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TECHNICAL NOTE

Status quo of Standard Penetration Test in India: A Review of Field Practices and Suggestions to Incorporate in IS 2131

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Abstract SPT (Standard Penetration Test) being the most widely used field test has not been effectively regulated in India. Guidelines regarding hammer weight, the height of fall and use of liner are not followed correctly in the field, and guidelines for energy transfer efficiency and hammer blow rate are not addressed in the BIS (Bureau of Indian Standards) code for SPT. In this paper, some standard provisions on SPT in India and other countries are compared, and few observations on field SPT tests are presented. Operational and equipment-related variables, such as weights and dimensions of hammer, anvil, and drill rod, were noted in the field. Furthermore, hammer blow rate and inclination of guide rods during the field tests were also observed and are presented. It is found that IS 2131 (1981) does not provide standard dimensions of components of SPT set-up, and hence, there is a large variation in SPT set-up in practice and the whole set-up is usually an ensemble of locally manufactured components. This is a major defect in the SPT code and needs to be addressed. Sixteen different SPT set-ups were observed, which were employed on field SPT tests on 30 boreholes. Thirteen of the observed set-ups were used for the soil investigation for a large infrastructure project. Hammer blow rates are found to be very low as compared to those stated in IS 1893 (2016), DSO-98-17 (1999) and ASTM D6066 (2011). The inclination of guide rods in field was observed to be more than 5°, which causes friction between guide rod and drive weight and, hence, reduces the free fall velocity. These variables affect *N* values and international studies have reported correction factors to account for these. Because of the fact that large variety of set-up was observed, it will be prudent to standardise the dimensions of hammer and anvil, and hammer release mechanism to bring uniformity in SPT operations. Furthermore, normalising field *N* values to a standard energy ratio of 60% as per the international practice will facilitate reliability of *N* values obtained from different set-ups.

Keywords SPT · Hammer blow rate · IS2131 · Guide rod · SPT set-up

Introduction

SPT is the most widely adopted field test in soil investigation works in India. SPT *penetration resistance*, i.e. *N* value is defined as the number of blows required to cause the sampler to penetrate last 30 cm of total 45 cm penetration, using the driving weight of 63.5 kg falling over anvil from a drop height of 75 cm. Like any other field test, *N* values are affected by the set-up used to perform the test [1–4]. During the operation of hammer lifting and dropping, the verticality of guide rods, hammer–anvil dimensions and weights, sampler type, and hammer blow rate are equipment related or operational variables that may affect *N* values. Penetration resistance is inversely proportional to input energy [5], and hence among other variables, energy transferred to drill rods is the most important factor. This variation is caused as a result of using non-standard drop weight and height, lifting mechanism, anvil size and inclination of guide rods. Although IS 2131 [1] specifies maintaining verticality of guide rods, due to lack of

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methods to quantify the inclination of guide rods in the field, guide rods are observed to have some degree of inclination in the field, which reduces the free fall velocity and hence the input energy. There are other factors which may affect *N* value, such as sampler size, drill rod type, borehole diameter, hammer blow rate, etc. As these factors are accounted in modern SPT codes, they also need to be incorporated in the Indian codes on SPT. Being the principle document providing guidelines for SPT in India, IS 2131 [1] needs to be revised to include standard dimensions of SPT set-up, standard lifting mechanisms, desired hammer blow rates and some additional corrections such as energy correction and liner correction. Many times SPT results are used for liquefaction studies, and the code on liquefaction assessment IS 1893 [2] recommends five additional corrections which are not specified in IS 2131 [1], these need to be explored while revising IS 2131 [1].

Current Status of IS 2131

IS 2131 [6] was first published in 1963 as a part of a series of Indian Standards on site investigation and field tests for foundations of structures. The code was revised in 1981, in which the mass of the drive weight was changed to 63.5 kg from 65 kg and the sampler specifications were changed by introducing a new standard—IS 9640 [7]. The 1963 version recommended the use of split spoon sampler with 35 mm inside diameter (i.e. sampler with no space for liner), similar to that recommended by British standards [8]. The present recommendations on sampler dimensions at barrel and shoe as per IS 9640 [7] are given in Table 1.

Drill rods are connected in series with a sampler at the bottom end to reach the bottom of the borehole. IS 2131 [1] and IS 9640 [7] recommends drill rod with stiffness equal to or greater than that of A-rod with 41.3 mm outer diameter shall be used for connecting SPT sampler with drive weight assembly. Spacers may be used to increase the stiffness for depths more than 10 m or stiffer rods may be used.

Indian standard does not include energy correction for *N* values, nor does it mention any standard energy ratio to which *N* values obtained from different SPT set-ups should be normalised. However, it suggests ensuring that the energy of the falling weight is not reduced by friction between the drive weight and the guide rods or between rope and winch drum. The code specifies two corrections, viz. overburden correction and dilatancy correction to be applied to the field *N* values.

Table 1 Cutting shoe and sampler barrel dimensions suggested in IS 9640 [7]

Type of sampler	Inner diameter at shoe tip (mm)	Outer diameter at shoe tip (mm)	Length of tapering section (mm)
Without liner	38 ± 0.2	41	20
With liner	35 ± 0.2	38	27

IS 1893-2016 Part 1-Annexure: F

The previous version of IS 1893 [9] did not account for the energy correction, however, Annexure-F of the revised version states the requirement of the standard equipment for the SPT. It specifies the standard and common hammer type as safety hammer and a desired blow rate of 30 to 40 blows/min. The code suggests use of N_{60}, i.e. *N* value normalised to a standard energy ratio of 60%. Furthermore, it provides normalising factors for two types of hammer release mechanisms for donut hammer, and it states that safety hammer has an energy transfer efficiency of 60% and, hence, requires no energy correction. Energy corrections recommended in the code are summarised in Table 2. However, the basis for these provisions is not explained in the code.

Corrections as per IS 2131

IS 2131 suggests two corrections, viz. Overburden correction (C_N) and is applied to the field *N* values (N_f) as per Eq. (1). In addition to overburden correction, dilatancy correction is also suggested but only for fine sands and silts below water table and having $N' > 15$. Hence N_f shall be first corrected for overburden correction, and then if the conditions are met, the dilatancy correction shall be applied as per Eq. (2)

$$C_N = 0.77 \log_{10} \frac{20}{\bar{p}} \quad (1)$$

where $\bar{p}$ is effective overburden pressure in kg/cm^2

$$N'' = 15 + \frac{1}{2}(N' - 15) \quad (2)$$

where $N' = C_N \times N$; $N'' = N' \times$ dilatancy correction.

Table 2 Energy correction suggested in IS 1893 [2]

Type of hammer release mechanism	Correction
Donut hammer with rope and pulley	0.75
Donut hammer with trip or auto release	1.33
Safety hemmer	1.00

Table 3 Overburden corrections reported in literature, summarised by Moghaddam et al. [10]

References	Overburden corrections	Remarks
Peck et al. [11]	$0.77\log\frac{20}{\sigma'_v}$	σ'_v in tsf (ton/ft^2)
Seed et al. [12]	$1-1.25\log\sigma'_v$	σ'_v in tsf
Tokimatsu and Yoshimi [13]	$\frac{1.7}{0.7+\sigma'_v}$	σ'_v in kg/cm^2
Skempton [14]	$200/(100+\sigma'_v)$ for D_R = 40–60% and NC Sand	σ'_v in kPa
	$\frac{300}{200+\sigma'_v}$ for D_R = 60–80% and NC Sand	
	$\frac{170}{70+\sigma'_v}$ for OC Sand	
Liao and Whitman [15]	$\sqrt{\frac{100}{\sigma'_v}}$ for NC Sand	σ'_v in kPa
	$\left[\frac{\sigma'_{REF}}{\sigma'_v}\right]^k$ for k = 0.4 to 0.6	
Clayton [16]	$\frac{143}{43+\sigma'_v}$ for OC Sand	σ'_v in kPa

Moghaddem et al. [10] summarised overburden corrections reported in the literature, which are given in Table 3. ASTM D 6066 [4] gives a comparison of the C_N values given by Peck et al. [11] Seed et al. [12], Skempton [14], Liao and Whitman [15]. British standards [8] recommend C_N similar to Skempton [14] and Liao and Whitman [15], whereas IS 2131 [1] recommends C_N similar to Peck et al. [11]. Figure 1 gives a comparison of overburden correction recommended in British standards [8] and IS 2131 [1]. It can be seen that for lower values of effective overburden pressure the values of C_N have very high discrepancy. IS 2131 [1] suggests a single correction for all soil types, and this can be revised by conducting tests for different types of soils under various overburden pressures. Both overburden and dilatancy correction need to be revised, and their efficacy be revisited, as both these corrections were suggested several years ago.

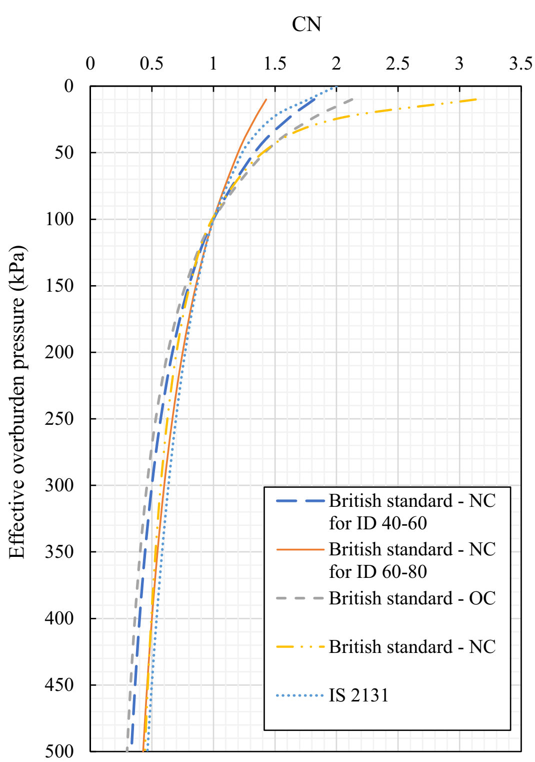


Fig. 1 Overburdern correction recommeded in British standard and Indian Standards

Corrections Stated in IS 1893

In addition to overburden correction and dilatancy correction suggested in IS 2131 [1], IS 1893 [2] states five more corrections to be applied to the field *N* values, viz. energy correction, correction for non-standard hammer weight and height of fall, liner correction, short rod length correction, and borehole diameter correction. Table 4 provides a comparison of liner correction suggested in the literature and that suggested in IS 1893 [2], it can be observed that there is significant ambiguity regarding the use of a liner. Rod length corrections suggested in IS 1893 [2] and the literature are illustrated in Table 5.

It states energy correction for two types of hammer set-ups. The code recommends that the sampler without the space for liner shall be used, however, if sampler with space for the liner is used with or without liner, the liner corrections shall be applied. Rod length corrections are similar to those recommended by Skempton [14]. And standard borehole diameter recommended in corrections is not similar to that suggested in IS 2131 [1]. IS 1893 [2] recommends a blow rate of 30–40 blows/min. Furthermore, the code also recommends a correction to normalise the effect of the non-standard weight of hammer and height of fall, which in a way legitimises the use of non-standard weight and drop height. Hence, this correction goes against SPT guidelines, as IS 2131 [1] recommends that drop height of 75 cm and hammer weight of 63.5 ± 0.5 kg shall be strictly followed in field.

Table 4 Liner correction reported in the literature (modified after Aggour and Rose [17])

Sampler	Robertson and Wride [18]	Bowles [19]	Skempton [14]	IS 1893 [2]	BS EN ISO 22476-3 [8]
No liner	1.1–1.3	1	1.2	1.1 (for loose sand) 1.2 (for dense sand)	1.1–1.2 (for sampler with space for liner is used without liner)
With liner: loose sand	1	0.9	1	0.9 (for loose sand)	1 (for sampler with space for liner is used with liner)
With liner: dense sand, clay	1	0.8	1	0.8 (for dense sand)	1 (for sampler with space for liner is used with liner)

Table 5 Rod length correction reported in the literature (modified after Aggour and Rose [17])

Total rod length (m)	Robertson and Wride [18]	Bowles [19]	Skempton [14]	IS1893 [2]	BS EN ISO 22476-3 [8]
>30	<1	1	1	–	1
10–30	1	1	1	1	1
6–10	0.95	0.95	0.95	0.95	0.95
4–6	0.85	0.85	0.85	0.85	0.85
3–4	0.75	0.75	0.75	0.8	0.75
0–3	–	0.75	0.75	0.75	–

Corrections Reported in Literature

Aggour and Rose [17] carried a thorough literature review of corrections to be applied to the N values for SPT operations carried by Maryland State Highway Authority. They suggested that in addition to the overburden correction, field N values (N_f) shall be subjected to the following corrections:

$$N_{60} = N_f \times n_1 \times n_2 \times n_3 \times n_4 \times n_5 \times n_6 \quad (3)$$

where N_{60} = N values normalised to 60% energy ratio (E_r), n_1 = energy correction factor, n_2 = rod length correction factor, n_3 = liner correction factor, n_4 = borehole diameter correction factor, n_5 = anvil correction factor, n_6 = blow count frequency correction factor.

Among all corrections, energy correction is underscored widely in literature [12, 14, 20–23]. Aggour and Rose [17] concluded that there is a wide range of energy corrections suggested in the literature, this means using a correction factor may not necessarily capture the energy efficiency of the SPT set-up effectively because of the large variation of energy among SPT set-ups and hammer types. Hence, the reliance on the corrections suggested in literature shall be avoided especially if the operator and equipment related variables are estimated to dominate the SPT operation (i.e. for safety or donut hammer). They further recommended that energy measurement shall be carried out on each and every measurement of SPT N values periodically as these values vary depending on several factors in present SPT practices.

Because several different types of set-ups are used in the field, and there is no set-up with all standard parameters, furthermore, there is no reference set-up suggested by BIS to which N values can be normalised to. Therefore, to bring uniformity in the result of SPT practices and to normalise N values, corrections regarding energy, liner, borehole diameter, etc., shall be necessarily applied.

SPT Guidelines in Other Countries

ASTM (American Society for Testing and Materials) provides very comprehensive specifications for determining penetration resistance by specifying test details, test procedure using different hammer set-up and drilling method, standard energy ratio, etc. ASTM has published three SPT related standard guidelines, which are updated frequently after substantial research and testing. ASTM D1586 [24] lays a standard procedure for the SPT test for general practice. ASTM provides a separate document specifying guideline for determining and correcting N values for use in liquefaction assessment studies, which is ASTM D6066

[4]. Furthermore, a separate document—ASTM D4633 [25]—is published for specifications of energy measurements in dynamic penetrometers. ASTM D1586 [24] recognises following mechanical and operational variables of *N* value. However, it does not recommend values of correction factors for these variables. It recognises that different configurations of these variables may exist in the field.

1. Sampler Split Barrel—Inside Diameter—Liners and No Liners:
2. Sampler Design:
3. Drive shoe
4. Drill Rod Type and Rod Length
5. Drilling Method
6. Drill hole diameter

ASTM D4633 [25] recommends measurement of force and acceleration time histories to calculate the energy transferred to the drill rod assembly using FV method. It also suggests that energy measurement is more reliable when the length L is 9 to 12 m or more. Force and velocity records shall return to near zero at the end of the record. It suggests that energy measurements shall be performed for at least 3 and preferably 5 depths with reliable (i.e. free from measurement error) data while using the SPT system in as nearly a routine manner as practical. However it further recommends that as many as possible measurements shall be taken and energy results shall be averaged.

ASTM D6066 [4] provides guidelines for obtaining normalised penetration in cohesionless soils for estimating soil liquefaction potential during earthquakes. The standard proposes normalising *N* value for standard energy ratio of 60% by two methods

A. by using hammer systems with estimated energy delivery. Safety hammers with the rope-cathead operation are assumed to deliver approximately 60% drill rod energy ($E_r \approx 60\%$). Automatic hammer energy must be documented in previous measurements for a particular make and model, either by the manufacturer or from previous measurements by other entities. **OR**
B. penetration resistance data is adjusted to 60% drill rod energy ratio through directly measured drill rod stress wave energy using Test Method ASTM D4633 [25].

The code recommends that unless otherwise specified method B should be followed.

BS EN ISO 22476-3 [8] standard is followed in European countries including Britain. The definition of *N* value is similar to that in IS 2131 [1], except in this code, seating drive is not necessarily 150 mm, instead, it is 150 mm or 25 blows, whichever is reached first. If the seating drive is terminated at 25 blows, the depth of penetration shall be recorded, and the next 300 mm shall be measured from that depth. The standard does not specify the standard hammer set-up, however, specifies drill rod dimensions with restricting the use of rods heavier than 10 kg/m. Importance of energy ratio is acknowledged in this standard, by defining terms—E_{meas}, E_{theor} and E_r as energy measured below anvil, theoretical maximum potential energy and energy ratio (E_{meas}/E_{theor}), respectively. It makes reporting the energy ratio (E_r) and the calibration report mandatory, and further provides an informative (non-mandatory) Annexure to include corrections to be applied to *N* values.

Following corrections are suggested in the annexure:

1. Energy correction (for 60%)
2. Rod length correction
3. Overburden correction
4. Liner correction in sands

BS EN ISO 22476-3 [8] also lays general specifications for Energy measurement equipment to be used during energy calibration of SPT set-up. These specifications include the use of equipment for recording force and acceleration, to calculate energy using the FV method. Minimum five energy records (blows) shall be made and the mean should be recorded to report E_r.

Hammer and anvil dimensions affect energy transfer efficiencies, as reported by various studies [12, 23, 26]. Considering this Japanese Institute of Standards (JIS) [27] standardised hammer and anvil dimensions for donut hammer to avoid the effect of different hammer–anvil impedance ratios. the hammer shall be 180 mm in diameter with 43 mm hole and anvil diameter shall be 71 mm. Recording of penetration length is to be done using sensors to 3 mm accuracy, and *N* value when exceeds 50 is to be reported as refusal as per Japanese standard.

IRTP 1988

Variation of SPT procedure was reported in the literature since its inception [28], considering this, various symposiums were held in Europe to discuss and standardise a procedure for all penetration tests. After several symposiums on penetration testing, ISSMGE recognised the variabilities in SPT and other penetration tests practices followed in different member countries, and hence, a special symposium called International Symposium on Penetration Testing (ISOPT) was held in Orlando, Florida in 1988. Working parties for different penetration tests consisting of experts were formed during ISOPT. The working party for SPT drafted a document delineating its origin, current practices, standard guidelines, and recommendations for SPT. This document is known as the International Reference Test Procedure (IRTP). IRTP [29] recognised the variabilities associated with SPT, especially in the case where results are to be used for international research or for comparison purposes. Hence, a reference test procedure was necessary to better the communication of results between countries, to understand differences in procedure between different countries and to use best suited correlations.

The IRTP [29] provides recommendations for the type of boring, borehole diameter, the unit mass of drill rod and their sizes, seating drive limits and blow rate. It suggested energy measurement using F^2, i.e. only force measurements (because FV method, i.e. force and acceleration measurements were not yet developed). The split sampler suggested in the document had a constant internal diameter of 35 mm at the shoe and barrel sections, i.e. without space for liner.

The document attributed anvil size and shape to be the primary cause of loss of energy, therefore IRTP [29] recommends a uniform hammer-anvil sizes and shape shall be maintained in a country to help reduce the variability. This means that the same type of hammer system, with uniform dimensions, shall be followed in the country. It suggests the application of rod length correction for rod lengths less than the "*equivalent length*" (L_0), this L_0 is determined using Eq. (4)

$$L_0 = {}^{M_\mathrm{h}}\!/_{m_\mathrm{r}} \tag{4}$$

where M_h = mass of standard hammer; m_r = mass of the rod per unit length.

Even though IRTP [29] benchmarked some requirements for SPT, in many countries the test depends on local code of practice or in some countries based on ASTM guidelines. Furthermore, the IRTP document itself is old, and many different hammer lifting mechanisms are available now.

Some aspects of standard guidelines from various countries regarding SPT are compared in Table 6. It can be observed that the details are not matching, this shall be considered while using N values obtained from different countries, especially for research purposes. Also standard hammer type, standard hammer and anvil dimensions, standard lifting mechanism are not provided in any country's standard guidelines.

Field Observations

Field SPT tests were performed on 30 boreholes as part of a study conducted to record energy efficiencies of Indian SPT set-ups. During the study, 16 different SPT set-ups were observed which were used to conduct a total of 144 SPT tests, wherein energy was measured for each SPT blows, for more than 130 SPT tests. The database comprises of more than 6000 blows. Dimensions and weights of hammer and anvil, hammer blow rates, hammer-lifting mechanism were noted. Observations made on SPT field procedure, and operational and equipment related errors causing variability of field N values, are discussed in the following sections. Based on hammer lifting-dropping mechanism the observed set-ups were categorised into 3 types. Among them two types of set-ups had spool and winch for lifting the hammer, these are referred to as Hydraulic Drill rig with spooling winch (HRL), and Rotary Drill rig with spooling winch (RRL). Hammer lifting mechanism on these two types of set-up comprised a winch operated by labours to increase the tension in rope in order to lift the hammer and once the desired height was reached the operator released the tension hence, allowing the hammer to fall on the anvil. The third type of set-up consisted of hammer lifting using a rope and pulley system wherein labours were pulling and releasing the rope which ran over a crown pulley to lift and drop the hammer. This set-up is referred as Rotary drill rig with rope and pulley system (RRH).

Hammer and Anvil Dimensions

Hammer and anvil dimensions and weights were noted during the field study (Tables 7, 8), their dimensions varied with set-up. Most of the RRL and RRH rigs were manufactured in local lathe workshops and were comprised of larger drill rods and lower masses of hammer drive weight.

Drill Rods

Two types of drill rod are observed in field, viz. AW drill rod and CALYX drill rod, their dimensions and weights are given in Table 9. For Hydraulic drill rig (HRL), AW type drill rods were used which are Wireline Drill Rods made of cold drawn seamless steel tubes (Carbon steel) of SAE-1541. Both the HRL rigs and three RRL (Rotary drill rig) rigs had the same AW drill rods with outer diameter of 44 mm (± 0.5 mm) rod. These drill rods were connected with each other without any connectors or coupler.

Seventeen boreholes were tested using a rotary drill rig which used CALYX drill rod which had an outer diameter 51 mm (± 0.5 mm), It was connected using couplers (connectors) of size 63 mm (± 0.5 mm) outer diameter and 110 mm (± 0.5 mm) height. Figure 2 shows AW thread size and CALYX rod thread size comparison. Various sizes of drill rods are adopted in different countries, standard specifications on SPT of many countries does not specify one particular dimension to be followed as a standard size. International guidelines on drill rod size specify the use of drill rod with minimum stiffness of A-size drill rod (ID = 28.6 mm, OD = 41.3 mm). Indian

Table 6 Comparison of some aspects of SPT guidelines from various countries

Code	Hammer mass (kg)	Drop height (mm)	Theoretical potential energy (J)	Energy measurement suggested	Maximum borehole diameter (mm)	Space for liner	Type of drill rods
IS 2131 [1]	63.5	750	467	No	100 to 150	Yes	> A-rod
BS EN ISO 22476-3 [8]	63.5 ± 0.5	760 ± 10	473	Yes	150	No/Yes (3 mm)	AW and BW
AS 1289.6.3.1 [30]	63.5 ± 1	760 ± 15	473	No	minimum 65	No, but may have a core retainer,	> A-rod
JIS A 1219 [27]	63.5	760	473	–	maximum 150	No	> A-rod
ASTM D6066 [4]	63.5 ± 1	762	473	Yes	75 to 125	Yes	> A-rod
ASTM D1586 [24]	63.5 ± 1	762	475	Yes	75 to 150	Yes	> A-rod
IRTP- [29]	63.5	762	475	Yes	63.5 to 150	No	AW rods (limit 10.03 kg/m)

code as well specifies that minimum A-size drill rod is used; however, AW drill rods are used on all Hydraulic drill rigs. Locally manufactured drill rods are usually larger in size and weight than AW rods.

A comparative study where different types of drill rods are used in a controlled environment may show the effect of weight and dimensions of drill rods, also the effect of connectors needs to be explored as they increase the stiffness of connections. Besides drill rods, hammer and anvil dimensions also vary for different set-ups, largely because these components are not standardised by BIS guidelines and manufactured in local lathe machine workshops.

Inclination of Guide Rods

SPT procedure specifies the friction between guide rod and drive weight shall be negligible, in other words, the verticality of the guide rod shall be maintained. If the hammer and guide rod are constantly in contact while the hammer is falling, it reduces the free fall velocity, and hence, theoretical maximum impact velocity is not mobilised at the point of impact. Kovacs et al. [32] measured the inclination of guide rod during the drop of donut hammer, and they reported the reduction of impact velocity will be more than 5% if the inclination exceeds 3°. As shown in Fig. 3, a reduction of 5% in impact velocity will reduce 9.75% of kinetic energy, and it reduces at the higher rate for further reduction in impact velocity.

The Inclination of Drive Weight Assembly

Figure 4 shows 5.8° inclination of guide rod used in HRL_01 rig, this set-up consisted of a 7.5-kg cylindrical anvil connected with guide rods by adapters from top and bottom. It is difficult to measure the actual inclination of the guide rod and drill rod assembly in the field, and even more difficult is it to quantify the effect of the inclination on the impact velocity and *N* value. The inclination was observed by fixing a *DSLR* camera with a tripod in a true plumb line. As the operator lifted and dropped the hammer on the anvil, high-resolution pictures were clicked at a high frame rate. The horizontal thick red lines are marked on images to show deviation of guide rod with respect to a vertical rod fixed on the drill rig. The lines were marked on a fixed point in the image so as to articulate the change in inclination during the lifting and dropping, through a series of captured images. The longer red line marks indicate more inclination and vice versa. The guide rod and vertical rod are highlighted by drawing vertical yellow lines on the images to further articulate the inclined position of the guide rod.

The inclination of guide rod during lifting and dropping of the hammer is shown with two red lines marked at top of the guide rod and at the bottom of guide rod near anvil. Figure 5 depicts the hammer at rest (a), hammer lifted (b) hammer dropped (c) and hammer impacting anvil (d). Through this series of images, it can be inferred that the guide rod and drill rod assembly was wobbling in the vertical plane. Use of stiffer connections at guide rod–anvil–drill rod can reduce the inclination, but the free fall will still be obstructed because of wobbling of the drill rod assembly.

Table 7 Hammer and anvil dimensions observed during field SPTs

Sr. no.	Test	Rig name	Hammer mass (kg)	Anvil type	Drill rod type	Lifting and dropping
1	T_01	HRL-01	62	Cylinder-1	AW	Spooling Winch
2	T_02	RRL-01	NA*	Coupler-2	AW	Spooling Winch
3	T_03	RRL-02	NA*	Coupler	AW	Spooling Winch
4	T_04	RRL-03	54	Coupler	AW	Spooling Winch
5	T_05	RRL-04	58	Plate-1	CALYX	Spooling Winch
6	T_06	RRL-05	55	Coupler	CALYX	Spooling Winch
7	T_07	RRL-06	54	Coupler	AW	Spooling Winch
8	T_08	RRL-07	56.2	Coupler	CALYX	Spooling Winch
9	T_09	RRL-08	60	Plate-2	CALYX	Spooling Winch
10	T_10	RRH-01	64.5	Coupler	CALYX	Manual Lifting
11	T_11	RRL-09	60	Plate-2	CALYX	Spooling Winch
12	T_12	RRL-10	60	Plate-3	CALYX	Spooling Winch
13	T_13	RRL-11	56.2	Coupler	CALYX	Spooling Winch
14	T_14	RRH-02	64.5	Coupler	CALYX	Manual Lifting
15	T_15	HRL-01	62	Cylinder-1	AW	Spooling Winch
16	T_16	HRL-01	62	Cylinder-1	AW	Spooling Winch
17	T_17	HRL-01	62	Cylinder-1	AW	Spooling Winch
18	T_18	HRL-01	62	Cylinder-1	AW	Spooling Winch
19	T_19	HRL-02	65	Cylinder-1	AW	Spooling Winch
20	T_21	RRH-03	61.5	Coupler	CALYX	Manual Lifting
21	T_22	RRH-03	61.5	Coupler	CALYX	Manual Lifting
22	T_23	RRH-03	61.5	Coupler	CALYX	Manual Lifting
23	T_24	RRH-03	61.5	Coupler	CALYX	Manual Lifting
24	T_25	RRH-03	61.5	Coupler	CALYX	Manual Lifting
25	T_26	RRH-03	61.5	Coupler	CALYX	Manual Lifting
26	T_27	RRH-03	61.5	Coupler	CALYX	Manual Lifting
27	T_28	RRH-03	61.5	Coupler	CALYX	Manual Lifting
28	T_29	HRL-01	62	Cylinder-1	AW	Spooling Winch
29	T_30	HRL-01	62	Cylinder-1	AW	Spooling Winch
30	T_31	HRL-01	62	Cylinder-1	AW	Spooling Winch

*measurement not taken

Table 8 Different Anvil shapes and dimensions observed in field SPTs

Sr. no.	Anvil type	Height (cm)	Diameter (cm)
1	Cylinder-1	11	10
2	Cylinder-2	14	10
3	Coupler	11	6
4	Plate-1	2.5	10
5	Plate-2	2.5	11
6	Plate-3	2.5	22

The whole assembly was observed to be wobbling back and forth, which was a common observation at all hammer set-ups. This effect is reduced by assigning a worker with the task of holding the drill rod during the hammer lifting and dropping, even with this the wobbling persisted in all tests. Quantifying effect of inclined drill rod assembly on *N* value and transferred energies still remain elusive. It is apparent that the inclined guide rod will obstruct the free fall velocity and hence reduce transferred energy; hence, possible solutions may be to replace the components of the set-up causing weak connection and inclination and to measure the transferred energy wherever required for normalising the resulted *N* value for a standard energy ratio.

Varying Hammer Drop Height

Because of manual operation, the drop height of 75 cm is not efficiently maintained in most of the tests engaged for energy

Table 9 Dimensions of Drill rods observed in the field

Drill rod type	Weight per meter length (kg)	Outer diameter (mm)	Inner diameter (mm)	Thread thickness (mm)	Pitch of thread (mm)
AW	4.5	44	33	3.3	8
CALYX	7.6	51	37	2.8	5

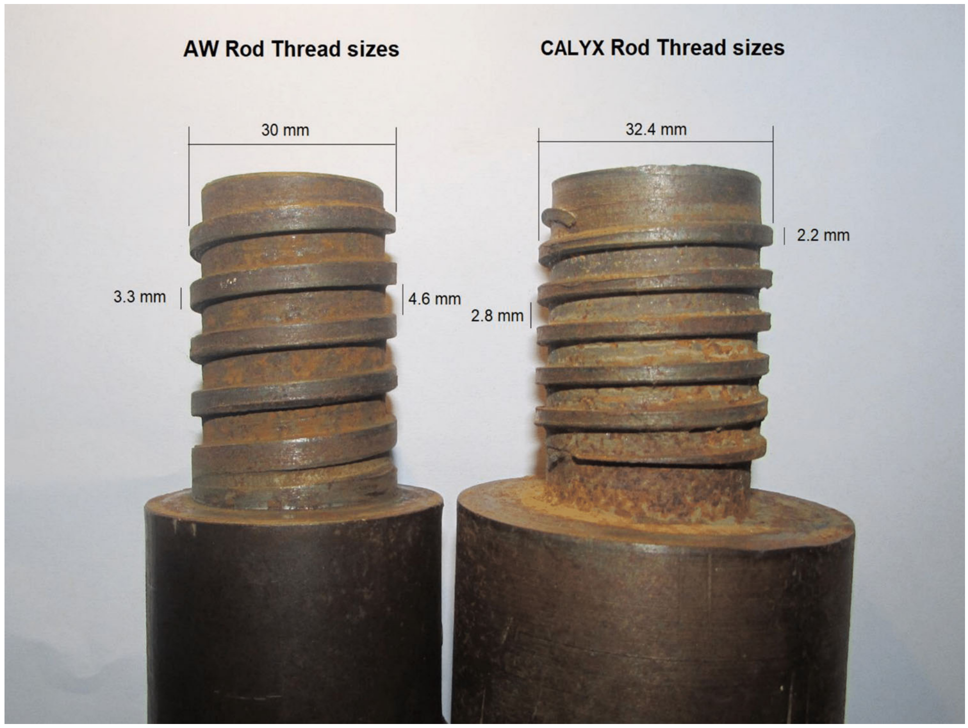


Fig. 2 Two types of drill rod and their end threading used during the study

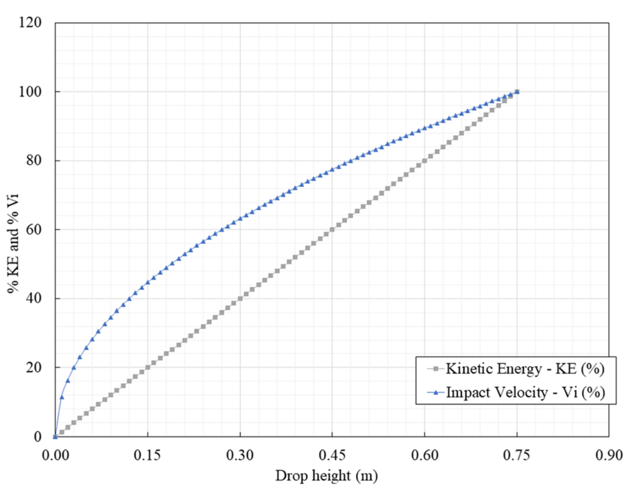


Fig. 3 Hammer Impact Velocity and Kinetic Energy as a function of drop height

measurements. It is observed that the guide rod did not have a permanent 75 cm mark, furthermore, guide rods with a permanent mark for 75 cm drop height are often not used in the field. As a result, one of the drill rods is attached as a temporary guide rod, this was observed on 15 out of 16 SPT set-ups (only one set-up had a guide rod, but it did not have a permanent 75 cm mark). During the field study, we insisted operators to mark a 75 cm line on guide rod with a chalk, which used to get erased during hammer lifting after few blows. Although the variation of the height of fall was not specifically measured but the videotapes of all SPT tests reveal it varied by approximately ± 2 to 3 inches. Use of a permanent guide rod with a mark for donut hammer will reduce this variability. Lower drop heights will reduce the hammer free fall velocity. Hence, it can be inferred that an inclined guide rod and an insufficient drop height, coupled with heavier anvil will result in a significant reduction in measured energy below the anvil. Hence, the resulting *N* value will be very high, giving a false impression of denser or stiffer soil.

Use of Liners in Split Samplers

Studies [23, 24, 28, 29] reported from various countries confirm that liners are rarely used in sampler during SPT.

Fig. 4 Inclination of guide rod with respect to vertical rod fixed on drill rig

Liner is a thin (1–1.5 mm) brass cylinder, placed inside sampler for better sampler recovery of loose cohesionless soils. Based on field observations and discussion with field practitioners it is found that in India as well, the samplers with a larger diameter at barrel section than shoe are widely used without liners. Use of liner has been long discarded in the field, though not by an official decree. Presence of liner would offer additional resistance to the penetration therefore when they are not used, lower *N* values will be obtained, hence, Skempton [14] and British Standards [8] suggest a correction to *N* values to account for not using a liner in a sampler with space for liner. It is observed that using sampler without liner has been practised for so long that it has become a new "standard" practice, therefore liner correction is seldom applied to *N* values. Sampler with a constant inner diameter, as suggested in British standard [8] shall be advised otherwise a correction factor similar to that specified in IS 1893 [2] shall be recommended in IS 2131 [1] as well.

Storage of Samples

It is specified in IS 2131 [2] that the soil sample obtained at the end of the test shall be stored without ramming in jars with self-sealing or waxed top. And liners shall be used when the jars are not available, in such case the code suggests the use of sampler with larger inside diameter. The liner shall be confirming the specifications of IS 407 [31]. However, in the field, neither jars nor liners are used to store the soil sample, instead, plastic bags are used. This shall be recognised by IS 2131 [1] and the difference in sample properties after storing using jars, liners, and plastic bags, if any, needs to be explored.

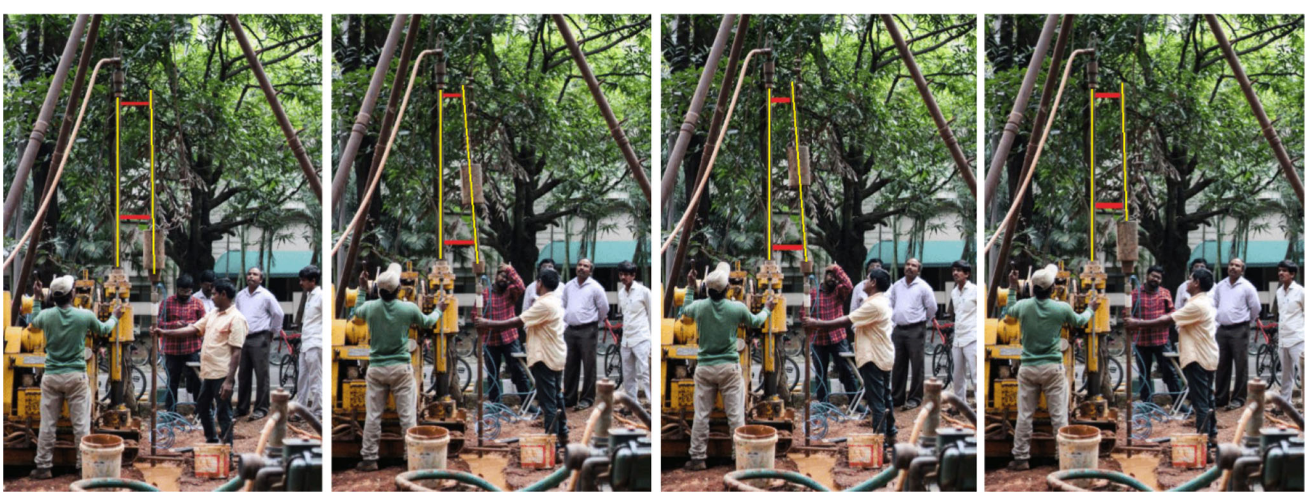


Fig. 5 Hammer lifting and releasing during a typical blow of HRL equipment showing inclination of guide rod during the operation of hammer lifting

Hammer Blow Rate Requirement for Liquefaction Studies

Seed et al. [12] studied SPT practices in various countries and reported that hammer blow rates were significantly lower in Japan compared to those in the US. In USA, hammer blow rates ranged typically between 30–40 blows per minute. But with the Japanese Tombi method it was in the order of 10–25 blows per minute and with the Japanese rope and pulley technique involving the special throw, it was only of the order of 17–20 blows per minute. Blow rates observed in this study also belong to the range of 10–25 blows per minute. Even if the energy ratio were the same, different *N* values can be expected in tests performed with significantly different rates of hammer blow applications. Seed et al. [12] attributed this to the process of release of excess pore water pressure in saturated sandy soils. They concluded that "During the penetration of the sampler into a cohesionless soil, pore pressures are developed. In loose sands, these pore pressures are likely to be positive (in excess of hydrostatic pressures). A lower frequency of blow application will permit more of this excess pore water pressure to dissipate between blows than with a higher frequency of blow application, resulting in a higher effective stress condition and a correspondingly higher resistance to sampler penetration (i.e. higher *N* values). For dense sands, the effect would be reversed."

Figure 6 shows average hammer blow rates observed on 30 boreholes and the standard range of blow rate specified in IS 1893 [2] and ASTM D6066 [4]. Though the criterion for blow rate during SPT N measurement is not explicitly mentioned in the BIS and ASTM codes on SPT, codes on liquefaction potential assessment recommend a range of blow rate. As shown in Fig. 6 the range specified in IS 1893 [2] is 30–40 blows/min and that specified in ASTM D6066 [4] is 20–40 blow/min. However, in a normal winch system, the number of strikes per minute cannot exceed 20 regardless of the type of hammer used. In the case of automatic hammer systems and manual lifting-dropping system with rope and pulley, the number of strikes per minute can be larger than 30. Hammer blow rate is neither recorded nor reported in India because of the manual operating of SPT set-ups. However, for automatic hammers, the blow rate needs to be predefined for equipment operation, but automatic hammers are not as predominantly used in India as the manually operated donut hammers. Data collected during an SPT may later be used for liquefaction assessment of the site in many seismic microzonation studies and liquefaction assessment for ground improvement. Hence, it is better to maintain the blow rate within some standard range. Also, the record of blow rate shall be part of the test reports so that it will help while using *N* values for liquefaction assessment and dynamic application.

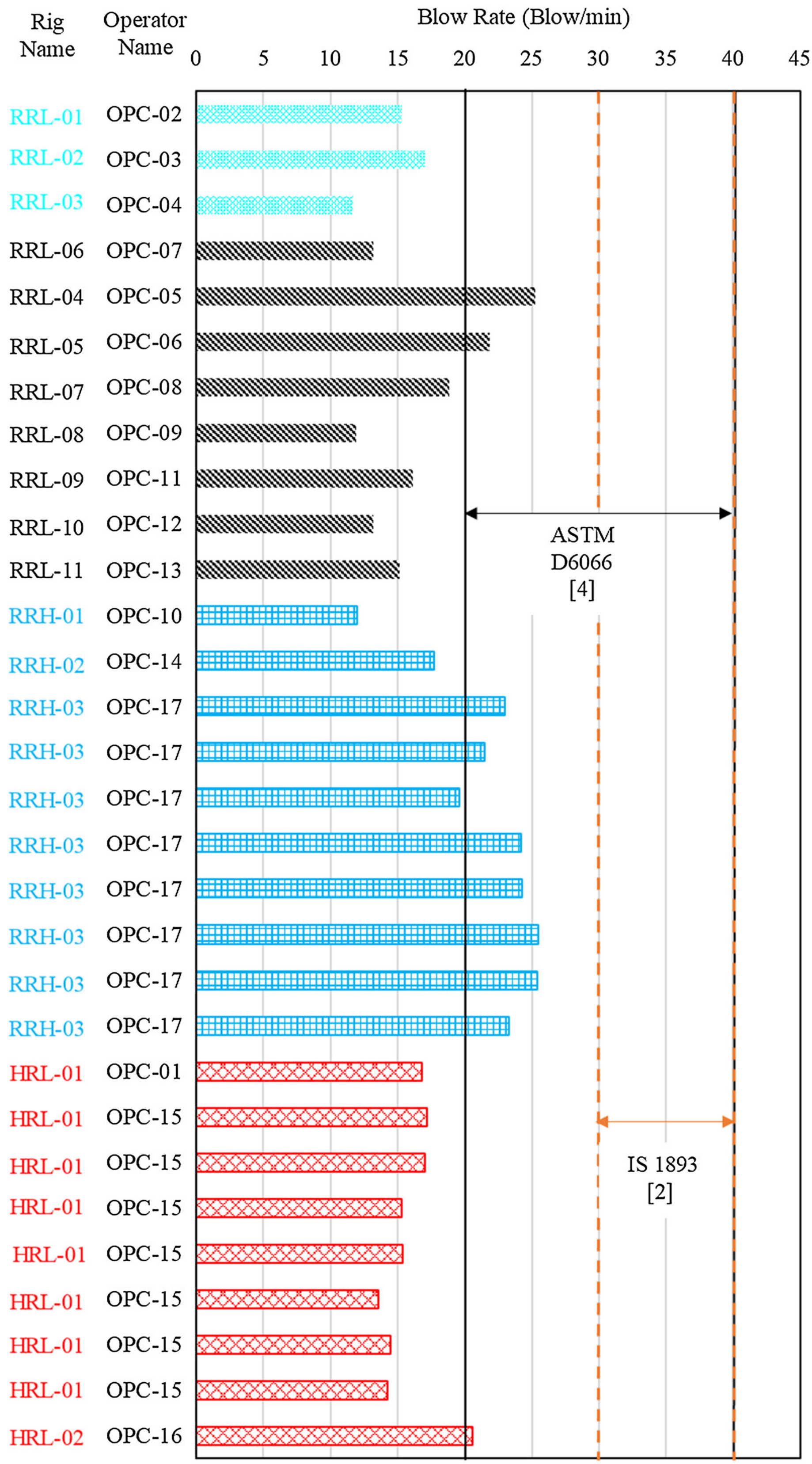
Suggestions to Revise the IS Code

1. IS 2131 [1] shall be revised to incorporate provisions for latest developments and modern field practices and additional corrections.
2. Hammer and anvil dimensions shall be standardised by IS code, the ambiguity of sampler and drill rods dimensions and use of connectors shall be cleared by IS code.
3. Spooling winch-type of lifting mechanism is reported to have very high energy variation [3], it also has high scope for equipment related variation [32, 33]. Therefore, we recommend using rope and pulley lifting system or automatic lifting system. Standard dimensions of hammer and anvil shall be decided by IS 2131 based on input energy and workability in the field.
4. Blow rate shall be noted during the SPT and shall be a part of the result reported in field bore-log. Furthermore, standard blow rate of the Standard SPT set-up shall be recommended by IS 2131, by considering blow rate of predominantly used Indian SPT set-up.
5. Energy corrections based on actually measured energies may account for several operational and equipment related variables. As specified in Table 6, many developed countries have recognised energy measurement as part of standard procedure. Furthermore, considering the manual operating of hammers, and wide variation in components, it is beneficial to record actual energies during SPT tests to derive energy correction.
6. Energy Measurement will be very important especially when multiple drill rigs are employed for a soil investigation of the large infrastructure project.

Conclusions

Guidelines on SPT in India and few other countries regarding some aspects such as, components of SPT set-up, *N* value corrections, were discussed. It is found that IS 2131 needs to be revised to account for the variation of SPT set-up, and *N* value corrections considering the type of SPT set-ups observed in the field. Hammer and anvil dimensions and lifting systems have huge variability this may affect free fall velocity and hence result in variations of *N* values. Hammer blow rates observed during the field tests are much lower than the range specified in IS 1893 [2], also the basis for blow rate recommendations made in

Fig. 6 Mean blow rates observed on 30 boreholes carried by 17 operators (OPC)



this code needs to be studied and some suggestions needs to be revised in order to be more realistic to Indian practices. A typical Hydraulic rig was studied and the inclination of the guide rod and whole drill rod assembly was shown to be more than 5°. Higher inclinations cause friction between guide rod and hammer drive weight, this affects hammer input energy and thereby increases the *N* values. Standard guidelines in developed countries recognise energy measurement as an important factor, hence, recommend the knowledge of energy efficiency of the SPT set-up being used in the field. Considering the wide variation of set-up and operational error resulting from reliance on manual operation in Indian SPT tests, energy correction of *N* values to a standard energy ratio of 60% or required level shall increase the reliability of *N* values and SPT.

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