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ORIGINAL PAPER

Effects of Hammer Energy on Borehole Termination and SBC Calculation Through Site-Specific Hammer Energy Measurement Using SPT HEMA

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Abstract Geotechnical investigation often engages several standard penetration tests (SPT) using different types of SPT equipment in a single project without energy measurement. It is a common practice in most Asian countries because there are no codal provisions for energy measurements during SPT. This study measured SPT hammer energy using two types of instrumented rods in a single project with multiple boreholes. Two different types of SPT equipment were used. This study was carried out with the aim of understanding the effects of hammer energy on the rebound or termination criteria and safe bearing capacity (SBC) estimation. SPT hammer energy measuring apparatus (SPT HEMA) is used for measuring energy below Anvil and above the Split spoon sampler. To validate the readings, SPT Analyzer is used below Anvil along with SPT HEMA at selected depths. SPT HEMA energy values recorded below Anvil closely match with those obtained from SPT Analyzer. Hammer energy at each SPT blow is used to estimate the average energy of SPT *N*-values at every depth, average borehole energy, average equipment energy, and average site energy from both SPT setups. A considerable difference was observed between these different energy ratio values. So adopting few energy measurements to assign energy ratio for correction factor estimation similar to developed countries should not be practiced as SPT equipment has different configuration and operation practices in developing countries. These differences in energy results have considerable variations in site-specific energy corrected *N*-values. In this study, the current method of correcting *N*-values as per IS 2131 resulted in *N*-values larger than actual, up to a depth of 6 m, thus giving in more SBC than actual. SBC for the site is estimated using codal procedure considering non-energy corrected *N*-values; energy corrected *N*-values for reference energy of 70% and measured shear wave velocity (V_s) in the same location. Net SBC estimated without applying energy correction is larger than SBC from energy corrected *N*-values and V_s values. So, there is a need to revisit SPT investigation practice, *N* correction, and SBC estimation in the places where no hammer energy is measured.

Keywords *N*-value · Energy measurement · *N* corrections · Shear wave velocity · Rebound · SBC

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Introduction

Standard penetration test (SPT) is the most common and widely used in situ tests in geotechnical investigations. The great merit of the test is its workability and cost-effectiveness. It is of great use in cases where undisturbed sampling is difficult, such as in gravelly, sandy, silty, sandy clay soils, or weak rock formations. SPT originated around the year 1902 by Colonel Charles R Gow. The procedure was standardized by Harry Mohr (1940). Terzaghi conceptualized the term “standard” in 1947 and developed correlations between blow counts and allowable bearing pressure in sands. In 1947, Terzaghi’s concept of “standard” blow counts to estimate soil properties was recognized. In 1948, Terzaghi named it as “Standard Penetration Test” in a presentation called “Recent trends in subsoil exploration.” Then, ASCE and the Corps of Engineers’ Hvorslev adopted “standard drive sampler” subsequently in the “Subsurface Exploration and Sampling of Soils for

Civil Engineering Purposes," in 1949. ASTM officially adopted the Mohr 2-inch diameter split spoon sampler as the apparatus and procedures as Test Method D1586 [1] (and last revised in 2018)."

Even though SPT is the most widely adopted test in all countries, codal provisions vary from country to county. The specifications of the SPT, test requirements, setup, test procedures, logging, energy measurement, and *N*-value normalizations adopted in major countries are presented in Table 1. Some countries have their code available in their own languages instead of English, and hence, it is not possible to list those codes here. It can be observed that energy measurement during the SPT is a well-accepted and established practice in countries such as UK, USA, Japan, and Brazil.

Major components such as hammer weight, drop height, theoretical potential energy, and type of drill rods used in SPT in different countries are almost similar and presented in Anbazhagan and Sagar [13]. The study also highlights that the general description provided in codes gives flexibility to custom-made SPT equipment and nonstandard components, resulting in variation of energy delivery to split spoon sampler. Since no codal recommendation in most developing countries including India, energy during SPT is not measured. Anbazhagan et al. [14] presented average hammer energy delivered during SPT in various countries.

Termination of SPT, i.e., the depth of investigation, is based on rebound. In most of the codes for routine projects, rebound criteria are used as termination criterion for borehole. Rebound criteria to stop the SPT for different codes are considered in the study, i.e., IS 2131 [8]; ASTM D1586 [1]; BS EN ISO 22476-3:2005+A1 [3]; AS 1289-6.3.1 [7]. ASTM D1586 [1] suggests terminating the test when the blow count exceeds 50 for any one of the three increments or overall 100 blow counts or no observed advance of the split spoon sampler for ten successive hammer blows. BS EN ISO 22476-3 [3] and JIS 1219 [6] suggest test termination if a total of 50 blow count is observed in soil; it can be increased to 100 blows in soft rocks. As per the Australian Standard AS 1289-6.3.1 [7], 30 blows/100 mm in the seating drive can be considered as refusal. IS 2131 [8] suggests a maximum of 50 blows for the last two penetration increments. This value also represents the "Hard" and "Very Dense" soil layers. Therefore, it is unnecessary to extend the hammer blow in this layer. Maybe a limitation of a maximum of 50 blows or 100 blows in soft rock (BS1377 [15]) is to prevent damage to the driving shoe.

From above, it can be clear that *N*-values of 50 in soil and 100 in weathered rock are widely used as terminating criteria. Since Hammer energy delivered during the SPT test varies from 25 to 85% [13], associated SPT *N* measured in the field for termination is not similar when multiple types of equipment are used in the same site. Besides, termination *N*-value of 50 or 100 is not similar universally as the energy delivered is not uniform, which can result in deviation in estimation of any soil properties using *N*-values. Hence, this study has attempted to understand how hammer energy affects *N*-values by different SPT equipment in the same site. Further, corrected *N*-values with and without considering hammer energy influence on termination depth (rebound criteria) and SBC from shear and settlement criteria by conducting a detailed study at four boreholes. The importance of hammer energy is highlighted by comparing SBC from SPT *N* corrected and alternate estimation using measured V_s values in the same site.

Table 1 Codal provision related to SPT in selected countries

Code for	USA	Europe	Japan	China	Australia	India
Minimum requirements for agencies	D3740 [2]	ISO 22476-3 [3]				
Visual soil identification	D2488 [4]	ISO 22476-3 [3]		GB 50021 [5]		
Test method for SPT	D1586 [1]	ISO 22476-3 [3]	JIS 1219, 2013 [6]	GB 50021 [5]	AS1289.6.3.1 [7]	IS2131 [8]
Split spoon sampler			JIS 1219, 2013 [6]	GB 50021 [5]		IS9640 [9]
Energy measurement	D4633 [10]	ISO 22476-3 Annex B [3]	JIS 1219, 2013 [6]			
Field logging	D5434 [11]					
Determining the normalized *N* for liquefaction	D6066 [12]	ISO 22476-3 Annex A [3]				

SPT Correlation and *N*-Value Corrections

N-value is the most used soil data to estimate soil properties required for foundation design, site response, and liquefaction hazard estimation. The *N*-values being correlated with different soil parameters, i.e., unit weight (γ), angle of internal friction (φ), relative density (Dr), and undrained compressive strength (Su). Many empirical relationships have been developed between *N*-value and soil properties measured in laboratory or field. Most of these correlations are found in commercial software like NovoSPT [16] and textbooks [17–19]. None of these textbooks or software gives applicability and energy ratio of SPT data used in correlations except a very few [14]. It is well known that hammer energy plays a significant role in the estimation of any soil property using *N*-value correlations [20]. Summarizing SPT-based correlations with energy ratio of data and applicability range of soil may be a reasonable effort, but it is not the objective of this study. Hence, a few selected correlation from the literature and frequently for SBC and settlement calculations for the shallow foundations presented here.

A group of correlations between SPT *N* and the bearing capacity of soil provided by different researchers depends on various factors. The important factors among them are type of foundation (isolated, continuous, etc.), features of foundation (depth, width, etc.), type of soil (cohesive, non-cohesive, etc.), and allowable settlement. Table 2 summarizes the bearing capacity equations for silty sand soil with traces of clay.

Where q_a = allowable bearing pressure for a settlement of 25 mm in kN/m^2; q_s = net safe bearing pressure for a settlement of 25 mm in kN/m^2; N_{cor} = corrected standard penetration *N*-value for 70% ETR; R_w = water table correction factor (only when $Dw/B \leq 1$, otherwise it is 1) = $0.5\left(1+\frac{D_w}{B}\right)$; K_d = depth factor = $\left(1+\frac{0.33D_f}{B}\right) \leq 1.33$, [21]; B = width of footing in meters; D_f = depth of foundation in meters; D_w = depth of water table from foundation level in meters; ΔH_a = allowable settlement such as 25, 40, 50, and 60 mm.

SPT blow counts related to driving weight and energy input versus sampler area were introduced by Burmister [23]. Original Mohr hammer has about 60% efficiency compared to Burmister energy correction of 100%, so N_{60} was started as practice [24]. In 1957, Gibbs and Holtz [25] presented correction for standard effective overburden pressure which was modified by Liao and Whiteman [26] into the currently used overburden correction.

For cohesive soils, there is no need for overburden pressure correction [19]. The overburden pressure affects the penetration resistance in cohesionless soils. The values are usually too low for SPT made at shallow depths. The same soil at the same density index would give higher penetration resistance at a greater depth. In 1957, Gibbs and Holtz [25] suggested corrections for field SPT *N*-values for depth. As the correction factor came into consideration only after 1957, available data published before then are considered as empirical. Since then, several investigators have suggested overburden correction. Gibbs and Holtz [25] took standard pressure of 280 kN/m^2 (corresponding to 14 m depth) and duly made overburden correction. Finally, Peck et al. [19] suggested a standard pressure of 100 kN/m^2 (equivalent to 1 kg/cm^2 overburden and corresponding to 5 m depth). Overburden correction reported in the literature has been summarized by Anbazhagan and Sagar [13].

In addition to overburden correction, researchers suggested corrections for the water table in the case of fine sand or silt below the water table. Apparently, higher *N*-values may be observed due to the dilatancy effect when

Table 2 Correlation between *N*-value and bearing capacity of soil for 25 mm settlement

References	Correlation	Energy ratio (%)	Soil type
Meyerhof [21]	$q_s = 12N_{cor}F_d \quad \text{for} \quad B < 1.2\,\text{m}$	55	Dry and moist sands
	$q_s = 8N_{cor}\left(\frac{B+0.3}{B}\right)^2 R_w F_d \quad \text{for} \quad B > 1.2\,\text{m}$		
	$q_s = \frac{N_{55}}{0.08}\left(\frac{\Delta H_a}{25}\right)K_d \quad \text{for} \quad \text{raft}$		
Teng [22]	$q_s = 35(N_{cor}-3)\left(\frac{B+0.3}{2B}\right)^2 R_w F_d$		Granular soils
Bowles [17]	Modified Meyerhof's equation:	70	Granular soils
	$q_a = \frac{N_{cor}}{0.04}R_w K_d \quad \text{for} \quad B \leq 1.2\,\text{m}$		
	$q_a = \frac{N_{cor}}{0.06}\left(\frac{B+0.3}{B}\right)^2 R_w K_d \quad \text{for} \quad B > 1.2\,\text{m}$		

the field N-value exceeds 15. In saturated, fine or silty, dense or very dense sand, the N-values may be abnormally greater because of the tendency of such materials to dilate during shear under undrained conditions. Correction for such behavior is called dilatancy correction. It was first introduced by Terzaghi and Peck [27], and is also recommended in Indian code IS2131 [8]. Most of the countries moved to modern correction factors to account for the operation of hammer dropping, verticality of guide rods, hammer–anvil dimensions and weights, sampler type, and hammer blow rate, which are equipment-related or operational variables that may affect N-values [28]. All necessary corrections need to be applied to field N-values (N_f). N_{cor} is the final corrected N-value; more details found in Anbazhagan and Sagar [13]. Even though these many corrections are required to account for variation in the field equipment and testing, very few are used in the SPT N correlations where soil properties depend on their development period. Bowles [17] suggested correction as unity for the case of a small borehole, no sample liner, and drill rod longer than 10 m. Thus, the measured N-value needs to be corrected only for hammer energy and the overburden pressure. There is no clear idea regarding how much each correction changes the final value and which one is highly influential. To study this in detail, a statistical analysis has been performed with a case study to evaluate the effect of applying only energy correction and overburden pressure correction on the overall correction factor. To apply correction factors, a soil column of 30 m depth is considered. The energy ratio range is taken from experience (25–95%), and the overburden pressure up to 400 kPa is accounted (counting the presence of water table at shallow depth). The soil is assumed to have a density of around 16–20 kg/m^3. Figure 1a presents the histogram of the frequency of the correction factors obtained after the analysis for considering all five corrections. Figure 1b shows the histogram of the frequency of correction with only energy and overburden corrections. Very little or no change can be observed in the plot from Fig. 1a to b. Figure 1c shows the probability density comparison of the two cases, and it is evident that there is a negligible difference between the two. The overburden correction is very low distribution in lower values. Only the overburden correction factor goes off from the final correction value by a large magnitude and it will not be sufficient. Thus, it can be said that overburden pressure and hammer energy are the two significant factors affecting the in situ N-values and these two alone will be sufficient for N-value correction [20]. Since overburden pressure can be accounted for the depth using soil test results, energy correction is of prime importance in N corrections. Hammer energy measurement and associated correction must be followed in non-practicing counties like India.

It is now established that hammer energy delivered to penetrate split spoon sampler in SPT test is a vital parameter. Energy can be measured just below Anvil and just above Split spoon sample. Until recently, very limited attempts have been made to produce measurements of hammer energy at the depth of sampler level to determine the energy loss during wave propagation along the rod [29, 30]. Due to the energy losses in the different mechanical components, the energy delivered to the rods and the sampler is not equal to the theoretical potential energy [29–31]. Odebrecht et al. [29] pioneered energy measurement at two different positions—just below Anvil and just above the Sampler in instrumented SPT under controlled boundary conditions. It was noted that the energy delivered at the sampler level can be very low beyond a certain depth (9 m) due to energy losses. On a contrary, for a long rod stem, the weight of the stem multiplied by permanent displacement contributes to the total energy applied to the sampler. Lukiantchuki et al. [30] showed that the energy measured at the sampler level is more reliable and more variable than the energy measured

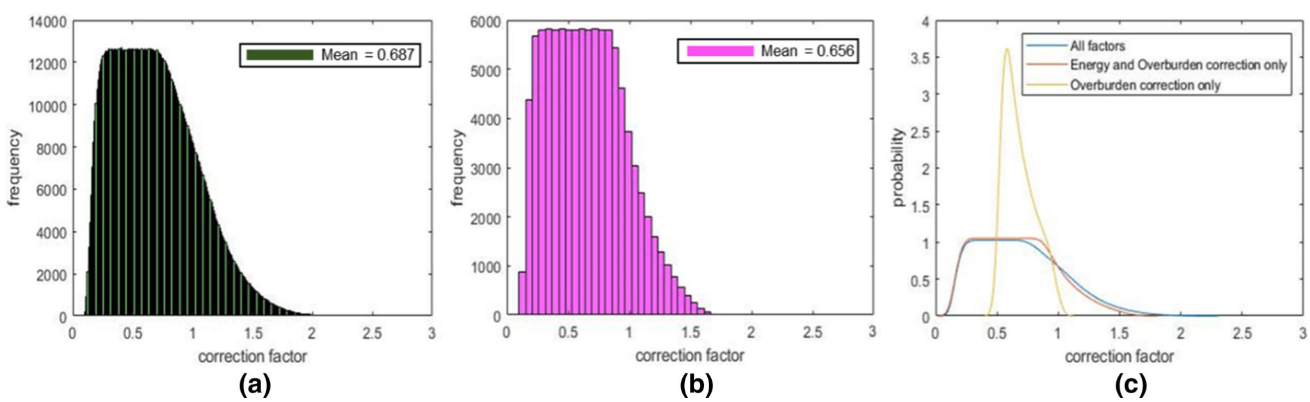


Fig. 1 Histogram of the frequency of the correction factors obtained after the analysis for considering **a** all five corrections and **b** only energy and overburden corrections, respectively, **c** shows the probability density comparison of the two cases

just below the Anvil. However, no study has been undertaken till now relating soil properties and *N*-values corrected with measured energy at the sampler level.

SPT Termination and Rebound Criteria

Recorded and assumed rebound *N*-values are widely used to determine φ, thereby bearing capacity factors, followed by bearing capacity values. Reporting correct rebound *N*-values is highly important, but most of the time, it depends on the borehole terminating conditions as per client specification. Some geotechnical practitioners in India use 50 or 100 as uncorrected *N*-values in soil layers, and over 50 or 100 along with penetration *N*-values in weathered rock layers. It is assumed as 50 or 100, or extrapolated from the recorded *N*-value for the rebound layer *N*-value and used for SBC estimation. ASTM D4633-16 [10] recommends the maximum blow count as 50 for any one of the increments or overall 100 blows for rebound criteria. Hence, *N*-value will possibly be between 50 and 100 for the rebound case. For example, if the 2nd increment's blow count is 40 and the 3rd (last) increment reaches its maximum blow count of 50, then the *N*-value will be 90. The maximum blow count of 50 for the last two increments to terminate the SPT is given in IS 2131 [8], which is different from the most widely used criteria given in ASTM D4633-16 [10]. Hence, it needs to be updated in the next revision of IS 2131 [8]. Most of the geotechnical firms in India do not specify the complete blow count and penetration depth at termination level in the report and just mention it as "Rebound". Instead of providing complete blow count and penetration depth. Hence, assuming all the rebound *N*-values like 50 or 100 may not be appropriate and will lead to error. Apart from this ambiguity, hammer energy transferred to the rebound layer also affects termination depth. In countries like India, where energy variations are significant in the same site, the rebound at different depths depends on the energy applied during SPT blows. Figure 2a, b shows energy corrected *N*-values for 55% and 70% of reference energy versus measured *N*-values. In Fig. 2a, b, it can be seen that if delivered energy is lesser than the reference energy of 55% or 70% during SPT test, then the borehole can be terminated before reaching the actual *N*-value of 50. For example, suppose SPT is operated with an energy ratio of 35%, then the borehole will be terminated at measured *N*-value of 50, which corresponds to 32 and 25 blows for reference energy ratio 55% and 70%, respectively. So by applying low energy during SPT, one can show a higher *N*-value than the actual and terminate a borehole much before terminating depth. Hence, giving termination criteria of borehole based on *N*-values without mentioning energy applied to respective *N*-values similar to IS2131 [8] may lead to unreliable soil investigation and early termination of a borehole. So, restricting the overall blows to 50 as mentioned in IS2131 [8] is not appropriate. Moreover, energy measurement during all SPT is essential. Different average energy transfer ratios (ETR) may be required based on the application and correlations used for a particular project. Most of the time, the energy measurement is taken for specific equipment in one borehole, and it is assumed as constant for the rest of the boreholes in the project, which is also not correct as energy ratio for different equipment varies in a project [13].

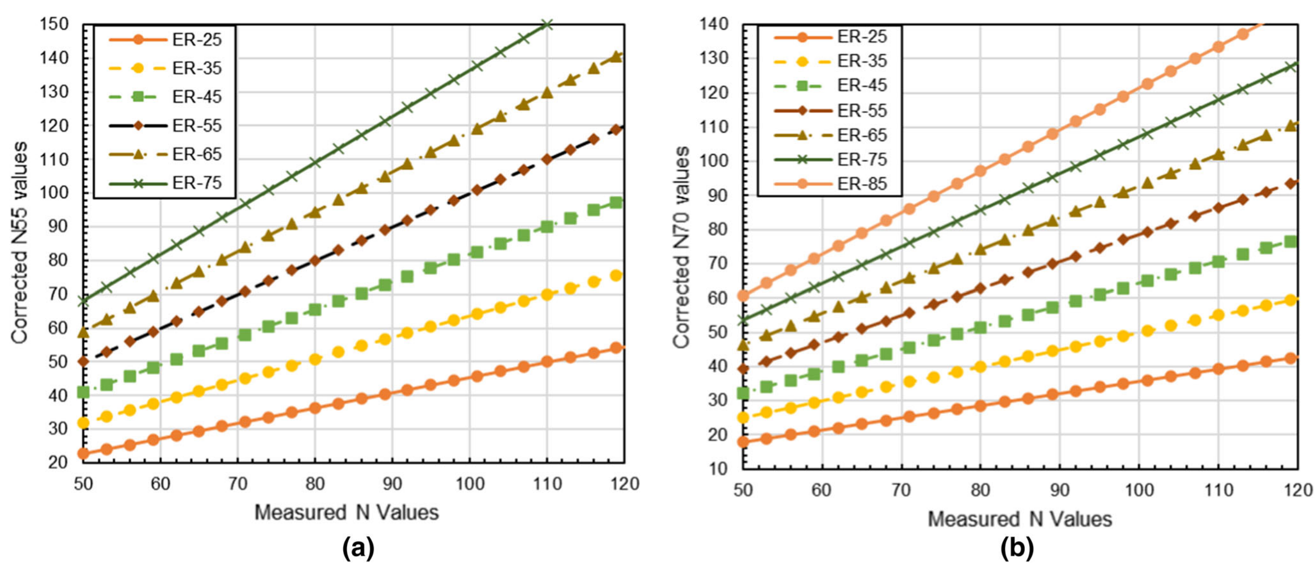


Fig. 2 Rebound *N*-values measured for different energy and corrected *N*-values for reference energy of **a** 55% and **b** 70%

Boreholes and SPT Field Testing

Even though *N*-values are commonly used for estimating SBC and settlement, it is a common practice to not account for the corrections corresponding to the *N*-value used in the respective correlation. Hence, a detailed field investigation was carried out to understand how rebound criteria and SBC varies in the same site due to energy variation during SPT tests. In the present work, a subsoil investigation was conducted at the selected site in the residual soil deposit region of Bengaluru. Four boreholes were drilled with *N*-value measurement using two types of drilling equipment (hydraulic and rotary drill rig). Hammer energy at each blow was measured using SPT HEMA by connecting sensors below the Anvil, similar to international practice and above the Split spoon sampler. After reaching the hard strata/rebound layer (SPT $N > 50/100$), coring was conducted with an NX core barrel. The percentage TCR (total core recovery) and RQD (rock quality designation) were recorded for the extracted rock cores and are presented in the bore logs (Fig. 4). SPT sampling and coring were carried out at every 1 m interval. All boreholes are advanced until specified termination depth or meeting the core recovery/RQD requirements (85%). The rebound layers of all the four boreholes were dense layers of silty sandy gravel or weathered rock layers. The locations of four boreholes are given in Fig. 3. In all the four boreholes, the SPT *N* was measured at every 1 m intervals, and soil samples were collected as per IS 2131 [8]. All boreholes were drilled with a diameter of 150 mm, and prepared as per IS 1892 [32]. Figure 4 shows the four borelogs obtained from the site. A sufficient number of disturbed samples were obtained, and tests on soils were conducted in accordance with IS 2720 [33, 34]. The physical properties of the soil were measured in the laboratory using the disturbed soil samples, and then, soil classification was done as per IS 1498 [35]. The groundwater table was found to be lower than 13 m [32, 36]. The *N*-values recorded ranged from 14 to 100. The total number of blows was continued till 100 for some depths of BH03 and BH04 as the ETR in the hydraulic rig was very less than other SPT

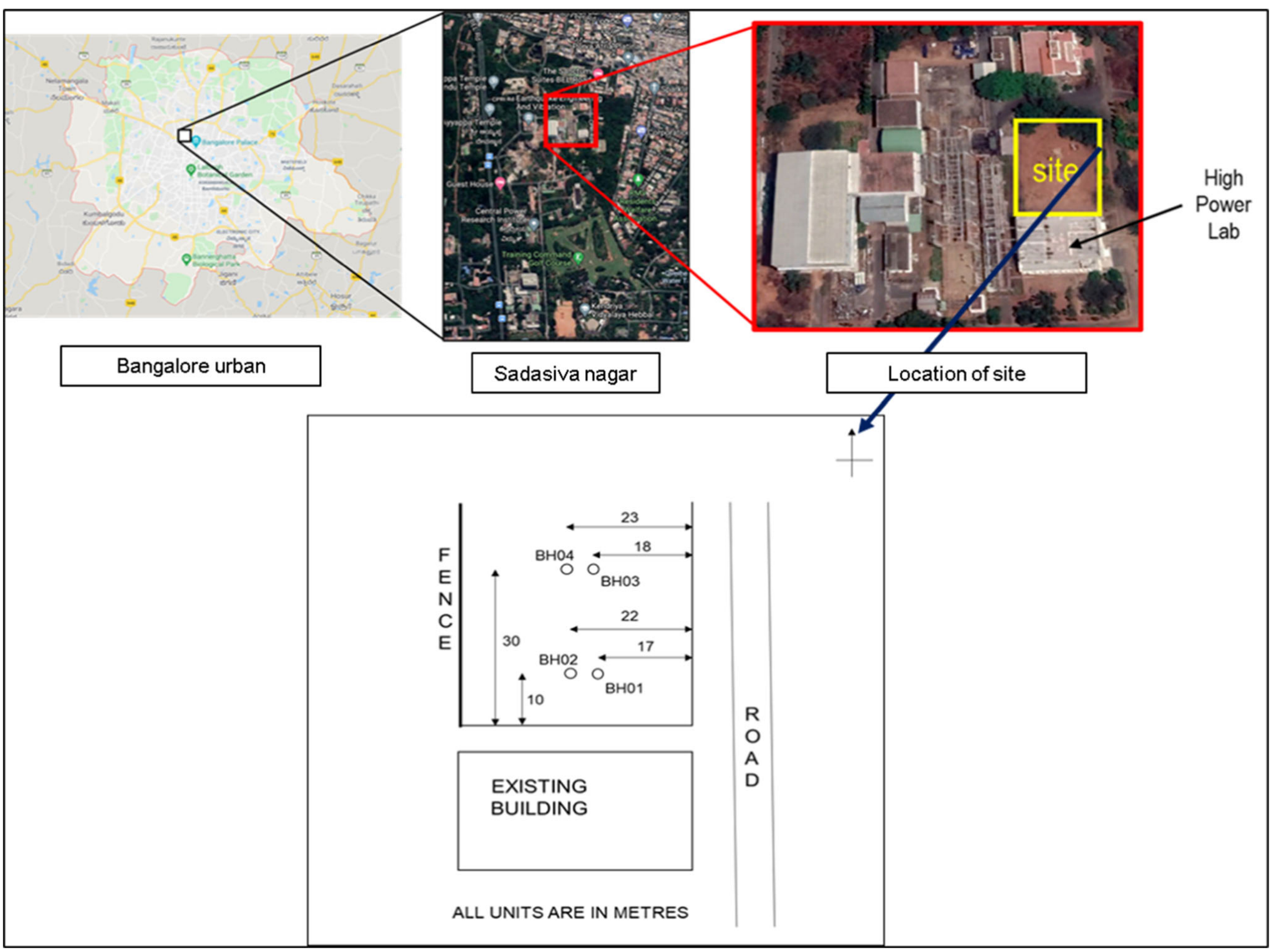


Fig. 3 Borehole locations in the proposed site

	Borehole No.1 : BH01						Borehole No.2 : BH02					
	Date of Test: 03/03/2020 to 07/03/2020						Date of Test: 09/03/2020 to 12/03/2020					
	Type of boring: Manual/Helical						Type of boring: Manual/Helical					
	Borehole diameter: 150mm/76mm						Borehole diameter: 150mm/76mm					
Depth (m)	Soil profile	Soil/Rock Description	SPT no. of blows			N	Soil profile	Soil/Rock Description	SPT no. of blows			N
1.0-		Brown Sandy Clay						Brown sandy clay				
			10	16	27	**43**			7	9	8	**17**
2.0-												
			9	14	27	**41**			8	7	6	**13**
3.0-		Grey Sandy Silt						Grey sandy silt				
			7	9	11	**20**			7	10	14	**24**
4.0-												
			10	12	17	**29**			23	50/7		**R**
5.0-		Brown Sandy Silt						Grey disintegrated rock				
			7	8	15	**23**		(washed sample)				
6.0-												
			9	53/6		**R**						
7.0-		Weathered Rock						Weathered Rock				
		(Washed Sample)						(Washed Sample)				
8.0-												
9.0-												
		Weathered Rock	50/1.5			**R**			50/1.5			**R**
10.0-		(Washed Sample)						Weathered Rock				
								(Washed Sample)				
11.0-												
12.0-		Disintegrated Rock										
		(4 pieces - 2/25/15/8)										
13.0-		25% CR, 20% RQD										
								Brown hard rock				
14.0-								10% CR, 0% RQD				
								Brown to white hard rock				
15.0-								63% CR, 60% RQD				
16.0-												
17.0-												

	Borehole No.3 : BH03						Borehole No.4 : BH04					
	Date of Test: 05/05/2020 to 08/05/2020						Date of Test: 19/03/2020 to 24/03/2020					
	Type of boring: Hydraulic						Type of boring: Hydraulic					
	Borehole diameter: 150mm/76mm						Borehole diameter: 150mm/76mm					
Depth (m)	Soil profile	Soil/Rock Description	SPT no. of blows			N	Soil profile	Soil/Rock Description	SPT no. of blows			N
1.0-		Dense Silty Sand						Dense Silty Sand				
			20	24	17	**41**		with Clay	24	24	15	**39**
2.0-												
			5	5	9	**14**			8	11	13	**24**
3.0-												
		Dense Sandy Silt	7	11	15	**26**			10	16	20	**36**
4.0-		with mica										
			12	25	33	**58**		Dense Sandy Silt	10	14	21	**35**
5.0-								with Mica				
			17	37	50/12	**R**			13	22	28	**50**
6.0-												
			24	76	50/1	**R**			20	40	50/12	**R**
7.0-		Dense Silt										
		with Fine Sand	47	50/9		**R**			50/4			**R**
8.0-		and Mica						Dense Silty Sand				
			32	50/8		**R**		with Mica	50/10			**R**
9.0-												
			33	51	50/9	**R**			50/10			**R**
10.0-		Dense Silty Sand						Dense Silty Sand				
			23	38	50/10	**R**		with Mica	50/14			**R**
11.0-												
			25	50/10		**R**			50/10			**R**
12.0-												
			26	50/7		**R**			50/15			**R**
13.0-								Weathered Rock				
		Weathered Rock						Weathered Rock				
14.0-								49% CR, 49% RQD				
								Hard Rock				
15.0-								88.67% CR, 68.7% RQD				
		Hard Rock										
16.0-		64% CR, 60.66% RQD						Hard Rock				
								96.67% CR, 90.67% RQD				
17.0-		Hard Rock										
		100% CR, 88% RQD										

Fig. 4 Borelogs of all four boreholes obtained from the site

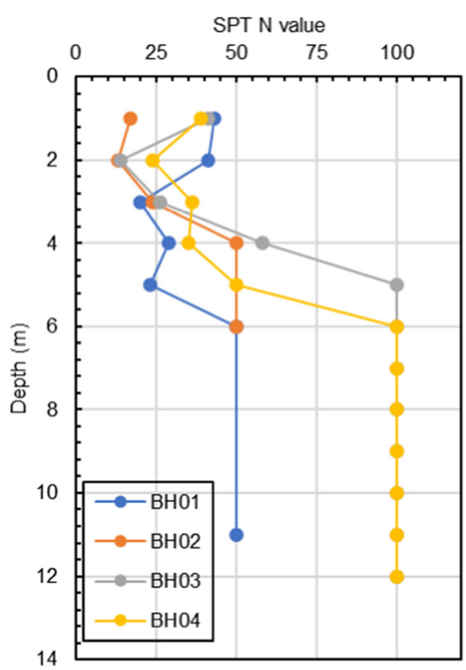


Fig. 5 Plot of recorded *N*-value versus borehole depth

rotary drill rig [13]. The SPT N versus depth plot for the four boreholes used in this study is shown in Fig. 5.

The soil profile encountered generally consists of loose, silty to slightly silty sand, overlying medium-dense, slightly silty sand formation. At shallow depth up to 5 m, the soil layer consists of sandy silt and silty sand; dense sandy silt with mica and weathered rock layer is present from 5 to 12 m; dark disintegrated to hard rock layers are present from 12 m onwards. SPT rebound occurred from 6 m depth onwards in all the boreholes. The complete data from each borehole were separated into fine-grained and coarse-grained soils, based on a standard classification system as per IS 1498 [35], which is similar to that of ASTM D2487-06 [37]. The classification of the soil present at the site was done based on the percentage weight passing through standard sieves and Atterberg limits. According to IS 1498 [35], coarse-grained soils are subdivided into gravel and sand based on the percentage of coarse fraction, whereas fine-grained soils are subdivided into three categories: high, intermediate, and low compressible silt/clay, depending on the value of the liquid limit. Liquid limit and plastic limits are used to classify the same as per the “A” line chart. Most soil samples almost have a similar liquid limit of 38.25 and are non-plastic. These samples can be classified as SM, i.e., silty sand with non-plastic fines.

SPT Hammer Energy Measurement and Results

Previously, hammer energy measurements were carried out by Anbazhagan and Sagar [13] on 18 types of SPT equipment and energy was reported to vary between 25 and 85%. Most tests were from different sites, and at a given site, only one type of SPT equipment was engaged. In this study, two types of SPT equipment are engaged in one site to ascertain the effect of the energy ratio on the rebound and SBC calculation. Energy measurement was carried out on each blow of SPT at all depths up to rebound using SPT HEMA [13] in all the Boreholes. In one borehole, energy was measured using SPT HEMA and also SPT Analyzer. Apart from energy measurement, video recording has made during each SPT test, and later the video footage was used to verify the height of fall and to recheck the hammer blow rate. Figure 6 shows a typical photo from the site showing SPT tests and energy measurement in the site. Typical force and acceleration variation with time and energy estimated as per ASTM D4633-16 [10] from the site are shown in Fig. 7a–c. Typical energy measurement of each blow below Anvil and above Split spoon sampler at a given depth is shown in Fig. 8. It was found that ETR at top (just below the Anvil) and bottom (just above the Sampler) sensors was 14–41% and 12–50%, respectively. The energy delivered by the Rotary drill rig was higher than the Hydraulic drill rig. The top and bottom sensor ETR is 25–41% and 15–50% for BH01 and BH02, drilled by rotary drill rig, 14–33%, and 12–36% for BH03 and BH04, drilled by Hydraulic rig, respectively.

Fig. 6 Typical photo from the site showing SPT tests and energy measurement

Another instrument PDI SPT Analyzer is used widely in the USA for energy measurement; it is also introduced in India by some geotechnical agencies recently. SPT at six depths was carried out in BH04 using a hydraulic drill rig where instrumented rods of both SPT HEMA and SPT Analyzer were installed in drill rod assembly. Energy values obtained from both the equipment were found to be comparable (Fig. 9). SPT Analyzer used during the test had one instrumented rod with two acceleration and two force channels. The accelerometers were of 5000 g capacity, similar to that used in SPT HEMA. This test was carried using instrumented rods of SPT Analyzer and SPT HEMA simultaneously one over the other. The lower values from SPT HEMA at the first three depths are because of the placement of instrumented rod of SPT HEMA below-instrumented rod of SPT Analyzer and more than 1 m below the point of impact. Results show that 0.11 times higher ETR values were recorded using SPT Analyzer when instrumented rods of HEMA were placed below the instrumented rod of SPT Analyzer. However, when the instrumented rod of SPT HEMA was placed above that of SPT Analyzer for next three depths, very low variations were observed in results. This indicates that energy passing through different rod joints may change actual energy transferred, which needs to be studied further [13]. These results are from preliminary tests, and further tests can be carried in the future by placing multiple instrumented rods in different positions.

Energy Variation and *N* Corrections

The ETR variation in the top sensor of all four boreholes at each *N*-value measurement is shown in Fig. 10. Further, all energy values in each borehole are used to calculate the average energy ratio of a borehole, and two boreholes of the same equipment are used to estimate an average equipment energy ratio. Based on these field observations, four different Average ETR are considered, (1) an average of all blows of a depth (average each depth energy: ADE), (2) an average of all depth of a borehole (average borehole energy: ABE), (3) an average of all boreholes of equipment (average equipment energy: AEE), and (4) an average of all boreholes with different equipment of a site (average site energy: ASE). Figure 10 also shows the average energy ratio with variation in each borehole, equipment, and entire site. Figure 10 clearly shows that within a borehole, about 8–18% difference observed, similarly within two boreholes of the same equipment can case ETR ratio of 1.5–5%. Using multiple types of equipment on the same site can result in an energy difference of 10%. This

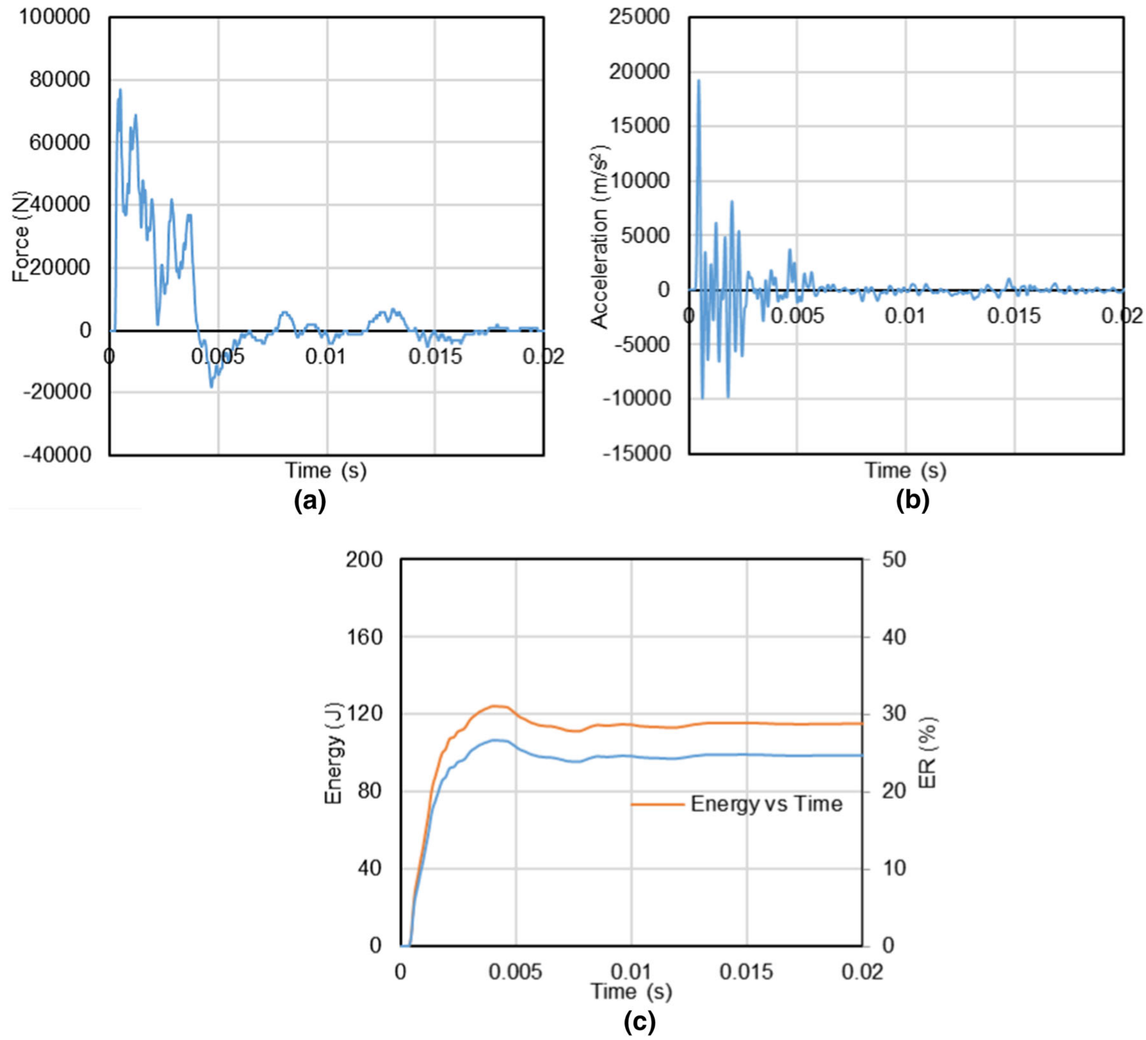


Fig. 7 Typical **a** force and **b** acceleration variation with time and **c** energy estimated as per ASTM D4633 (2016) from the site

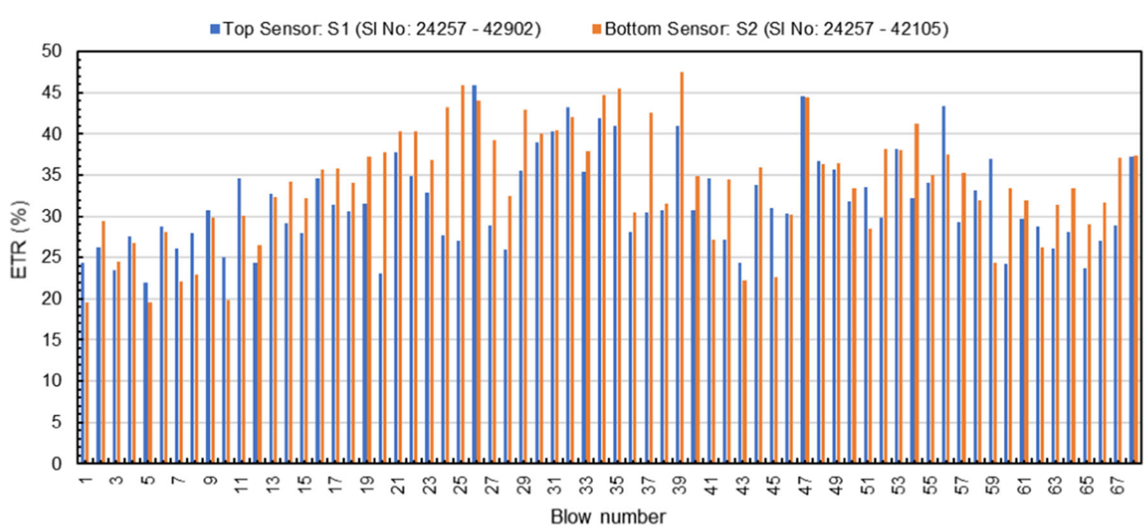


Fig. 8 Typical plot of ETR variation of top and bottom sensor for each hammer blow at a given depth

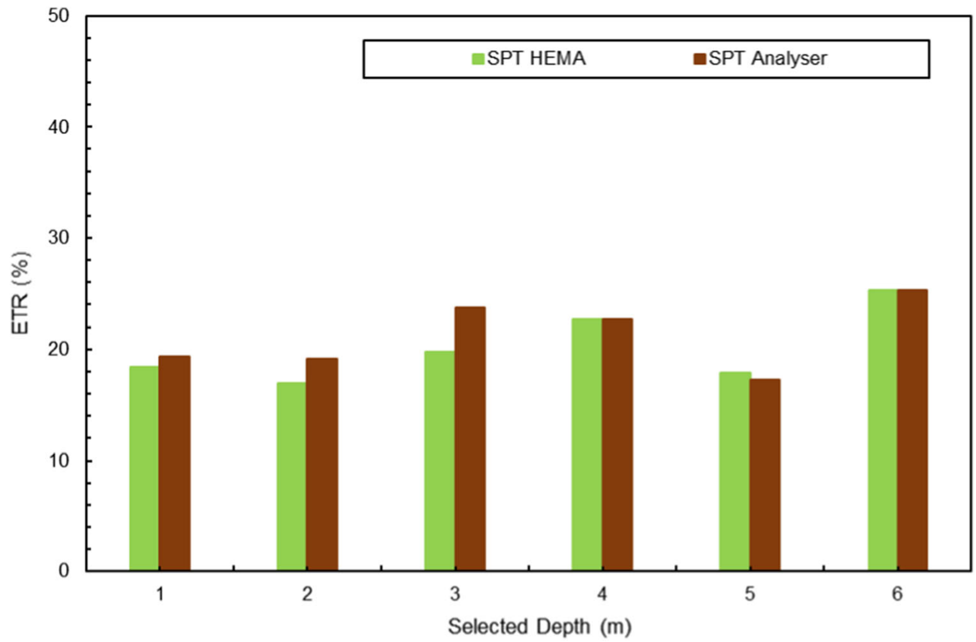


Fig. 9 Comparison of mean ETR of SPT HEMA and SPT Analyzer in BH04

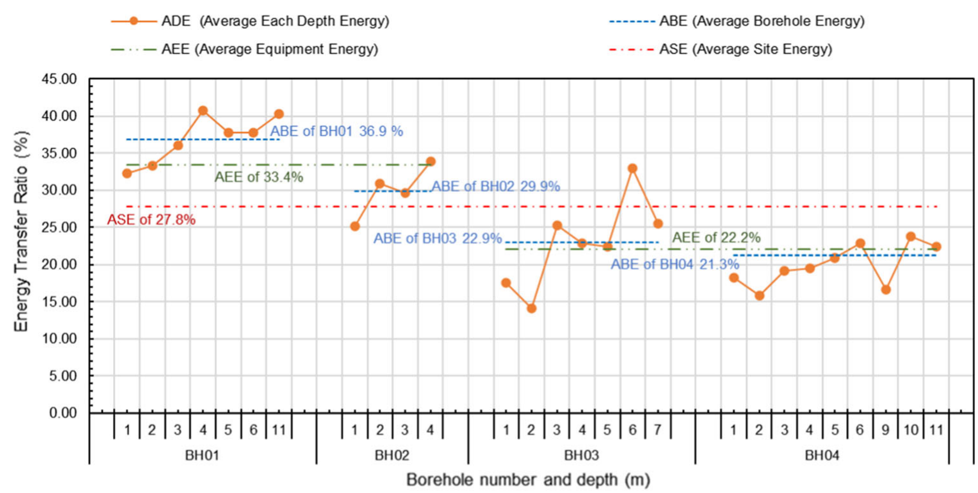


Fig. 10 The energy transfer ratio (ETR) variation in the top sensor of all four boreholes for each *N*-value measurement

variation clearly shows the importance of measuring energy at each blow and making average energy for *N*-values in each borehole rather than measuring at only one depth and recommending it for other depths or boreholes. Suggesting few energy measurements may be acceptable in developed countries as all SPT equipment is similar and automatic; and also, all tests are carried out by minimum qualified and certified technicians. In developing countries like India, it is necessary to measure energy at each blow and make respective average of *N*-values as the SPT equipments are locally fabricated and untrained people are carrying out SPT tests.

After understating variation of energy within small sites due to equipment and people carrying SPT test, let us see how these values change corrected *N*-value used in practice without knowing applied energy. Measured field *N*-values are corrected by applying correction as per IS2131 [8], reference energy of 70% as per Bowles [17]. Therefore, there are six sets of corrected *N*-values. One set is a measured field value; four sets are energy and overburden corrected *N*-values for the reference energy 70% as per Bowles [17], and the last set has corrected *N*-values as per IS1893 [38]. It can be noted here that the suggestions given in IS1893 [38] are taken from the USA and not verified and validated for Indian conditions. Moreover, most of the bearing capacity equations were developed for the energy ratio of 55% and 70%. Figure 11 shows uncorrected *N*-value and corrected *N*-values as per IS2131 [8], IS1893 [38] and reference energy of 70% for all *N*-values; and rebound *N*-value is considered as 50 and 100. It can be seen that if SPT *N* is corrected without knowing energy values as per current practice, corrected *N*-values are more than

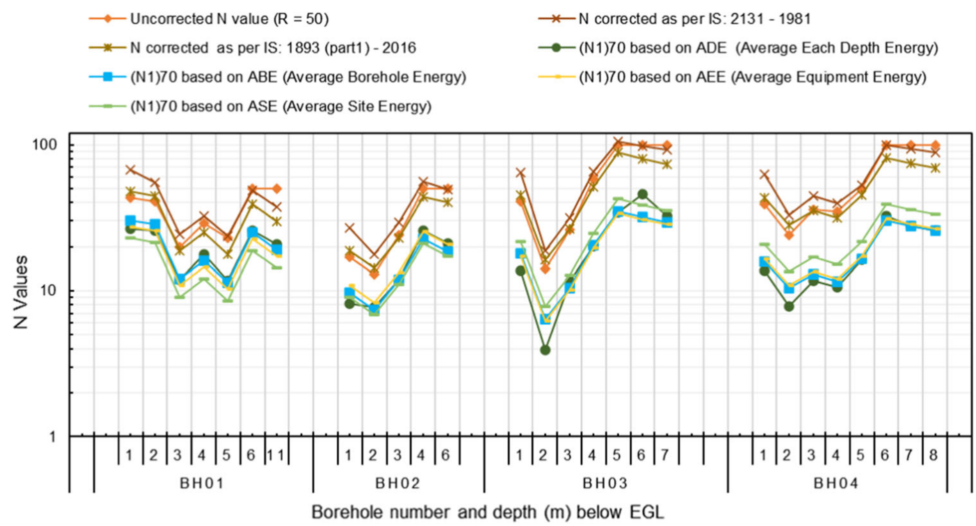


Fig. 11 Uncorrected and corrected *N*-value versus borehole depth for the site

field *N*-values up to a depth of 6 m, and are slightly lower or close to field *N*-values beyond 6 m. It is worth noting that the Indian code does not apply any correction for nonstandard SPT equipment and practice in the field. Correcting field *N*-values based on site-specific four average energy values to the reference energy ratio of 70% reduces corrected *N*-values considerably. Based on this analysis, correcting *N*-values based on the energy of each *N*-value is appropriate and taking the average energy of borehole, equipment, and site is not appropriate due to nonstandard SPT equipment and practices.

Further, assuming an energy ratio based on the equipment as per IS 1893 [38] is inappropriate as the actual field energy values are entirely different due to Indian equipment and practices. The energy delivered during *N*-value measurement plays a vital role in the termination of the borehole or stopping SPT at the rebound layer. In the study site, rebound level ETR is less than 35–40%. Core sample after rebound depth shows medium to dense soil layer and not a weathered rock as given in the bore logs (Fig. 4) in the absence of energy. Figure 12 shows a typical recovered intact medium to dense soil sample beyond the rebound layer from the site, obtained soil sample confirmed that the

Fig. 12 Recovered intact medium to dense soil sample beyond rebound layer

particular layer cannot be considered as a rebound. Due to low ETR, 50 blows were reached before reaching a very dense/weathered rock layer. Since the ETR of both the SPT rigs are lesser than the reference energies, total blows for termination depth in the supposed rebound layer will be lesser than the maximum value of 50. It leads to a misjudgment of the lesser dense soil layer as denser. This is evident from the sample shown in Fig. 12. For further studying the rebound condition, blows were continued till 100 for some depths of BH03 and BH04.

Bearing Capacity of Soil and *N*-Value

In India, *N*-value has also been used to estimate soil bearing capacity for foundation designs, stress–strain modulus (Es), and settlement calculation of soil layers. *N*-value has been widely used for designing foundations and other earth structures. A group of correlations between SPT *N* and the bearing capacity of soil have been developed depending on different factors [17, 19, 21, 39, 40]. The use of *N*-value directly in bearing capacity analysis has been reported in the literature [17, 41–44]. Most of the correlations are developed in the countries like Brazil, Egypt, Canada, Japan, US, etc. Very few attempts have been made in Asian countries, especially in India.

Terzaghi et al. [17] suggested methods for estimating settlements and bearing pressures of footings on sand from *N*-values based on the findings of Burland et al. [40] as the corrected value in all the cases. Parry [45] gave the allowable bearing capacity of cohesionless soils for 55% ETR. One of the earliest published relationships was that of Terzaghi and Peck [39] which has been widely used but are overly conservative. Meyerhof [21, 46] gave equations for allowable bearing capacity for a 25 mm settlement. These curves are similar to those of Terzaghi and Peck, thus very conservative. These equations have been in existence for quite some time and are based primarily on *N*-values from the early 1960s, and thus ETR is likely on the order of 50–55% and not 60%. Bowles [17] adjusted the Meyerhof equations for an approximate 50% increase in allowable bearing capacity; the respective equation is given in Table 2. Thus, it is necessary to understand how the change in ETR affects bearing capacity.

The most widely used Net ultimate bearing capacity equation from the shear criteria in general shear failure is shown in Eq. 1 as per IS 6403 [47]. Net SBC from settlement criteria is given in IS 8009 Part1 [48]. The building load (dead load and live load) is assumed as per the IS 875—1987 (part 1 to part 4) [49–52]. Immediate settlements were calculated to be within safety limit for the assumed foundation contact pressure of 1000 kPa.

$$q_{\mathrm{d}} = CN_{\mathrm{C}}s_{\mathrm{C}}d_{\mathrm{c}}i_{\mathrm{c}} + q\left(N_q - 1\right)s_q d_q i_q + \frac{1}{2}B\gamma N_\gamma s_\gamma d_\gamma i_\gamma W', \tag{1}$$

where q_{d} = Net ultimate bearing capacity (kN/m^2); N_{c}, N_q, N_γ = bearing capacity factors; B = width of the footing (m); C = cohesion of soil (kN/m^2); γ = unit weight of soil (kN/m^3); q = effective surcharge at the base level of foundation (kN/m^2); s_{c}, s_q, s_γ = shape factors; d_{c}, d_q, d_γ = depth factors; i_{c}, i_q, i_γ = inclination factors; W' = correction for water table.

As per the Indian code of practice, *N*-values need to be corrected by applying overburden correction and excluding dilatancy correction as the water table was below 13 m. It can be noted here that overburden correction in IS 2131 [8] is outdated and needs to be updated based on detailed study or universally adopted corrections [13]. In this study, *N*-values were corrected by applying overburden and SPT hammer energy correction similar to western countries. These *N*-values are further used to estimate friction angle (@@φ) and then bearing capacity factors as per IS 6403 [47]. The φ is used to get the bearing capacity factors from linear interpolation. The same shape, depth, inclination factor, and water table corrections are applied to calculate the Net ultimate and Net SBC. Factor of safety against bearing capacity failure is assumed as 3 [53]. Figure 13a, b shows the variation of Net SBC for shear and settlement criteria for different *N*-values with and without energy ratio correction. All other factors were considered same and only the corrected *N*-value was varied, which is reflected in changes in φ. A significant difference can be seen in Net SBC in both criterion due to application of energy corrections to the measured *N*-values, which is not considered in the current SBC calculation of codal practice in most Asian countries. Further, how site-specific energy values affect site-specific SBC values are discussed in the next section.

Effect of Energy on Net SBC at Site

As ASTM D6066 [12] recommends, energy measurement shall be performed for at least three and preferably five depths with reliable data. While using an SPT system as nearly a routine manner as practical, many possible measurements shall be taken and averaged. Since developed countries use similar kinds of SPT equipment and auto trip hammer, the energy variation may be negligible within a borehole, equipment, and site. At the same time, no such extensive energy measurement was reported in the literature. But since the variation of the energy at each depth is high, it is recommended to take energy measurement at all the depths. Then apply corrections for *N*-value instead of taking average energy for a borehole or equipment or site, as these values vary depending on numerous factors in current SPT practices. The average energy of all the blows

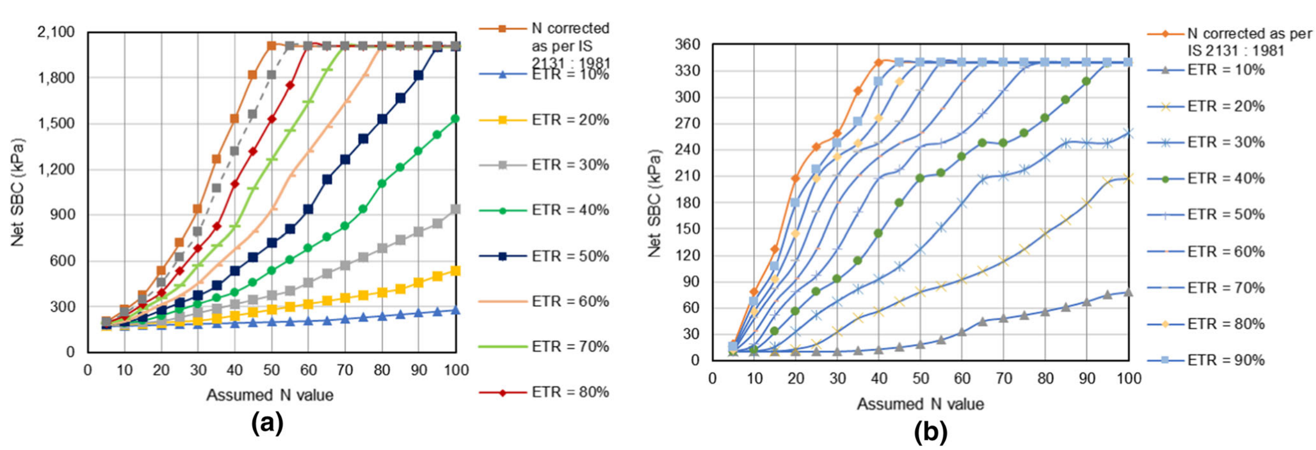


Fig. 13 Typical Net ultimate bearing for different *N*-value corrected for different ETR (%) by assuming all other aspects constant capacity from **a** shear criteria **b** settlement criteria

at a particular depth may not be uniform, but it is the most reliable value to correct *N*-values. Hence corrected *N*-values using ETR at each depth are considered further for SBC estimation.

N-values and hammer energy measured in the field were used to obtain corrected *N*-values as per IS 2131 [8] and for reference energy of 70%. Unit weight required for calculating SBC and N correction is taken from Anbazhagan

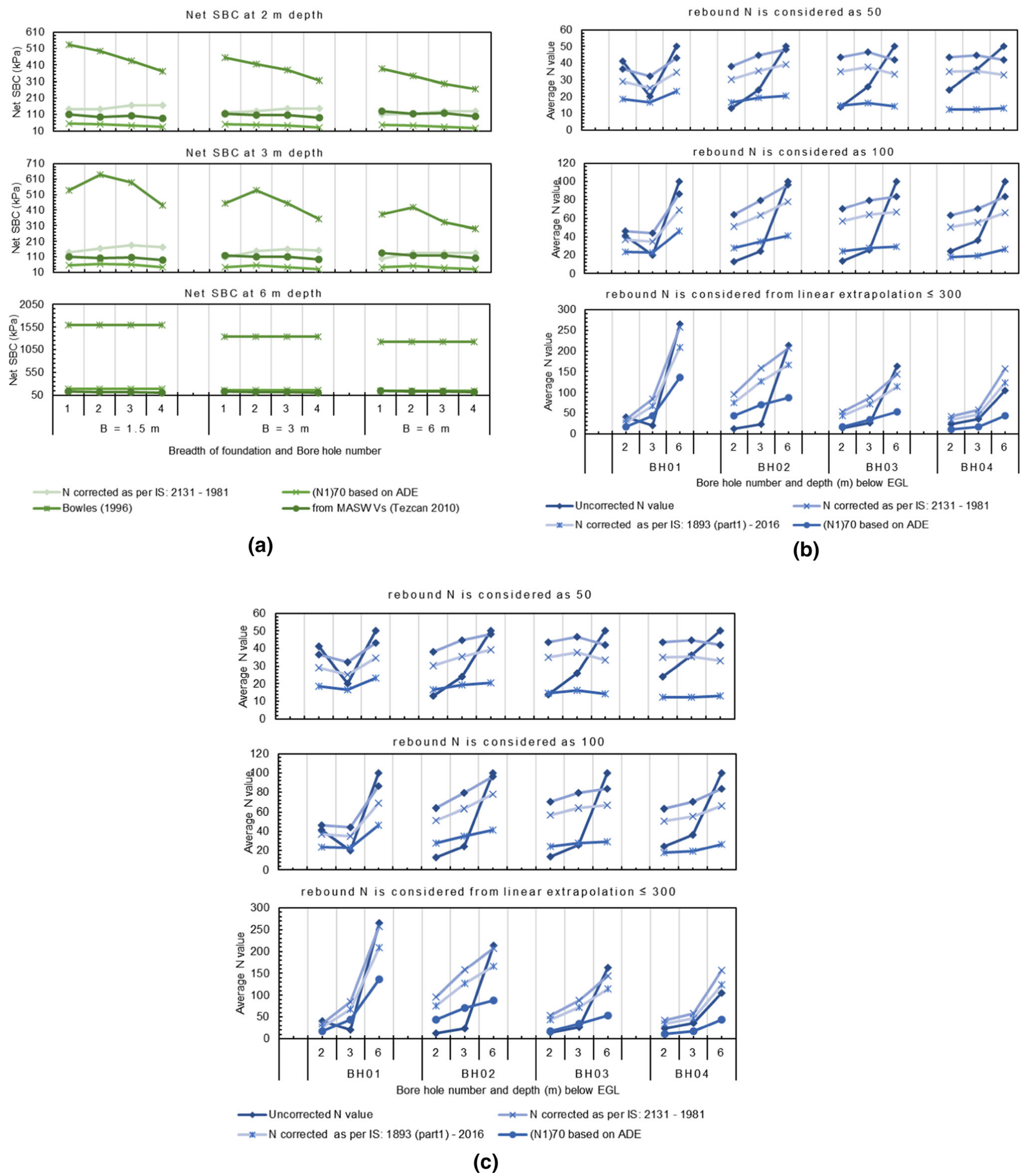


Fig. 14 **a** Uncorrected and corrected average *N*-value for the width of the foundation is 1.5 m. **b** Uncorrected and corrected average *N*-value when the width of the foundation is 3 m. **c** Uncorrected and corrected average *N*-value the width of the foundation is 6 m

et al. [54] based on the *N*-values. Three rebound *N*-values were considered at rebound level for correction, i.e., 50, 100 and the linear extrapolation with the condition that *N*-value is $\leq$ 300. In this study, three square footing sizes were considered, i.e., 1.5, 3, and 6 m, similar to major construction sizes in India and foundation depth of 2 m, 3 m, and 6 m for ground and basement foundation configuration. For each depth, corrected *N*-value is further used to estimate the average *N*-values for three foundation depths and three square footing sizes. Figure 14a–c shows the average *N*-values required for the calculation of SBC in the site. When the rebound *N*-value is considered as 50, then the corrections are applied, which further reduces the *N*-value as the ETR of the equipment is lower than the reference ETR. If the rebound *N*-value is considered as 100 or from the linear extrapolation ($\leq$ 300), then the values are not realistic. Due to the overburden effect, the corrected *N*-values are reduced considerably beyond 6 m. Since it is more or less rock, it does not make sense to consider the overburden effect because the overburden effect is predominantly applicable in soil. Hence, the rebound *N*-value is restricted to 50 (all corrected range) for the SBC calculations. These *N*-values are further used to estimate the factors required for SBC calculation in shear and settlement criteria.

SBC is estimated for three depths of 2 m, 3 m, and 6 m for foundation sizes of 1.5, 3, and 6 m square. Average *N*-values above foundation depth are considered to estimate the unit weight of soil adopting Anbazhagan et al. [54] and average corrected *N*-values up to 2B below the foundation depth are considered for arriving bearing capacity factors as per IS 6403 [47]. Correction factor of 1.3 for a square shape is accounted and no water table factor is considered as the depth of water was at 13 m. Similarly, no depth correction as the soil is virgin ground and no slope factor is considered as the ground is flat. These values are used to estimate q_d as per Eq. 1 and further Net SBC with a factor of safety 3 at each case and plotted in Figs. 16 and 17. Since there are lots of ambiguity in *N*-values and φ given in IS 6403 [47] and related SBC estimation, it may be necessary to estimate SBC by an alternate method other than *N*-value-based. Hence, shear wave velocity-based SBC estimation is carried out in the same site and presented in the next section.

Shear Wave Velocity and SBC

Important properties of soil like unit weight and φ are estimated based on correlations with *N*-values from SPT. These correlations are not validated for any of the Indian soil types. Also, it is very difficult to check the validity of these correlations as the original correlations between *N* and φ data are not traceable in the literature. But authors are certain that chart followed in SBC estimation may not be applicable to the Indian condition and specifically to residual soil deposit where the present study is taken up. Hence, SBC estimation based on the in situ shear wave velocity values suggested by Tezcan et al. [55] is used to compare SBC estimated in this study. MASW survey [56, 57] has been carried out in the exact location to measure the shear wave velocity (V_s) of different layers. It can be noted here that both MASW and SPT were carried out in the same period. All MASW surveys were carried out using Geode seismograph with 12 number of 4.5 Hz geophones by adopting geophone spacing of 1 m and source distance of 3 and 5 m to align average V_s measurement exactly with borehole area. Figure 15a–d shows typical photographs of field testing, data recorded, dispersion curves, and V_s values measured at four boreholes. Field *N*-values are well comparable with V_s values measured at the site. V_s of soil reduces after 2 m and increases after 6 m, and similar observations can also be found in Fig. 5 of *N*-value plot. Here, the energy values change the *N*-values but not the trend with V_s values, which means that irrespective of energy applied for *N*-values, one can get the correlation between SPT *N* with V_s or shear modulus (G_{max}) [58]. But depending on the energy applied to *N*-value in correction, estimated V_s or G_{max} will be different, as explained by Anbazhagan et al. [20].

Equation for allowable bearing pressure (q_a) [55, 59] in kN/m^2 for sites having V_s values less than 750 m/s with sufficient factor of safety is given below:

$$q_a = 0.025\gamma V_s \beta \tag{2}$$

where γ—unit weight of soil above foundation depth in kN/m^3; β is a correction factor applied only to sandy soil based on the width of the foundation (*B*). Unit weight above the foundation depth is estimated using density–V_s relation given by Anbazhagan et al. [54] and used to calculate SBC. The V_s-based SBC is used to verify SBC estimated using SPN *N*-values in the site, and the comparison is shown in Figs. 16 and 17.

Results and Discussion

The SBC values estimated using *N*-values and V_s values are compared in Figs. 16 and 17 for shear and settlement criteria. Figure 16 shows huge difference among SBC values evaluated differently by considering shear criteria, whereas Fig. 17 shows very less difference among SBC values evaluated differently by considering settlement criteria. Hence, SBC estimation given in IS code and its applicability to the residual soil (Bangalore) region need to be revisited. In Fig. 16, it can be noted that Net SBC values

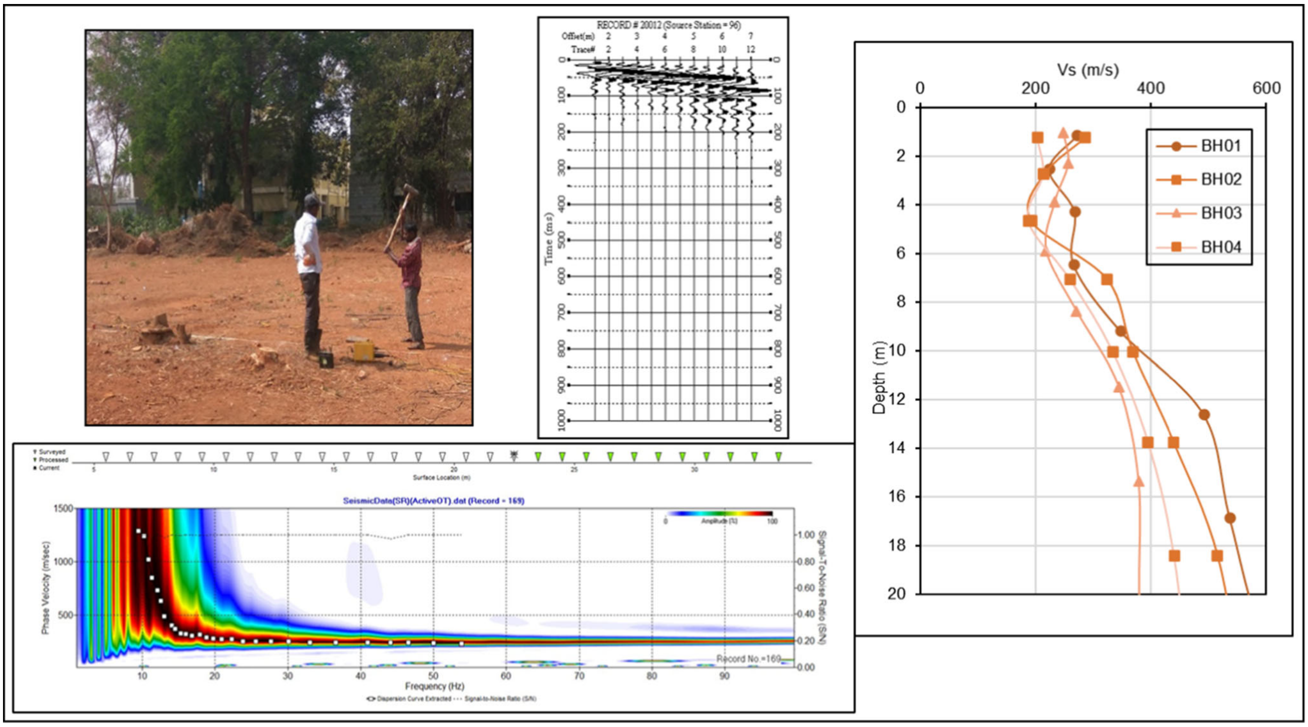


Fig. 15 Plot of shear wave velocity profiles from MASW of all the four boreholes

are different in soil layers for each borehole and the same for rebound layer. Effect of ETR on SBC is predominantly noticed in shallow depth of foundation, i.e., soil layers, and it is not significant at rebound or rock layers. Also, Net SBC estimated by energy corrected *N*-values is close to V_s-based SBC values in the same foundation at soil layers. At foundation depths of 2 and 3 m, Net SBC values from IS 2131 [8] are higher than any other Net SBC values when shear criteria are considered (Fig. 16) and Bowles method gives higher SBC when settlement criteria are considered (Fig. 17 If Bowles method is removed in 2 m and 3 m foundation depth, then Net SBC values from IS 2131 [8] are higher than any other SBC values for both shear and settlement criteria when soil *N*-values are used for SBC. This may be due to increased *N*-values because field *N*-values are not corrected for energy. At the same time, when *N*-values are restricted for a rebound or rock case, all *N*-values, i.e., corrected for ETR, do not give similar Net SBC and these values are generally higher than V_s-based SBC. It can be concluded that effect of hammer energy is high when ETR corresponding to the soil layer are used with *N*-values for Net SBC estimation. Net SBC estimated from energy corrected values is close to V_s-based SBC values. Peck et al. [19] and IS 6403 [47], the maximum limit of the friction angle is 45 degrees for an *N*-value greater than or equal to 75. This leads to the saturation of bearing capacity factors, which in turn limits the SBC value to a certain extent. When the Net SBC values from shear criteria are compared in between the different dimensions of the foundation, namely 1.5, 3, and 6 m, no significant difference except a slight decrease in the Net SBC value when dimension and depth of foundation increased from 1.5 to 6 m. This is because when all the soil parameters are kept constant, the SBC mainly depends on both the depth and depth factor of the foundation, and the angle of shearing resistance saturates at a higher *N*-value (> 75).

Figure 17 shows Net SBC for settlement criteria for different depths and widths of footing considered in this study. V_s-based SBC is similar for settlement and shear criteria as per Tezcan et al. [55, 56]. Net SBC values variation in the boreholes for settlement criteria is identical to shear criteria. SBC estimated using direct SPT N-based correlation is higher than any values in settlement criteria. SBC estimated using V_s values is between the SBC from site-specific energy considered *N*-value (i.e., corrected for ETR values) and not considered *N*-value (i.e., IS 2131 [8]). In general, *N*-values not corrected for measured energy at the site give higher SBC when compared to SBC values based on V_s and *N*-values corrected for measured energy at the site. In Net SBC by settlement criteria, no significant difference is observed except a slight decrease in the Net SBC value when dimension increased from 1.5 to 6 m. Saturation of SBC value can be observed because of the restriction of maximum allowable settlement, depth factor, and settlement from *N*-value. Net SBC from shear criteria is around 10–15 times greater than the settlement criteria.

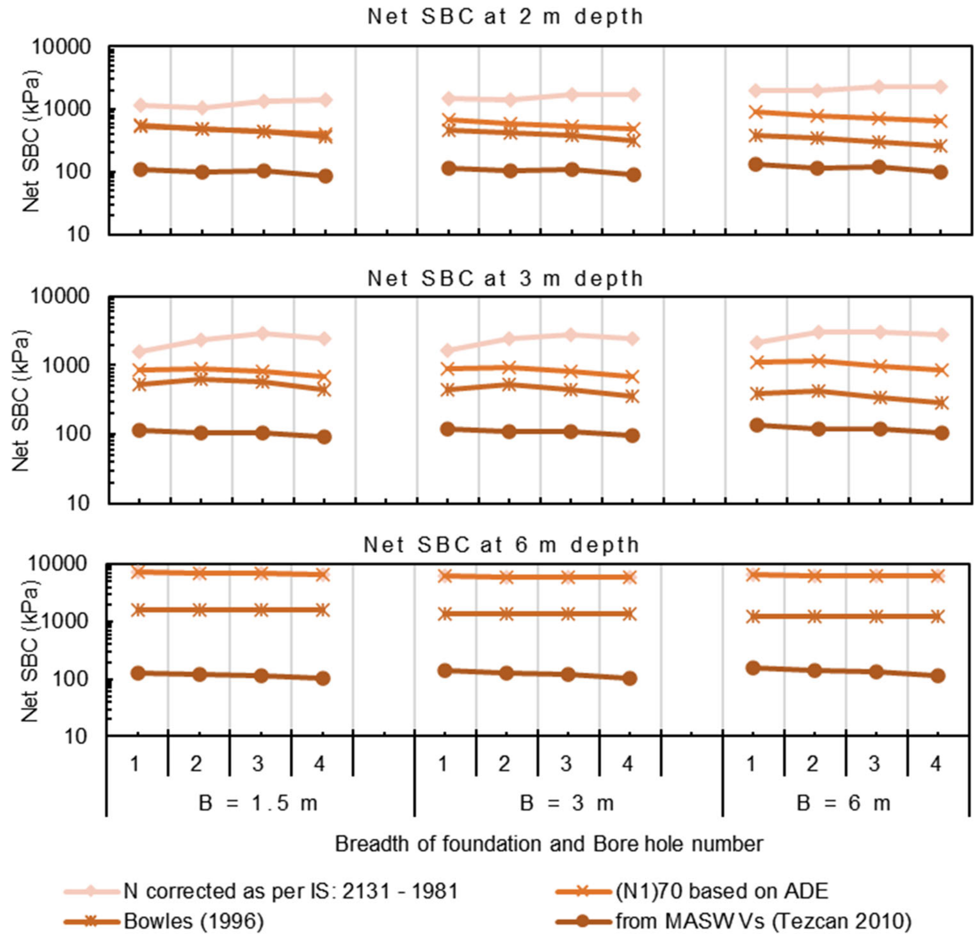


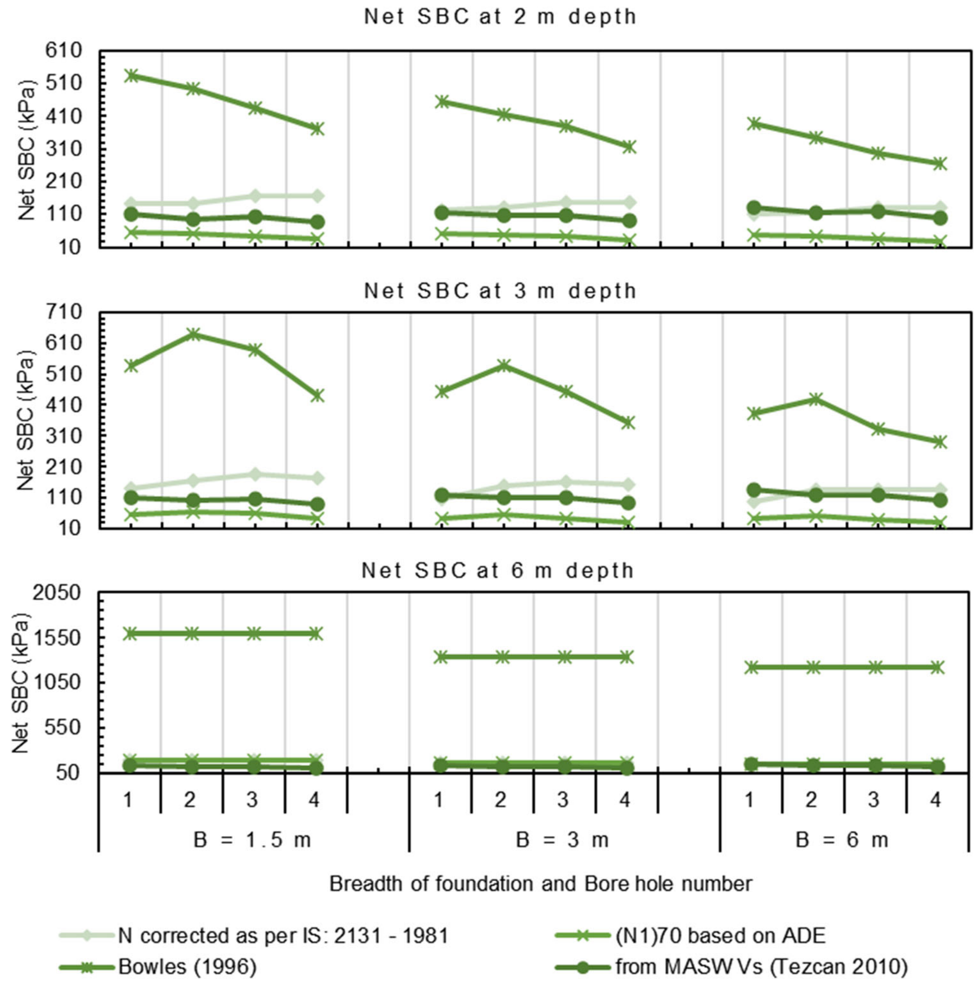
Fig. 16 Net SBC by shear criteria at 2 m, 3 m and 6 m foundation depth for 1.5 m, 3 m, and 6 m foundation breadth

This is because of the restricted settlement of the foundation. To ensure the building not to undergo settlement for the required load. The lesser SBC out of settlement and shear criteria need to be considered for the design of the foundation, which will always be a safer design. When the Net SBC for settlement criteria is compared, it shows a very clear match between Net SBC from V_s and N-value corrected based on ADE (Average each depth energy) at 6 m depth. For all the foundation dimensions, this holds good. As mentioned in the shear criteria section, there is a slight decrease in the Net SBC when the foundation dimension increases. Here, only four borehole data and two SPT equipment were studied; there may be a need to take a large number of similar experiments, understand the effect of Hammer energy, and establish an SBC estimation alternate method.

Summary and Conclusions

In India, drilling of borehole with SPT N measurement is almost adopted in all geotechnical designs, especially for SBC estimation and liquefaction assessment. But in none of the SPT tests, hammer energy is measured, and energy corrections are applied for N-values, as it is not mandatory in IS 2131 [8]. At the same time, locally fabricated SPT setups and untrained operators are applying 25–85% of the theoretical hammer energy during SPT tests. In this study, hammer energy in four boreholes with two types of SPT equipment in the same site is measured and reported using SPT HEMA (developed by IISc) and SPT Analyzer (developed by PDI, USA). Energy estimated using SPT HEMA is well comparable with energy from SPT Analyzer except for minimal difference due to joints between instrumented rods. SPT HEMA is capable of measuring energy below Anvil and above split spoon sampler; the energy measured below Anvil is used in the paper to understand the effect of energy on rebound and SBC values. The energy measured for each SPT N blows is used to create four cases, i.e., average depth energy, average borehole energy, average equipment energy, and average site energy. Because of the difference in each blow energy, taking the average energy for the site and among different equipment is not recommended. Until similar equipment and certified operator are adopted, it may be necessary to measure energy at each N-value measurement.

Fig. 17 Net SBC by settlement criteria at 2 m, 3 m, and 6 m foundation depth for 1.5 m, 3 m, and 6 m foundation breadth



In India, boreholes are terminated, or test at a depth is stopped when blow counts reach 50 irrespective of energy delivered. This termination of *N*-value (50) is different from the international practice of 50 and above count in ASTM for 15 cm penetration, which also needs to be adopted in India. One can apply less hammer energy and terminate the borehole in medium soil by showing an *N*-value of 50 as IS 2131 [8] does not insist on the energy measurement as part of SPT test. Corrected *N*-values as per IS 2131 [8] are more than uncorrected *N*-values up to 6 m and significantly reduced when site-specific measured energy is used for correction with reference energy of 70%. Net SBC obtained from *N*-values corrected as per IS 2131 [8] is higher than energy corrected *N*-values and far away from the alternate Net SBC by measured shear wave velocity in the same site. Net SBC estimation given in IS codes [47, 48] for shear and settlement criteria must be revisited, as Net SBC estimated as per code is more than other methods when influence stress zones are soil layers.

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Authors Contribution P.A. was involved in conceptualization, methodology, validation, re-sources, writing—review and editing, visualization, supervision. M.E.Y. helped in methodology, software, validation, investigation, re-sources, formal analysis, data curation, writing—original draft, visualization. A.K. contributed to MASW investigation, formal analysis, data curation re-sources.

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Declarations

Conflict of interest The authors declare that they have no conflict of Interest.

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