa derived by laboratory tests: $E = v\sigma^w$, where v is determined from the void ratio with the aid of isotopic soundings and $w = 0.522$.	Schultze and Melzer [2]
5	5a	Saturated sand	$E = 500\,(N + 15)$	(i) Based on screw plate load tests involving relatively small-sized circular plates (0.02-0.123 m^2) conducted below the water table.	Webb [16]
	5b	Clayey sand	$E = 330\,(N + 5)$		
	5c	For average profiles	$E = 400\,(N + 12)$		
6	6a	Sand, normally consolidated NC	$E = 755(N + 25)$	(i) E is a constrained modulus (E_M). (ii) Based on data from seven case records of bridge footing settlement. (iii) Cone penetration data converted to SPT ($N = q_c/4.5$). (iv) Often difficult to differentiate between NC and OC granular soils, to use the correlations. (v) Even soil with SPT N value of 66 has been considered as NC.	D'Appolonia [5]
	6b	Sand, over-consolidated (OC)	$E = 1{,}050\,N + 4{,}000$ (Equation by Bowles from the plot of D'Appolonia)	(i) E is secant-constrained modulus (E_M). (ii) Based on the measurement of footing settlements of a steel plant in Northern Indiana, USA, on natural dune sand and vibratory compacted sand. (iii) Often difficult to differentiate between NC and OC granular soils to use the correlations. (iv) Sudden increase in E value estimated using correlation 6b for OC soils compared to E value for NC soils obtained using Correlation 6a. The degree of consolidation in OC soils is not factored in Correlation 6b.	

(Continued)

Table 1: *Continued*

Sr. no.		Soil type	Correlation (E in kN/m^2)	Basis/Limitations/Remarks	Contributors
				(v) Data of dry sand with groundwater table lowered by dewatering. (vi) Correlation is based on data of a single site only.	
7	7a	Silty sand, sand, gravel	$E = 700\,N$	(i) Derived from results of pressure meter tests. (ii) E is the pressure meter modulus (E_p).	Yoshida and Yoshinaka [17]
	7b		$E = 2{,}100\,N$	(i) E is obtained from horizontal loading on square plates of 30 cm width. (ii) This E value was shown to be 3 E_p as evaluated in Correlation 7a.	
8	8a	Silt with sand	$E = 300\,(N + 6)$ for $N < 15$ $E = 4{,}000 + 300\,(N - 6)$ for $N > 15$	(i) Reported by Begemann [18] as used in Greece. (ii) Basis of this correlation is not provided in the report. (iii) Almost identical correlations were subsequently presented with the basis of formation, by contributors from Greece, Anagnostopoulos and Papadopoulos [15] for 3 different soil types.	Reported by Begemann [18] as being used in Greece
	8b	Fine sand	$E = 350\,(N + 6)$ for $N < 15$ $E = 4{,}000 + 350\,(N - 6)$ for $N > 15$		
	8c	Medium sand	$E = 450\,(N + 6)$ for $N < 15$ $E = 4{,}000 + 450\,(N - 6)$ for $N > 15$		
	8d	Coarse sand	$E = 700\,(N + 6)$ for $N < 15$ $E = 4{,}000 + 700\,(N–6)$ for $N > 15$		
	8e	Sand with gravel	$E = 1{,}000\,(N + 6)$ for $N < 15$ $E = 4{,}000 + 1{,}000\,(N - 6)$ for $N > 15$		
	8f	Gravelly sand	$E_S = 1{,}200\,(N + 6)$ for $N < 15$ $E = 4{,}000 + 1{,}200\,(N - 6)$ for $N > 15$		
9	—	Sand	$E = (35{,}000–50{,}000)\,(\log(N))$	(i) Correlation was based on USSR Practice. SPT blow counts considered in this may not be standard.	Trofimenkov [19]
10	—	Sand	$E_s = 15{,}000\,(\ln(N))$ to $22{,}000(\ln(N))$	(ii) Correlation mentioned by Bowles [11]. Source could not be located.	Bowles [11]
11	11a	Sand	$E = 500\,N$	(i) Correlation 11a is based on pressure meter tests.	Komornik *et al.* [21]
	11b	Sand	$E = 4{,}000\,N$	(ii) Correlation 11a was later updated to form correlation 11b, utilizing data of rebound and reloading pressure meter tests. (iii) As per Komornik [20], the E value obtained using rebound and reloading test data is 5–8 times higher than that obtained from initial loading.	Komornik [20]
12	—	All soils	$E = 35{,}000\,N^{0.8}$	(i) E is the dynamic modulus obtained from shear wave tests. (ii) Dynamic E values are suitable only for the design of sub-structures subjected to low-strain dynamic loads.	Ohsaki and Iwasaki [22]
13	—	Silica sand	$E = 16{,}900\,N^{0.9}$	(i) E is the dynamic modulus obtained from shear wave tests. (ii) Dynamic E values are suitable only for the design of sub-structures subjected to low-strain dynamic loads.	Ohsaki and Kawasaki [22]
14	—	Sand	**For driven piles:** $E = 55{,}000$ (for $N = 10$) $E = 70{,}000$ (for $N = 30$) $E = 110{,}000$ (for $N = 50$) **Typical values:** $E = 20{,}000$ for $N = 10$, $E = 50{,}000$ for $N = 30$ $E = 100{,}000$ for $N = 50$	(i) Correlation obtained using data from load tests on driven piles which are known to alter ground conditions during driving.	Poulos and Dais [23]
15	—	Sand	$E = 1{,}600\,N$	(i) Correlation is obtained from reloading data of pressure meter tests.	Kishida and Nakai [24]

(Continued)

Table 1: *Continued*

Sr. no.		Soil type	Correlation (E in kN/m^2)	Basis/Limitations/Remarks	Contributors
				(ii) Kishida and Nakai [24] states that reloading E is three times that of initial loading E, whereas, Komornik [20] suggests that reloading E is five to eight times higher than initial loading E.	
16	—	Sand	E = 5,000 N modified to E = 3,600 N in 1977	(i) Correlation is based on published data of plate load tests (plates of diameter 0.3–0.76 m) and validated with case studies. (ii) Case studies used for validation involved large mat foundations, which exhibited relatively low settlements. (iii) Original correlation subsequently modified in 1977 based on six additional case records.	Parry [25]
17	—	Gravelly sand	E = 1,500–2,500 N	(i) Correlation established based on a SCPT and E values derived from screw plate tests (involving relatively small-sized plates – 0.1 m^2) in USA. (ii) This correlation was converted to SPT N values using the relation between SCPT and SPT N values. (iii) Based on tests conducted on filled up soils in a tank with small-sized footings (dia – 152 mm), the original correlation $E = 2.5q_c$ was revised in 1978 to $E = 2.5q_c$ for spread foundations and $E = 3.5q_c$ for strip foundations. (iv) Value of soil modulus E obtained using this correlation is used for the estimation of settlement using the Schmertmann [26] settlement equation.	Schmertmann *et al.* [26]
18	18a 18b	Sand (NC) Sand (OC)	E = 3,500 N E = 40,000 N	(i) Correlation is based on light-weight dynamic penetrometer (weight: 10 kg) and triaxial tests on sand samples of 430 mm diameter prepared by sedimentation.	Clayton *et al.* [27]
19	—	Sand	E = 12,330 N + 18,852	(i) Correlation cited in CIRIA Report 143 (1995) [10] as obtained from data of load tests on driven piles which are known to alter ground conditions during driving.	Christoulas and Pachakis [28]
20	—	Dry fine sand or silty sand	E = 7,000 ($N^{0.5}$)	(i) Correlation is based on data from a relatively small-sized screw plate (<150 mm diameter) load tests and pressure meter tests for 3 sites in Denmark. (ii) E denotes the pressure meter modulus (E_p).	Denver [29]
21	—	Clay and sand	E = 395,000 ($N^{0.68}$)	i) E is the dynamic modulus obtained from shear wave tests. ii) Dynamic E values are suitable only for the design of sub-structures subjected to low-strain dynamic loads.	Imai and Tonouchi [30]
22	—	Alluvial sand	E = 400 N	(i) Correlation is based on data from pressure meter tests conducted in Japan. (ii) E denotes the pressure meter modulus (E_p). (iii) Correlation is best-fit line to data with wide scatter.	Ohya *et al.* [31]
23	23a 23b	Fine to medium sand Sand	E = 500 N + 5,000 E = 420 N + 3,900	(i) E is tangent-constrained modulus (E_M) obtained from laboratory oedometer tests on undisturbed and semi-disturbed samples.	Anagnostopoulos and Papadopoulos [15]

(Continued)

Table 1: *Continued*

Sr. no.		Soil type	Correlation (E in kN/m^2)	Basis/Limitations/Remarks	Contributors
	23c	Silt	$E = 300\,N + 2{,}800$	(ii) Correlation for sand was subsequently modified (Correlation 32).	
24	—	Sand	$E = 2{,}600–2{,}900\,N$	(iii) Cited by Bowles [11]. Basis of correlation is not mentioned.	Bowles [11]
25	—	Alluvial sand	$E = 360\,N$	(i) Best-fit line from pressure meter test data with wide scatter.	Tsuchiya and Toyooka [32]
26	—	Glacial sand	$E = 660\,N$		
27	—	Sand	$E = 400\,N–5{,}300\,N$ for $N = 4$ $E = 700\,N–7{,}000\,N$ for $N = 10$ $E = 1{,}500\,N - 10{,}000\,N$ for N = 30 $E = 2{,}300\,N - 13{,}500\,N$ for $N = 60$	(i) Derived from compression index (Ic) values, which are based on data of 100 case records for foundation settlements collated by Burland and Burbidge [9]. (ii) Due to spread of these case studies across various countries coupled with SPT tests conducted during early periods with lower rod energies, the consistency of SPT N values may vary. (i) According to Stroud [8], N_{60} values in modern UK practice are expected to be 0.8 times lower compared to the N values reported in earlier case studies.	CIRIA Report 143 (1995) [10]
	—	Partially saturated sand and gravel	$E = 222\,N^{0.888}$	(i) Correlation cited by Akguner [33]. (ii) Derived from horizontal loading on plates. (iii) Original data could not be located.	Wrench and Nowatzki [34]
29	—	Sand	$E = 60{,}000 + 3{,}200\,N$	(i) Correlation cited by Akguner [33]. (ii) Derived from pile load tests with SPT N averaged along the pile shaft. (iii) Original data could not be located.	Bazaraa and Kurkur [35]
30	—	Granular cemented gneissic residual soil	$E = (29\,N + 270)\,98.7$ for $15 < N < 30$	(i) Correlation obtained from the data of three footing load tests (footings of diameter of 0.4, 0.8, and 1.6 m) in Brazil.	Rocha Filho [6]
31	31a	Silt, sandy silt	$E = 400\,N$	(i) Cited by Navfac Manual. The original source or basis could not be located.	Navfac Manual DM 7.01 [36]
	31b	Silty sand, fine to medium sand	$E = 700\,N$		
	31c	Coarse sand	$E = 1{,}000\,N$		
	31d	Sandy gravel	$E = 1{,}200\,N$		
32	—	Sand	$E = 800\,N + 7{,}500$	(i) E is tangent-constrained modulus (E_M) (ii) Updated from Correlation 23 by same contributors.	Papadopoulos and Anagnostopoulos [37]
33	33a	Loose to dense sand	$E = 1{,}200\,N + 18{,}000\,N$	(i) Correlation obtained based on records of bored pile load tests in Japan and previous E value correlations of D'Appolonia *et al.* [5], Kishida and Nakai [23], and Papadopoulos (1982) [15]. Correlations for very dense sand based on E values reported by AIJ, 2974. (ii) Additional correlations involving soil shear strengths inherent in the analysis will influence derived correlation. (iii) Correlation is the approximate best-fit line with wide scatter.	Yamashita *et al.* [38]
	33b	Very dense sand	$E = 3{,}920\,N$		
34	—	Sand	$E = 1{,}800$ N	(i) Based on a single chimney settlement data. (ii) N values of 8 to above 50 averaged as 30 over the influence zone. (iii) Subsurface layers of fine to coarse sand with occasional silt layers and frequent cobbles and boulders will introduce uncertainties in the derived correlation.	Davie and Lewis [7]

(Continued)

Table 1: *Continued*

Sr. no.		Soil type	Correlation (E in kN/m^2)	Basis/Limitations/Remarks	Contributors
35	—	Clay and sand	$E = 3{,}000\ N$	(i) Correlation relies on load test data on driven piles which are known to alter ground conditions during driving. (ii) N value is along the pile–soil interface.	Decourt [39]
36	—	Piedmont sandy silt	$E = 220\ N^{0.82}$	(i) Correlation derived from relatively small dilatometer tests in Washington DC. (ii) E denotes the dilatometer modulus (E_d). $E_{25} = 0.9\ E_d$ for NC and (2–10) E_d for OC soils. (iii) Correlation reported to have been verified using analysis of data from eight locations (4 mats, 3 pile load tests, and 1 footing). (iv) Data from adjacent sites were utilized for locations with mat foundations.	Mayne and Frost [40]
37	37a	NC sand	$\frac{E}{N_{60}} = 3,200\left[\frac{q_{\text{net}}}{q_{\text{ult}}}\right]^{0.7}$	(i) Correlations obtained from E–N graphs provided by Stroud [8] are presented in the equation form. (ii) Correlation graphs are based on foundation and plate load test data compiled by Burland and Burbidge [9]. (iii) As per CIRIA Report 143 (1995) [10], significant assumptions were required to develop this correlation. (iv) Identification of q_{ult} value involved in this correlation is subject to considerable uncertainty as per CIRIA Report 143, (1995) [10]. (v) Lower range of E values pertains to the dataset from Levy and Morton [41]. Total 17 tests were presented by Levy et al.; however, Stroud considered only ten (10) test results yielding a lower range of E values. Load settlement *Graphs of the data set* suggest the influence of onset of shear failure on the derived E–N correlation. (vi) Twelve out of the 24 data points used in the development of correlation for OC sands are sourced from D'Appolonia's work. Whereas a separate E–N correlation (Correlation 6b) presented by D'Appolonia based on the same work is independent of pressure variations. (vii) Several case records with relatively low SPT N values of 10–14 are also included for developing correlation for OC soils, while one case record with SPT N of 44 is considered for NC soils. (viii) Correlation for NC sands is based on the limited data of 13 case records from 6 locations. Of these, 2 case records of Nonveiller [42] pertain to complex foundation conditions (Schmertmann [25]. Three case records of Farrent [13] pertain to subsurface conditions with cohesive soils (clay) below 10 m depth and intermediate soft rock layers, lying within the pressure influence zone of 24 m wide foundations.	Stroud [8]
	37b	OC Sand	$\frac{E}{N_{60}} = 4,500\left[\frac{q_{\text{net}}}{q_{\text{ult}}}\right]^{0.7}$		

(Continued)

Table 1: *Continued*

Sr. no.		Soil type	Correlation (E in kN/m^2)	Basis/Limitations/Remarks	Contributors
38	38a	Sand with fines	E = 500 N	(i) The basis of these correlations could not be located. (ii) These correlations with SPT N are mentioned for first-order approximations only. (iii) Separate correlations of the constrained elastic modulus (M) with static cone penetration q_c from calibration chamber tests provided in this reference.	Kulhawy and Mayne [1]
	38b	Clean sand	E = 1,000 N		
	38c	Clean OC Sand	E = 1,500 N		
39	—	Sand	900(N = 16)	(i) Correlation obtained as mode of 16 previous existing correlations.	El Sayed and El Kasaby [43]
40	40a	Silts	E = 400 N	(i) No data or basis shown for the correlations. Similar correlations are mentioned in Navfac Manual DM7.01 [36] (Correlation 30).	Sabatini *et al.* [44]
	40b	Sandy silt and fine sand	E = 700 N		
	40c	Coarse Sand	E =1,000 N		
	40d	Sandy gravel	E =1,200 N		
41	—	Cohesionless soil	E = 1,000 (70 ln(N) − 100)	(i) Correlation obtained from data of load tests on driven concrete and steel piles at bridge locations in California, USA. Driven piles are known to alter ground conditions during driving. (ii) Correlations with a single SPT N assumed along the shaft and tip of piles for relatively long (6–29 m) piles. (iii) Mindlin's closed-form solution which includes approximate corrections for layered soils has been utilized for analysis. (iv) The analysis involved other correlations of soil shear strength with SPT N along pile shaft. (v) Correlation is best fit line with wide scatter.	Akguner and Olson [45]
42	—	Sand	E = 500(N + 15)	(i) The original source or basis not mentioned. However, this correlation is similar to correlation of Webb (Correlation 5). (ii) E values obtained from this correlation can be increased by 1.5–3 times for OC sand, Robertson and Campanella [47]	Bowles [46]
43	—	Sand (saturated)	E = 250(N + 15)	(i) The original source or basis not mentioned. (ii) E value from this correlation for saturated sand is exactly half of Webb's correlation (Correlation 5). However, Webb's original correlation was developed based on tests below G.W.T.	Bowles [46]
44	—	Clayey sand	E = 320 (N + 15)	(i) The source or basis is not mentioned.	Bowles [46]
45	—	Gravelly sand	E = 600 (N + 6) if N < 15 E = 600 (N + 6) + 2,000 if N > 15	(i) The original source or basis of this correlation is not mentioned. However, it appears to be nearly similar to the correlations cited by Begemann [18] as being used in Greece (Correlation 7).	Bowles [46]
46	—	Sand	E_s = 6,000 N	(i) Original source or basis is not mentioned.	Bowles [46]
47	—	Sand	E = 10(N + 15)	i) Basis of this correlation is not mentioned in reference. However, it appears to be based on past experience.	Bowles [46]
47	—	Clean sand	E = 5,000 sqrtOCR + 1,200 N	(i) Source or basis is not mentioned.	Coduto [48]
48	—	Silty sand and clayey sand	E = 2,500 sqrtOCR + 600 N	(ii) Source or basis is not mentioned.	Coduto [48]

Komornik [21] introduced Correlation 11a based on the initial loadings of pressure meter tests. Komornik [20] subsequently updated the correlation by considering rebound and re-loading data of pressure meter tests and presented a new correlation (Correlation 11b). The *E* value obtained from the updated correlation is noted to be 5–8 times higher.

Schmertmann [26] introduced Correlation 17, which is derived from the standard cone penetration test (SCPT) and screw plate tests (using relatively small 0.1 m^2 plates) conducted in the USA. The resulting *E* value from this correlation is specifically intended for use within the Schmertmann [26] settlement equation.

2.1 Novelty statement

The present study has developed a precise and reliable correlation for determining the elastic modulus "*E*" for granular soils. This study relies on an extensive database comprising 85 footing load tests and accompanying SPT data conducted in India and Nigeria, as well as 5 footing load tests carried out by FHWA in the USA. The proposed correlation yields higher "*E*" values than a majority of the existing correlations. This improvement offers significant economic advantages in the design of foundations and substructures.

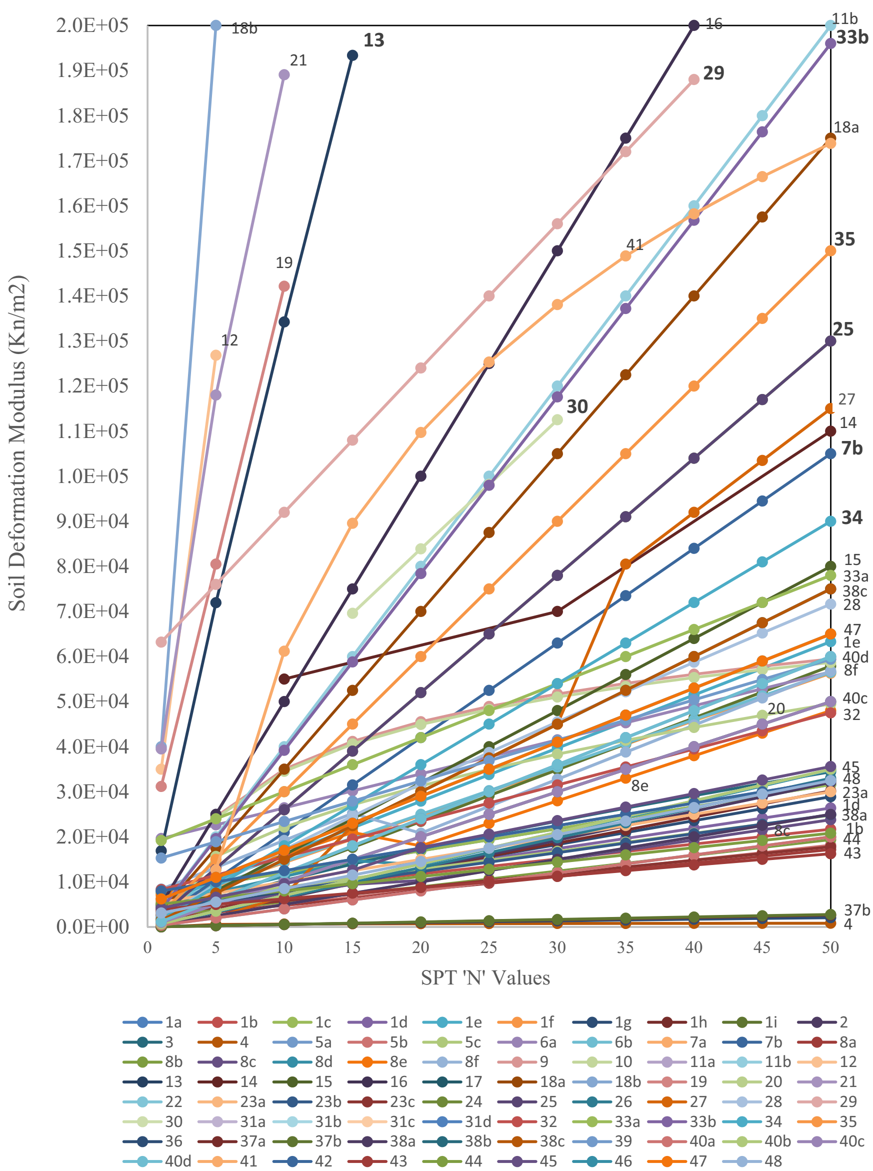

Figure 1: Graphical illustration of the existing published correlations of *E* and SPT *N* values for granular soil.

3 Footing load test details

3.1 Site details

The locations of footing load tests are distributed across different parts of India and at a refinery site in Nigeria. Tables 2 and 3 provide detailed information of these tests, including relevant soil properties and groundwater levels. As observed from the tables, a majority of the footing load tests in this study were conducted on fine-grained granular soils, such as silty sand, sandy silt, or silt. Table 2 presents the data for 19 footing load tests conducted in India, 7 tests at a refinery site in Nigeria, and 5 tests conducted in USA (by FHWA), while Table 3 presents the data exclusively for additional 59 tests conducted at the refinery site in Nigeria after dynamic compaction.

3.2 Experimental setup of footing load tests

The footing load tests (85 tests) were conducted in accordance with ASTM D1195 (2004) and also conforms to IS1888 (1985) standards. The tests were performed on large square RCC footings ranging from 1.5 to 3 m in size. Figure 2 illustrates the typical setup of footing load tests. The data obtained from the 85 footing load tests and an additional five tests carried out by FHWA were collectively analysed for this study.

4 Results and discussion

4.1 Pressure *vs* settlement curves of footing load tests

Pressure–settlement curves derived from footing load tests (31 tests) conducted at various locations across India, at a refinery site in Nigeria, and the USA (FHWA data) are presented in Figure 3. Conversely, Figure 4 exhibits pressure–settlement curves obtained from footing load tests (59 tests) conducted on dynamically compacted soil at the refinery site in Nigeria. The soil E values (secant) from each of the

Table 2: Data for footing load test at 31 different locations in India

Sr. no.	Project	B (m)	D (m)	N	G	S	$M + C$	LL/PL	G.W.T. (m)
1	Brys Buzz, Noida	1.5	2.5	10	0	80	20	NP	3.5
2	Ajnara, Noida	2	5.5	10	0	64	36	NP	2.0
3	ORB, Radiant, Noida	2	10	49	0	93	7	NP	12.9
4	ORB, Opulent, Noida	2	10	71	0	88	12	NP	12.5
5	Assotech BreezeFLT1, Gurgaon	1.5	7.5	21	0	70	30	NP	11.0
6	Assotech BreezeFLT2, Gurgaon	2	7.5	21	0	92	8	NP	10.9
7	AssotechBlith, Sec 99, Gurgaon	1.5	5	7	0	53	47	25/18	11.2
8	Gaur City Mall, Noida	2	10	15	2	84	14	NP	13.3
9	Gaursons, GY16 Area, Noida	2	3	11	1	92	17	NP	13.9
10	Equinox, Bangalore (FLT1)	2	6	18	0	85	15	NP	5.0
11	Equinox, Bangalore (FLT2)	2	6	18	0	85	15	NP	5.0
12	FHWA 3 m North, Texas, USA	3	0.8	17	0	85	15	NP	5.0
13	FHWA 1.5 m, Texas, USA	1.5	0.8	15	0	85	15	NP	5.0
14	FHWA 3 m South, Texas, USA	3	0.9	21	0	85	15	NP	5.0
15	FHWA 2.5 m, Texas, USA	2.5	0.8	15	0	85	15	NP	5.0
16	FHWA 1 m, Texas, USA	1	0.7	13	0	85	15	NP	5.0
17	Dangote Refinery, Nigeria FLT 1	2.5	1.5	5	0	98	2	NP	1.4
18	Dangote Refinery, Nigeria FLT 2	2.5	1.5	2	0	87	13	NP	1.5
19	Dangote Refinery, Nigeria FLT 3	2.5	1.5	2	0	95	5	NP	2.1
20	Dangote Refinery, Nigeria FLT 5	2.5	1.5	3	0	80	20	NP	1.8
21	Dangote Refinery, Nigeria FLT 6	2.5	1.5	5	0	77	33	NP	2.0
22	Dangote Refinery, Nigeria FLT 7	2.5	1.5	7	0	91	9	NP	1.5
23	Dangote Refinery, Nigeria FLT 8	2.5	1.5	7	0	86	14	NP	1.9
24	DLF (Cyber Park), Gurgaon	2.0	13	31	0	45	55	22/17	>25
25	DLF Midtown, Gurgaon-FLT1	3	13.5	28	4	25	71	27/20	20.0
26	DLF Midtown, Gurgaon-FLT2	3	13.5	32	3	23	74	27/20	20.0
27	Amaravati High-court-FLT1	2	7.4	31	0	99	1	NP	8.1
28	Amaravati High court-FLT2	2	7.0	25	26	69	5	NP	7.7
29	Bhivani Medical, Haryana, FLT1	1.5	2.0	4	0	6	94	NP	2.4
30	Bhivani Medical, Haryana, FLT2	1.5	2.0	5	11	29	60	NP	3.0
31	Bhivani Medical, Haryana, FLT3	1.5	2.0	7	0	35	65	NP	3.0

Table 3: Data of footing load tests conducted after dynamic compaction at 59 locations at Dangote Refinery, Nigeria

Sr. no.	Footing load test	*B* (m)	*D* (m)	*N*	*G*	*S*	*S* + *C*	LL/PL	G.W.T. (m)
1	Tank 13A	3	1.5	18	0	77–98	2–33	NP	1.3
2	Tank 13B	3	1.5	11	0	77–98	2–33	NP	1.16
3	Tank 14A	3	1.5	9	0	77–98	2–33	NP	1.3
4	Tank 15A	3	1.5	29	0	77–98	2–33	NP	1.4
5	Tank 15B	3	1.5	29	0	77–98	2–33	NP	1.2
6	Tank 16A	3	1.5	26	0	77–98	2–33	NP	1.2
7	Tank 16B	3	1.5	26	0	77–98	2–33	NP	1.1
8	Tank 17A	3	1.5	14	0	77–98	2–33	NP	1.2
9	Tank 17B	3	1.5	27	0	77–98	2–33	NP	1.3
10	Tank 18B	3	1.5	31	0	77–98	2–33	NP	1.3
11	Tank 19C	3	1.5	14	0	77–98	2–33	NP	1.25
12	Tank 19D	3	1.5	10	0	77–98	2–33	NP	1.31
13	Tank 23E	3	1.5	21	0	77–98	2–33	NP	1.3
14	Tank 23F	3	1.5	11	0	77–98	2–33	NP	1.4
15	Tank 25C	3	1.5	13	0	77–98	2–33	NP	1.3
16	Tank 25D	3	1.5	21	0	77–98	2–33	NP	1.3
17	Tank 26A2	3	1.5	21	0	77–98	2–33	NP	0.6
18	Tank 26B1	3	1.5	29	0	77–98	2–33	NP	1.2
19	Tank 33A	3	1.5	15	0	77–98	2–33	NP	1.3
20	Tank 33B	3	1.5	28	0	77–98	2–33	NP	1.4
21	Tank 34A1	3	1.5	23	0	77–98	2–33	NP	1.3
22	Tank 34A2	3	1.5	22	0	77–98	2–33	NP	1.3
23	Tank 34B1	3	1.5	17	0	77–98	2–33	NP	1.2
24	Tank 58A1	3	1.5	25	0	77–98	2–33	NP	1.1
25	Tank 27A	3	1.5	24	0	77–98	2–33	NP	1.3
26	Tank 27B	3	1.5	29	0	77–98	2–33	NP	1.28
27	Tank 35A	3	1.5	14	0	77–98	2–33	NP	1.4
28	Tank 35B	3	1.5	17	0	77–98	2–33	NP	1.2
29	Tank 36C	3	1.5	25	0	77–98	2–33	NP	1.4
30	Tank 36D	3	1.5	23	0	77–98	2–33	NP	1.3
31	Tank 38G	3	1.5	20	0	77–98	2–33	NP	1.2
32	Tank 38H	3	1.5	21	0	77–98	2–33	NP	1.3
33	Tank 39A	3	1.5	23	0	77–98	2–33	NP	1.4
34	Tank 39B	3	1.5	26	0	77–98	2–33	NP	1.3
35	Tank 41E	3	1.5	22	0	77–98	2–33	NP	1.2
36	Tank 41F	3	1.5	24	0	77–98	2–33	NP	1.1
37	Tank 42A	3	1.5	23	0	77–98	2–33	NP	1.4
38	Tank 42B	3	1.5	25	0	77–98	2–33	NP	1.4
39	Tank 44E	3	1.5	25	0	77–98	2–33	NP	1.3
40	Tank 44F	3	1.5	19	0	77–98	2–33	NP	1.2
41	Tank 45A	3	1.5	22	0	77–98	2–33	NP	1.35
42	Tank 45B	3	1.5	26	0	77–98	2–33	NP	1.4
43	Tank 46C	3	1.5	22	0	77–98	2–33	NP	1.2
44	Tank 46D	3	1.5	22	0	77–98	2–33	NP	1.3
45	Tank 49A	3	1.5	13	0	77–98	2–33	NP	1.2
46	Tank 49B	3	1.5	10	0	77–98	2–33	NP	1.1
47	Tank 50A	3	1.5	23	0	77–98	2–33	NP	1.1
48	Tank 50B	3	1.5	21	0	77–98	2–33	NP	1.1
49	Tank 52C	3	1.5	27	0	77–98	2–33	NP	1.7
50	Tank 52D	3	1.5	28	0	77–98	2–33	NP	1.2
51	Tank 53B	3	1.5	28	0	77–98	2–33	NP	1.6
52	Tank 53D	3	1.5	16	0	77–98	2–33	NP	1.2
53	Tank 54A	3	1.5	44	0	77–98	2–33	NP	1.4
54	Tank 54B	3	1.5	30	0	77–98	2–33	NP	1.2
55	Tank 54C	3	1.5	31	0	77–98	2–33	NP	1.4
56	Tank 55A	3	1.5	48	0	77–98	2–33	NP	1.0

(Continued)

Table 3: *Continued*

Sr. no.	Footing load test	*B* (m)	*D* (m)	*N*	*G*	*S*	*S* + *C*	LL/PL	G.W.T. (m)
57	Tank 55B	3	1.5	25	0	77–98	2–33	NP	1.0
58	Diesel Tank A	3	1.5	15	0	77–98	2–33	NP	0.4
59	Diesel Tank-B	3	1.5	7	0	77–98	2–33	NP	1.1

Figure 2: (a) Typical setup of footing load test (India and Nigeria). (b) Setup of footing load test (Dangote refinery site, Nigeria).

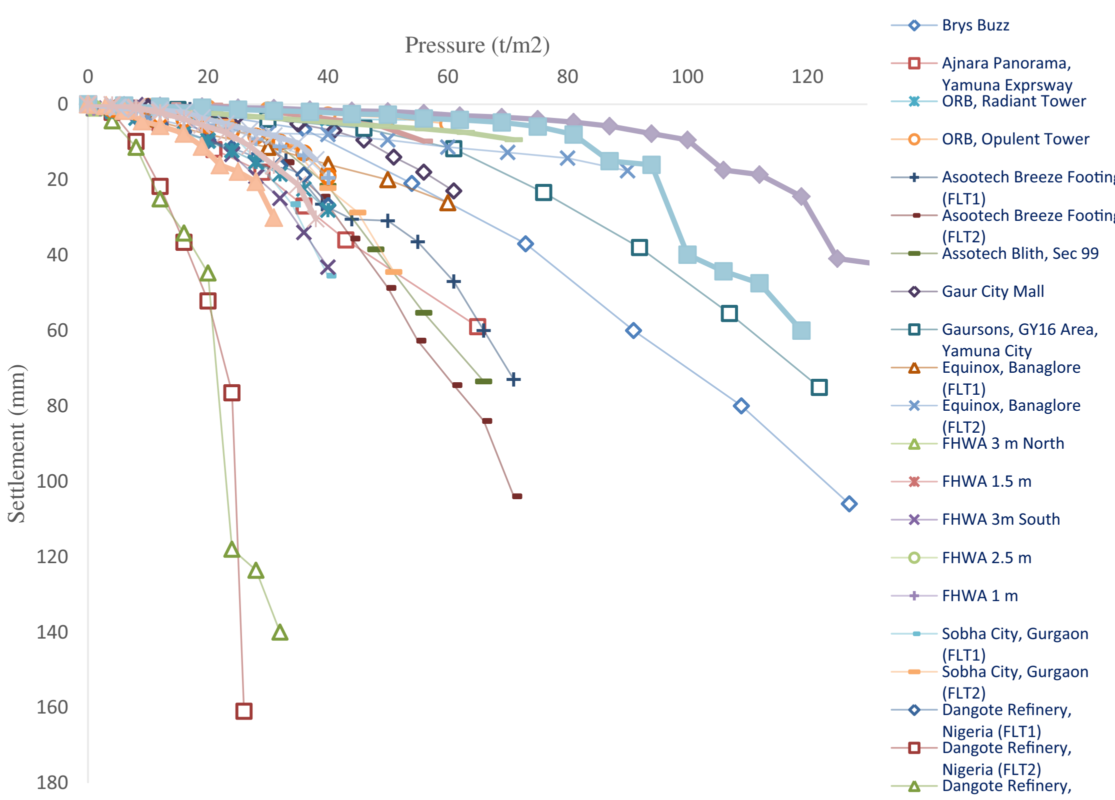

Figure 3: Footing load test results (pressure *versus* settlement curves – India, Nigeria, and USA-FWHA data).

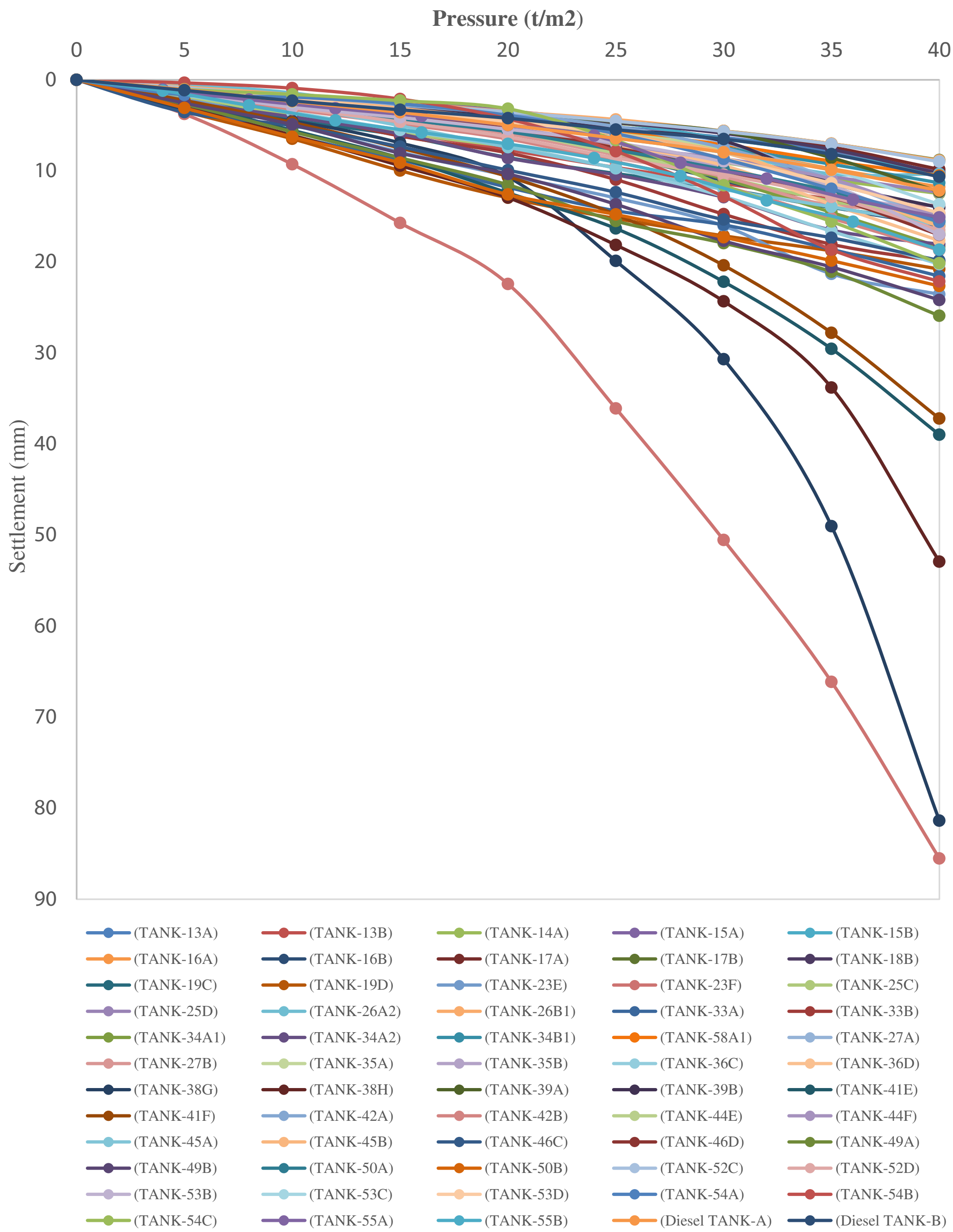

Figure 4: Footing load test results (pressure *versus* settlement curves – Dangote refinery site, Nigeria – after dynamic compaction).

footing load test results were determined using the elastic settlement formula given by Bowles [11].

$$S = q_o B' \frac{1 - \mu^2}{E} m I_s I_f, \quad (1)$$

where S is the settlement (m), q_0 is the footing pressure (kN/m^2), B' is $B/2$ (m), μ is the Poisson's ratio of soil (assumed as 0.33), E is the soil modulus of deformation (kN/m^2), I_s is the Steinbrenner influence factor based on the footing size (B) and thickness of soil layer (H) (I_s assumed as 0.43 for $H = 2B$), m is 4 for the centre of footing, and I_f is the depth factor (adopted as 1.0 since test footing is at the ground surface).

The E value (secant) was calculated using equation (1), with the data point corresponding to a footing pressure of 0.5 times the ultimate bearing capacity (q_{ult}). The selection of 0.5 q_{ult} for the footing pressure is based on the commonly used factor of safety of 2 in the foundation design.

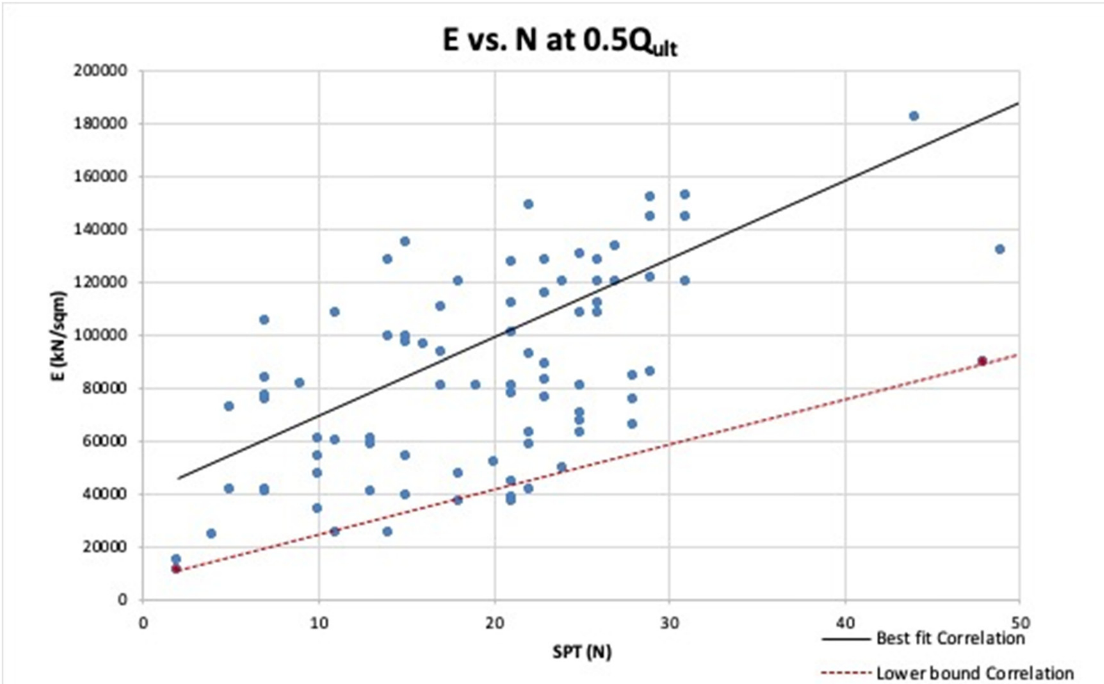

Figure 5: Correlations between *E* and SPT *N* values (based on the results of footing load tests).

The ultimate bearing capacity (q_{ult}) is regarded as the pressure where a distinct change is observed in the slope of the pressure–settlement curves (Figures 3 and 4). The distinct change in the slope of the pressure–settlement curve indicates the onset of shear failure in soil.

4.2 Development of *E*–*N* correlation for granular soils

The soil *E* values (secant) determined from the footing load tests were plotted with SPT *N* values obtained from tests conducted in close proximity, as depicted in Figure 5.

A linear plot through the lower range of the data of Figure 5 establishes a lower-bound *E*–*N* correlation, as depicted in Equation (2). Additionally, a linear plot representing all the data points establishes the best-fit correlation, expressed as Equation (3).

$$E = 1{,}705\,N + 7{,}705(\text{in kN/m}^2), \tag{2}$$

$$E = 2{,}920\,N + 41{,}287(\text{in kN/m}^2). \tag{3}$$

The correlation established in this study is compared with existing correlations in Figure 6. As observed from the figure, even the lower bound correlation established in this study results in a higher *E* value than the majority of the existing correlations. Notably, the best-fit correlation from this study yields an *E* value that is more than double the lower bound value.

A few existing correlations are found to yield higher *E* values than the value obtained using best fit correlation proposed in this study. Notably, these correlations yielding higher *E* values are associated with dynamic *E* values rather than static ones. It is an established fact that dynamic *E* values of soil are around 2.5–4 times higher than that of the static *E* value.

5 Conclusions

The primary objective of this study was to establish a reliable and sound correlation between the *E* value (secant) and the SPT *N* value for granular soils. To achieve this, the present study utilizes the data from 85 large-scale footing load tests conducted on granular soils, at various locations in India and at a refinery site in Nigeria and from 5 tests conducted by FHWA in USA. Based on the analysis of data of these footing load tests, the following conclusions are drawn:

1. According to the findings of this study, a near lower-bound correlation was found between the *E* value (kN/m^2) and the SPT *N* value, expressed as $E = 1{,}705\,N + 7{,}705$. Furthermore, a best-fit correlation of $E = 2{,}920\,N + 41{,}287$ was established. For design purposes, the best fit line should

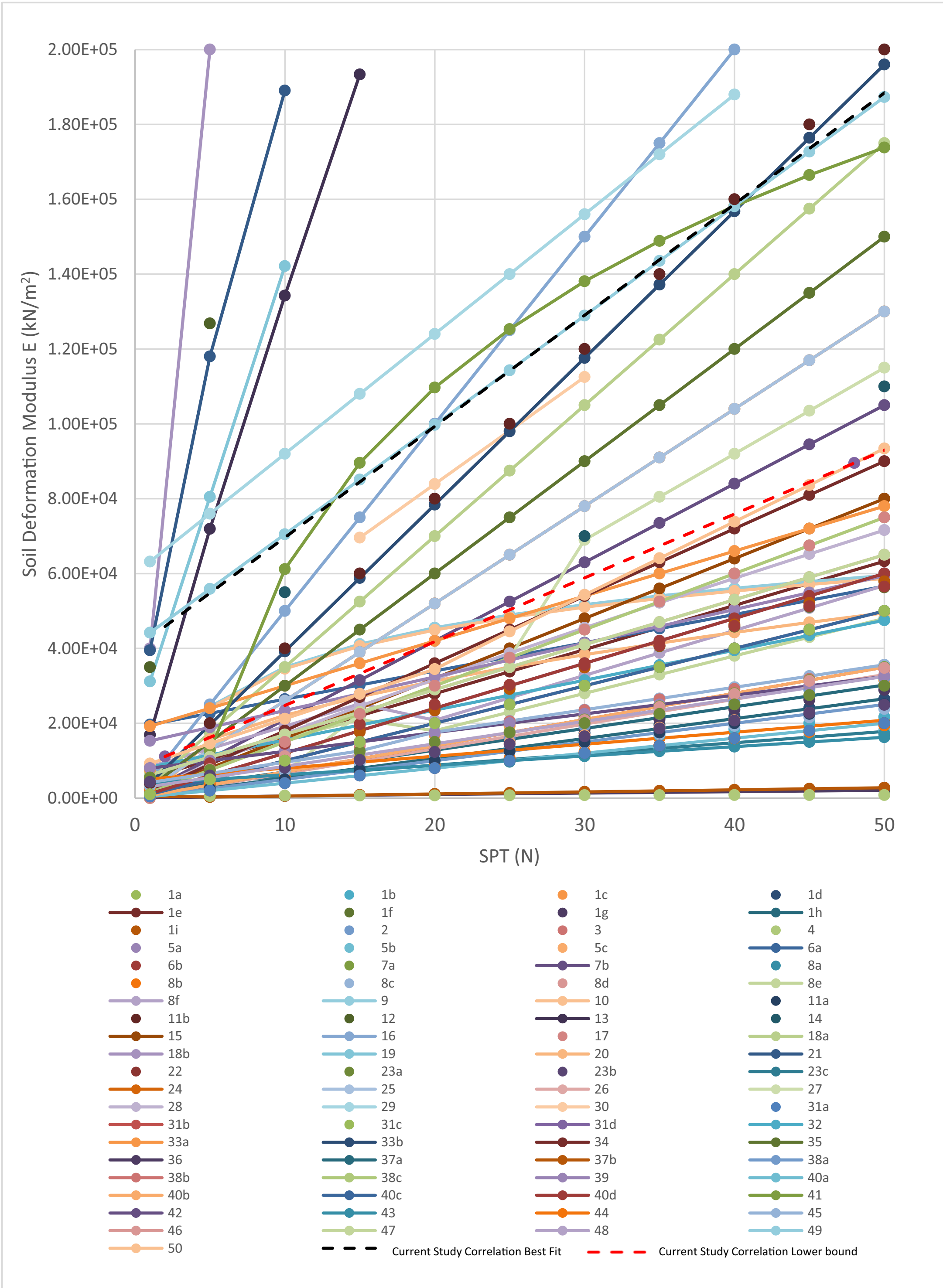

Figure 6: Proposed correlations superimposed on existing previously published best-fit correlation.

be used cautiously, and a lower-bound correlation is conservatively recommended.

2. It is worth highlighting that the resulting E values are notably higher than those obtained by most of the available correlations. This has important practical implications, as higher E values result in lower estimated ground movements, leading to substantial cost reductions in the design of sub-structures. It is interesting to note

that several other correlations yielding larger E values are primarily intended for low-strain dynamic applications.
3. The E and N value correlation was not found to exhibit significant stress dependence within the common stress range (≤0.5 q_{ult}) typically utilized for foundation and substructure designs, contrary to what was suggested by Stroud [8].
4. It is noteworthy that a majority of the footing load tests in this study were conducted on fine-grained granular soils, such as silty sand, sandy silt, or silt, which are relatively more compressible among granular soils and which yield lower E values. Therefore, the lower-bound correlation derived in this study can be conservatively utilized for any granular soil.
5. It is important to note that additional tests and research are required to ascertain whether separate correlations that produce higher E values can be developed for coarser categories of granular soils (medium to coarse-grained).

5.1 Relevance and potential applications

The findings of this study have significant practical relevance and potential applications in the field of foundation and sub-structure design. The following points highlight the practical implications:
1. Reliable correlation: The study establishes a reliable correlation between the soil deformation modulus E and the SPT N value based on sound large-scale database. Overall, the study's findings and the established correlation will enable engineers to more accurately estimate soil deformation modulus (E) based on readily available SPT N values. The correlations established in this study have the potential to enhance the reliability and efficiency of foundation designs, leading to substantial cost reductions in construction projects.

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Conflict of interest: Author J.D.W. is an employee of Geocon International Pvt. Ltd. The authors declare no other conflict of interest.

Data availability statement: The data that supports the findings of this study are available from any of the authors upon reasonable request.

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