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Effect of Hammer Energy and Corrections on the Correlation between SPT N-Value and Shear Wave Velocity

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ABSTRACT

The Standard Penetration Test (SPT) is the most widely adopted method in geotechnical exploration, as the SPT N-value is correlated with many static and dynamic soil properties. In developing countries, different SPT rigs with various SPT components are engaged to measure N-values without Hammer energy measurement. As a result, the N-value is subject to multiple variabilities of error. The most important things affecting the N-value are overburden and Hammer energy corrections (known as Energy Transfer Ratio: ETR %). Several studies have tried to link N-values to soil strength and Shear Wave Velocity (Vs), but these relations were developed in specific places without specifying ETR, even though SPT N-values highly depend on ERT. Correlating ETR corrected N-value with any soil properties is a meaningful way of developing such correlation, but limited studies are available in this line. It was often impossible because of the non-availability of energy measurement and/or the use of old multiple geotechnical agency reports with or without energy measurement. Hence, in this study, for the first time, in-situ measurements of SPT with hammer energy as per ASTM D4633 (2016) and Vs using Multichannel analysis of surface (MASW) are carried out at the same time. SPT-HEMA (Anbazhagan et al., 2022a) is used to measure ETR during SPT. These measurements allowed the authors to categorise N-values based on energy measurements and correlate them with corresponding Vs measurements. This study revealed notable findings that the reduced energy value increases the N-value, and vice versa, while stiffness and Vs values remained consistent. This highlights the critical importance of energy measurement during every SPT test. In this study, the authors introduce new correlations, highlighting that incorporating energy measurements enhances the meaningfulness of these correlations. Also, this study suggests energy and N-value corrections to enhance and update existing N-Vs correlations.

Keywords: SPT Hammer Energy Measurement, SPT HEMA, MASW, Shear Wave Velocity, N vs Vs correlation.

1. Introduction

Static and dynamic soil properties can be accurately determined using many in-situ tests. Because in-situ measurements reliably represent the true state of the soil. Standard penetration test (SPT) and Multichannel Analysis of Surface Waves (MASW) tests are very popular and convenient in geotechnical engineering for sub-surface exploration. SPT test is the only test that simultaneously gives the soil strength and sample. On the other hand, MASW is a non-destructive test and is quickly carried out to get average Shear Wave Velocity (Vs). The vital advantage of this test is that it is economical & simple compared to other tests, such as Cross-hole and Downhole. N value obtained from SPT and Vs obtained from MASW are used to identify many static and dynamic soil properties. The combination of both tests is very useful for estimating the sub-surface soil profile and its properties. Additionally, it resolves many geotechnical problems effectively (Anbazhagan et al., 2022b).

SPT has few standardisations for the test procedure, test interval, borehole diameter, hammer weight and height of fall (Anbazhagan and Ingale, 2021). Additionally, other SPT components like drill rig, guide rod, hammer, and anvil type and their dimensions are not standardised in many countries. The codal provision related to SPT in selected countries is given by Anbazhagan and Ingale (2021). Hence, the owners manufacture the SPT components locally with convenient design and dimensions, and conduct the test. Because of these variabilities, the reliability of the test is affected. Overburden and Hammer energy corrections are the most predominant (Anbazhagan et al. 2022a). Hammer energy correction can eliminate almost all SPT component errors (Anbazhagan and Ingale 2021). Hence, without energy measurement, it is meaningless to get any reliable information from SPT N, as well as static and dynamic soil properties.

1.1. Effect of Energy on N value

In developing countries, many types of SPT rigs are used and Fig. 1 shows typical SPT setups in the southern part of India, using different types of equipment. It can be noticed that several SPT rigs are used to conduct the test in the same site, and the hammer release mechanism is mainly different in those tests. Additionally, other SPT components like SPT drill rod, anvil weight and its dimension, hammer and its dimension, and guide rod are different. Because of these variabilities, the SPT test results are difficult to maintain consistency. Hence, Hammer energy correction for SPT N value is the best option to eliminate most of the errors.

Figure 1. Variation in SPT Equipment and its Testing Components.

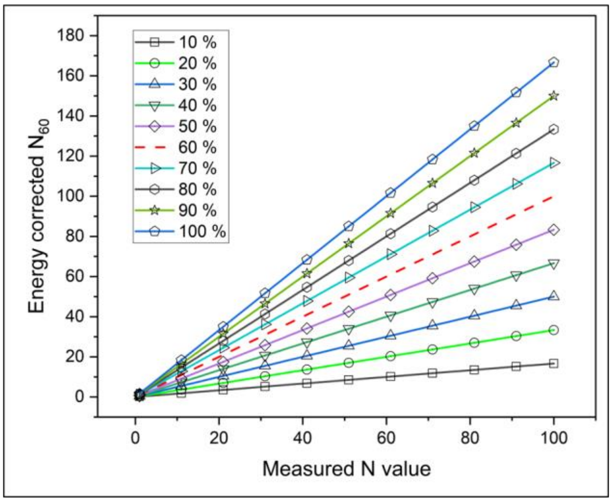

Figure 2. Measured N value and corresponding N_{60}, for with and without Energy consideration

The amount of energy applied in SPT significantly influences the interpretation of N values. Fig. 2 illustrates how the energy-corrected N value (N_{60}) varies when SPT is performed with different levels of hammer efficiency (also known as the Energy Transfer Ratio: ETR, %). The N values are assumed to be from 0 to 100, and then corrections are made based on the hammer efficiency. The resulting lines in Fig. 2 illustrate that the N value could be unreliable if the ETR is not measured. For instance, assuming an ETR of 60%, the assumed and corrected N values remain the same. However, if the initial N value is 50, the corrected N_{60} becomes 37 for an ETR of 45 %, and the corrected N_{60} becomes 62 for an ETR of 90 %. This variability introduces the possibility of errors and misinterpretations in estimating soil strength and properties during the design and analysis stages. Additionally, this makes it challenging to determine these factors accurately.

1.2. N versus Vs correlation

Several correlations exist between the N and Vs values. Some widely used correlations are listed in "Table 1" and developed using statistical methods (Hanumantharao and Ramana 2008, Kumar et al. 2022, Thokchom et al. 2017, Maheshwari et al. 2010). They vary in terms of the data used and the model created. They apply to all kinds of soil, but there are other correlations specifically developed for different soil types like sand, silt, and clay. All these correlations are site-specific, meaning they might not be applicable to all sites (Anbazhagan et al. 2013; Bajaj and Anbazhagan 2019). It is important to note that these correlations are based on uncorrected N values because energy measurements were not conducted during those testing periods. Therefore, these correlations may not be suitable for all sites, even for the same soil type.

In earlier studies ("Table 1"), the uncorrected N correlation with Vs showed a good trend corresponding to an R^2 value above 0.7. The reason might be because of the usage of uniform types of SPT equipment and SPT components. But this is not always the case in big projects. In big projects, Multiple SPT rigs with variable SPT components are deployed for the subsurface investigation. This results in non reliable SPT N values for same soil type and condition. Hence hammer energy measurement will play crucial role in normalising the variation from these rigs. The nonstandardisation of SPT components and its effect on the N value was discussed by Anbazhagan et al. (2021). Additionally, the study showed how multiple equipments incorporated in the same project and consideration of different average ETR affects N value. Very limited studies have carried out hammer energy measurement during SPT and correlated with Vs values. Therefore in the present study, an attempt made to understand correlation between the energy corrected N values vs Vs values. The results are discussed in the upcoming sections.

Table 1. Summary of various correlations for predicting Vs from SPT N value and vice versa

Author(s)	Correlation, Vs =	SPT N value	Type of soil	Country	Average ETR (%) in the country	Hammer type	Energy corrected Correlation, Vs' =
Athanasopolous (1995)	$107.26N^{0.607}$	uncorrected	All soils	Greece	46	Manual	$107.26(0.76\ N_{60})^{0.607}$
					77	Automatic	$107.26(1.28\ N_{60})^{0.607}$
Kanai et al. (1966)	$19N^{0.6}$	uncorrected	All soils	Japan	67	Safety, rope & cathead	$19(1.12\ N_{60})^{0.6}$
					78	Trip	$19(1.3\ N_{60})^{0.6}$

Ohta and Goto (1978)	$85.35N^{0.348}$	uncorrected	All soils	Japan	67	Safety, rope & cathead	$85.35(1.12\ N_{60})^{0.348}$
					78	Trip	$85.35(1.3\ N_{60})^{0.348}$
Fujiwara (1972)	$92.1N^{0.337}$	uncorrected	All soils	Japan	67	Safety, rope & cathead	$92.1(1.12\ N_{60})^{0.337}$
					78	Trip	$107.26(0.76\ N_{60})^{0.607}$
Imai (1973)	$91N^{0.337}$	uncorrected	All soils	Japan	67	Safety, rope & cathead	$91(1.12\ N_{60})^{0.337}$
					78	Trip	$91(1.3\ N_{60})^{0.337}$
Imai and Tonouchi (1982)	$96.7N^{0.314}$	uncorrected	All soils	Japan	67	Safety, rope & cathead	$96.7(1.12\ N_{60})^{0.314}$
					78	Trip	$96.7(1.3\ N_{60})^{0.314}$
Sisman (1995)	$32.8N^{0.51}$	uncorrected	All soils	Turkey	60	Donut hammer	$32.8(\ N_{60})^{0.51}$
Iyisan (1996)	$51.5N^{0.516}$	uncorrected	All soils	Eastern Turkey	60	Donut hammer	$51.5(\ N_{60})^{0.516}$
Jafari et al. (1997)	$22N^{0.85}$	uncorrected	All soils	Eastern Turkey	60	Donut hammer	$22(\ N_{60})^{0.85}$
Kiku et al. (2001)	$68.3N^{0.292}$	uncorrected	All soils	Adapazari, Turkey	60	Donut hammer	$68.3(\ N_{60})^{0.292}$
Hasancebi and Ulusay (2007)	$90\ N^{0.309}$	uncorrected	All soils	Northwestern Turkey	60	Donut hammer	$90(\ N_{60})^{0.309}$
Jinan (1987)	$116.1(N + 0.3185)^{0.202}$	uncorrected	All soils	Shanghai, China	50	Donut, cathead	$116.1(0.3185+0.83\ N_{60})^{0.202}$
					55	Donut, dropped	$116.1(0.3185+0.917\ N_{60})^{0.202}$
					60	Donut, rope and pully	$116.1(0.3185+\ N_{60})^{0.202}$
					72	Automatic, Trip	$116.1(0.3185+1.2\ N_{60})^{0.202}$
Seed and Idriss (1981)	$61.4N^{0.5}$	uncorrected	All soils	–	60	Donut hammer	$61.4(\ N_{60})^{0.5}$
Bajaj and Anbazhagan (2019)	$64.23N^{0.48}$	uncorrected	All soils	India	unmeasured	Donut hammer	-
Anbazhagan et al. (2013)	$68.96N^{0.51}$	uncorrected	All soils	India	unmeasured	Donut hammer	-
Uma Maheswari et al. (2010)	$95.641N^{0.3013}$	uncorrected	All soils	India	unmeasured	Donut hammer	-
Hanumantharao and Ramana (2008)	$82.6N^{0.43}$	uncorrected	All soils	India	unmeasured	Donut hammer	-
Thokchom et al. (2017)	3.311N+160.5	uncorrected	All soils	India	unmeasured	Donut hammer	-
Kumar et al. (Kumar et al., 2022)	$72.21N^{0.409}$	uncorrected	All soils	India	unmeasured	Donut hammer	-
Aas and Sinha (2023)	$65.468N^{0.443}$	uncorrected	All soils	India	unmeasured	Donut hammer	-
Sykora and Stokoe (1983)	$100.5N^{0.29}$	N_{60}	Sands	United States	45	Donut hammer rope and pully	$100.5(0.75\ N_{60})^{0.29}$
					60	Safety hammer	$100.5(\ N_{60})^{0.29}$

					90	rope and pully Trip	$100.5(1.5\ N_{60})^{0.607}$
Pitilakis (1999)	$145.0N^{0.18}$	N_{60}	Silts and sands	Northern Greece	46	Manual	$145(0.76\ N_{60})^{0.18}$
					77	Automatic	$145(1.28\ N_{60})^{0.18}$

2. Data collection and analysis

For the first time, in-situ measurements of SPT with hammer energy [as per ASTM D4633 (2016)] and Vs using Multichannel analysis of surface (MASW) [as per ASTM D5777 (2018)] are carried out at the same time. Fig. 3 illustrates the schematic for hammer energy measurement in the SPT test and conducting the MASW test.

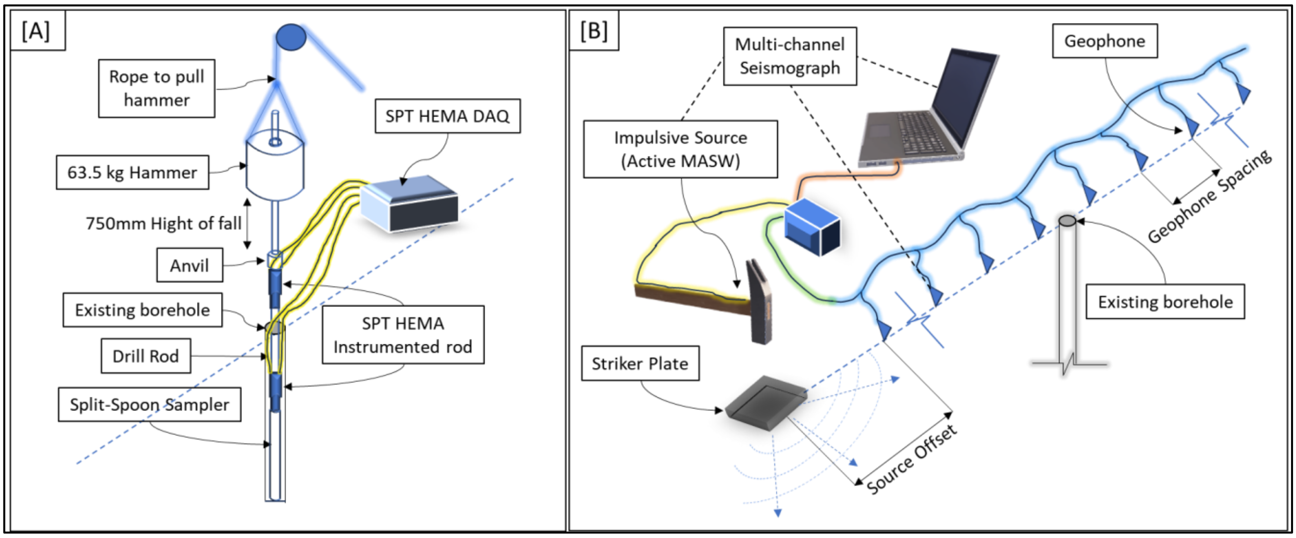

Figure 3. Schematic for [A] SPT Hammer Energy measurement and [B] MASW test

In our regular SPT test, the hammer energy measurement is done using two instrumented rods, with one connected just below the anvil and the other just above the sampler. For this study, we focus on measurements just below the anvil. The energy measurement at the sampler level is not within the scope of our current research. The SPT HEMA DAQ is used to record and store hammer impact Force and Acceleration data. These data are obtained from the instrumented rod, with a maximum load capacity of 240 kN for the load cell and a maximum Acceleration of 10,000 g. The data samples are recorded at a rate of 60 kHz. A MatLab program processes the data to determine the ETR in the drill rod.

After completing the SPT test, MASW is conducted in the same borehole location. For this test, 24 geophones with a frequency of 4.5 Hz are used. These geophones are placed in line with the borehole, with 12 on one side and 12 on the other. An impulsive source is set at a source offset, typically ranging from 5 to 15 m, based on available space. A minimum of 5 stacks are used for each test, with a geophone spacing of 1 m.

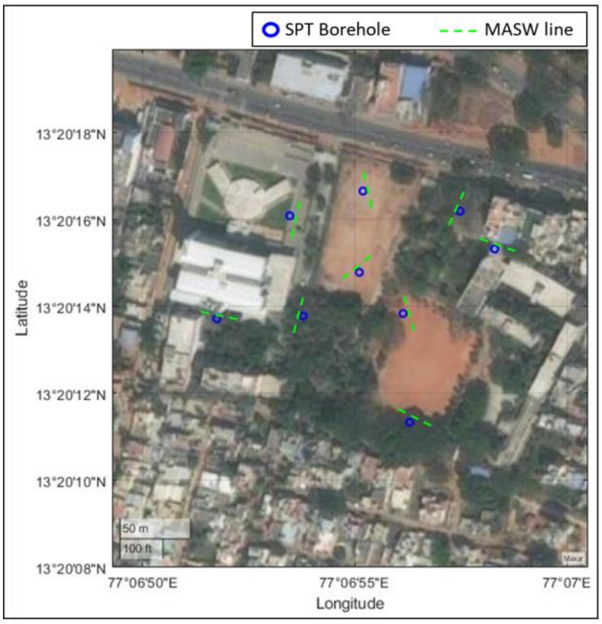

Figure 4. Typical test location of SPT and MASW tests

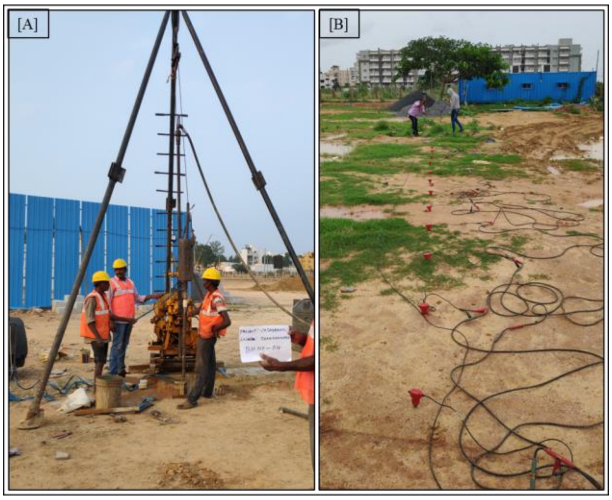

Figure 5. Typical field setup for data acquisition: [A] SPT test Hammer Energy measurement and [B] MASW test

The study sites are located in the peninsular region of India, including Bangalore, Bhubaneshwar, Chennai, Thumakur and YSR Kadapa. Notably, the location exhibits various soil subsurface features. The geological background of these areas relates to Deccan plateau formations and influences from crystalline and metamorphic rocks. The predominant soil type in this region remains unspecified in the provided content. However, Red soil is common in the Deccan plateau area. Black soil and Laterite soil are dominant in parts of southern India. Fig. 4 shows a typical test location of SPT and MASW tests. A Typical field setup of SPT hammer energy measurement and MASW in the same borehole location is shown in Fig. 5.

Fig. 6 shows a typical Time history data of SPT HEMA hammer energy measurement. The data was collected just below the anvil, as mentioned earlier. Force and Acceleration are recorded during testing. Velocity is obtained by the integration of the Acceleration. ETR is obtained by integrating the product of Force and Velocity and then normalising it to 100%.

Fig. 7 illustrates a typical ETR for each blow in an SPT test. The graph also displayed the Theoretical maximum, Average and 60 % ETR. Notably, even in well-supervised tests, variation in the ETR for each blow is unavoidable due to testing setup and operation in developing countries. This highlights the importance of hammer energy measurement in every SPT.

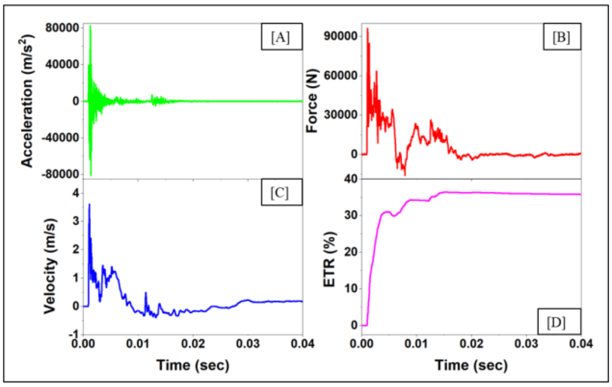

Figure 6. Typical Time histories of SPT HEMA hammer energy measurement: [A] Acceleration [B] Force [C] Velocity [D] ETR

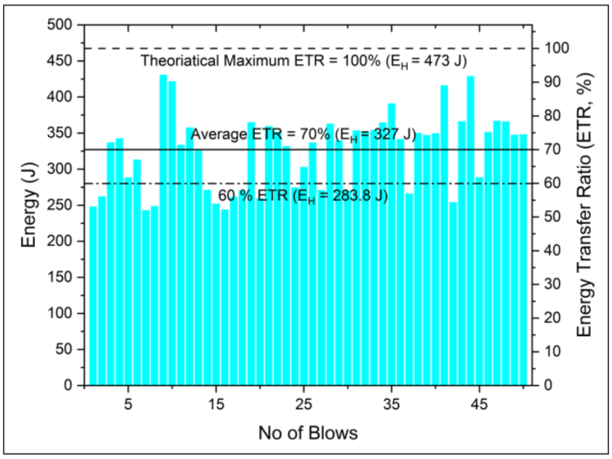

Figure 7. ETR of each blow in an SPT test.

Fig. 8 shows the data acquisition and processing involved in the MASW test. Fig. 8 [A] represents the normalised shot-gather process, which captures surface wave data collected during the field survey. Fig. 8 [B] illustrates the dispersion curve obtained from the shot-gather process. It characterises the behaviour of surface wave propagation through the subsurface materials.

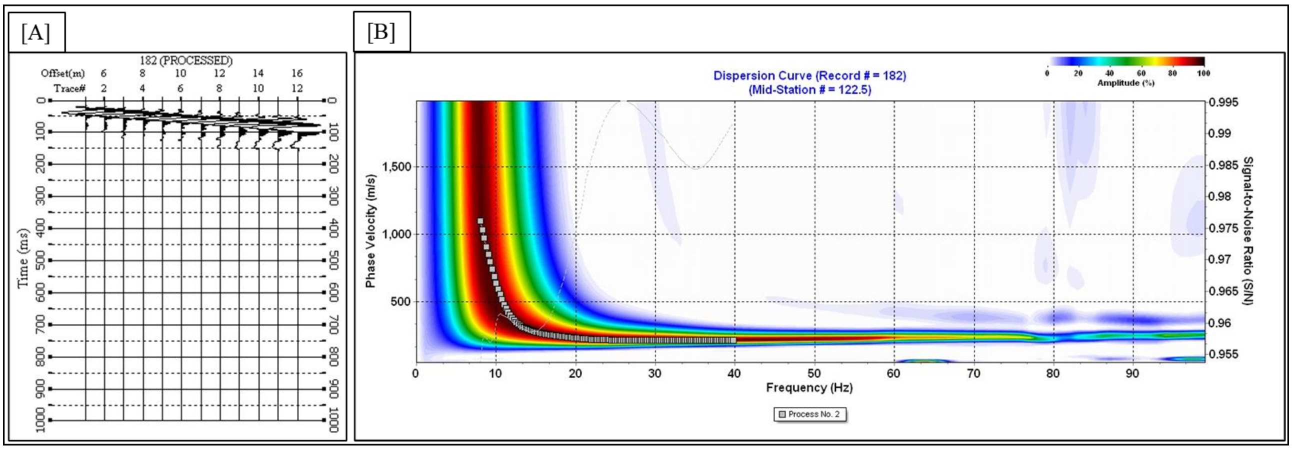

Figure 8. Typical MASW data acquisition and processing: [A] Normalised shot gather and [B] Dispersion curve from the shot-gather processing

Fig. 9 shows the data distribution for four parameters along the Depth from 0 to 30 m. It includes Measured N value, ETR, N_{60} and Vs value, respectively. This distribution provides sufficient data to understand the behaviour of these parameters.

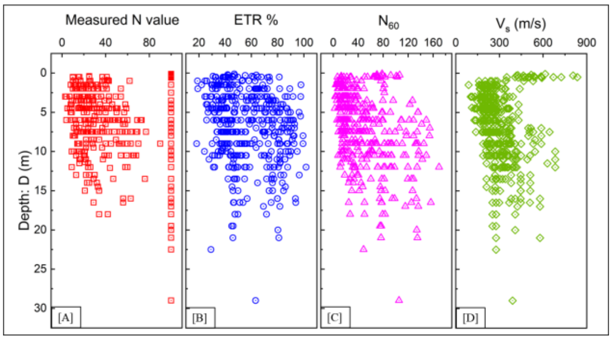

Figure 9. Distribution of [A] measured N value, [B] ETR [C] N_{60} and [D] Vs delivered with Depth

The data are categorised into different bins: 15-30 %, 30-50 %, 50-70 %, 70-90 %, and above 90 %. Instead of arbitrary average values, ETR bins are divided this way to account for ETR variation. Even for the same equipment, the average ETR varies in a site, project or region. Fig. 10 provides insights into data distribution across various ETR ranges. The distribution pattern suggests that the ETR values are concentrated in the middle range of 30–90 %. This might be the reason for standardising the hammer efficiency as 60 %. Notably, the 30-50 % ETR bin has the highest percentage (approximately 40 %) of data points. Less than 30 % and greater than 90 % rarely occur in the field. Hence, it can be given less importance.

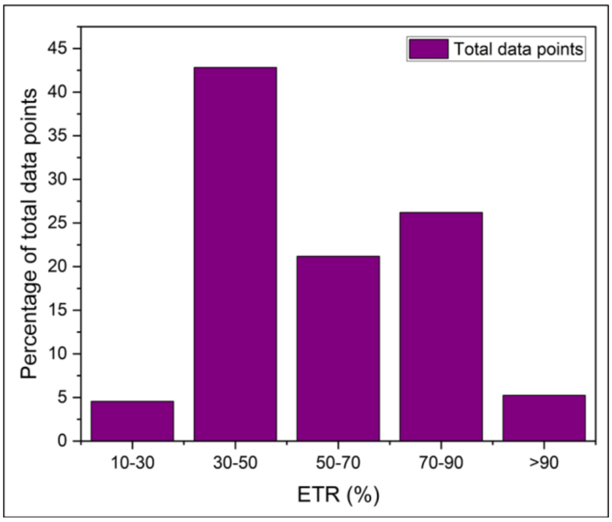

Figure 10. Distribution of recorded data in ETR bin showing % of total data in the bins.

3. Result and discussion

Fig. 11 presents typical results from data acquisition in a borehole using both SPT and MASW. Comparing the SPT N value profile with the Vs profile, we observe that the trend remains consistent. However, when comparing all the above profiles, we observe that, although Vs and E remain consistent, there is a variation in N and ETR profiles for the deeper Depth (greater than 6 m depth). Interestingly, reduced energy value increases N value and vice versa, while stiffness and Vs values remain consistent. This highlights the importance of hammer energy measurement for reliable SPT results. Hence, it is suggested that hammer energy should be measured in all SPT tests.

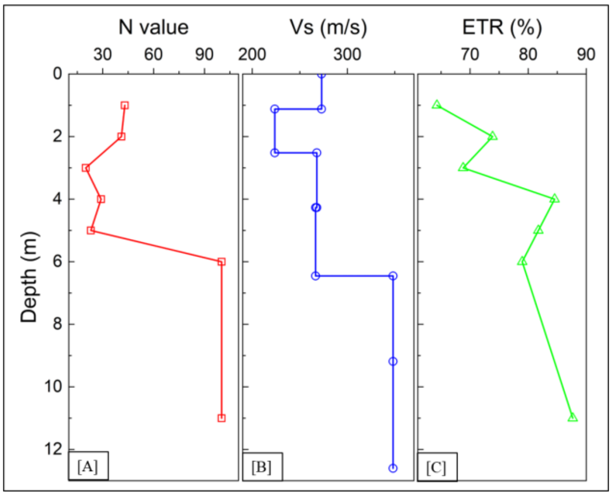

Figure 11. Typical data acquisition of a borehole: [A] N value, [B] Vs and [C] ETR

Figs. 12 to 16 illustrate the relationship between N with Vs and N_{60} with Vs for categorised ETR bins. A power law curve fit is applied to the data points. Comparing all five figures from Fig.12 to Fig. 16, each featuring two plots of N versus Vs and N_{60} versus Vs, it is evident that the trends in N_{60} versus Vs are more logical compared to N versus Vs. In the case of N versus Vs, the data points are scattered with no reasonable trend. It indicates the uncorrected N values do not correlate well with the Vs profile. However, in the case of N_{60} versus Vs, a noticeable relationship emerges and shows a good trend. Once again, this highlights the importance of hammer energy measurement in SPT. This helps to obtain reliable results, as evidenced here. There is a consistent and significant improvement in the R-square (Coefficient of Determination) value, as shown in "Table 2". Although the R-square range for N_{60} versus Vs may not be ideal, the improvement is significant. The lower R-square values are due to consideration of various soil types. Narrowing down to specific soil types is crucial. However, for this study, we aimed to highlight the importance of ETR in SPT and N versus Vs relationship. Additionally, energy-corrected N values are incorporated for the existing correlations if using old correlations, as mentioned in the literature review "Table 1".

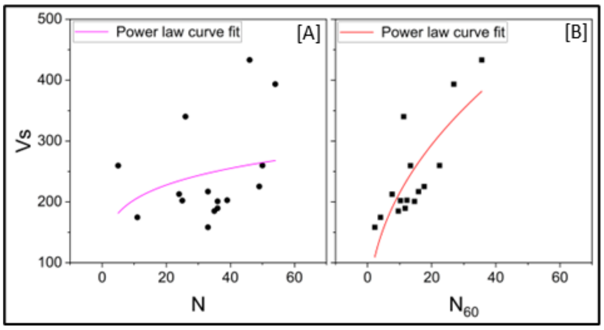

Figure 12. Comparative analysis of N and N_{60} with Vs relationships for ETR 15-30 %

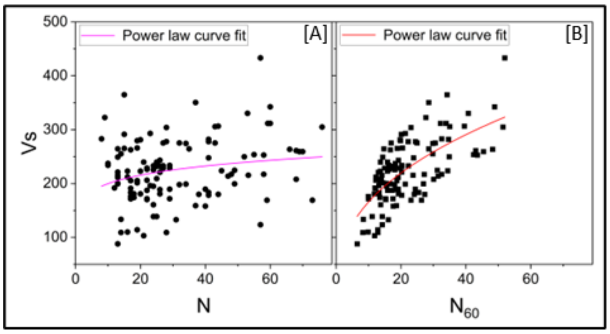

Figure 13. Comparative analysis of N and N_{60} with Vs relationships for ETR 30-50 %

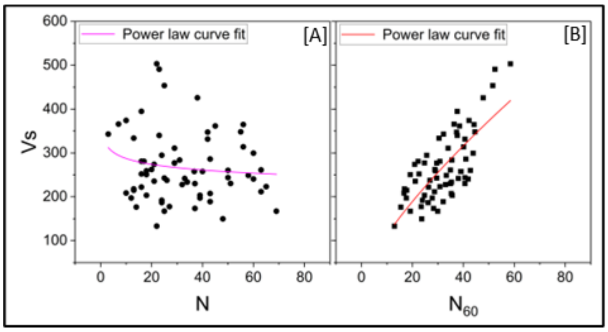

Figure 14. Comparative analysis of N and N_{60} with Vs relationships for ETR 50-70 %

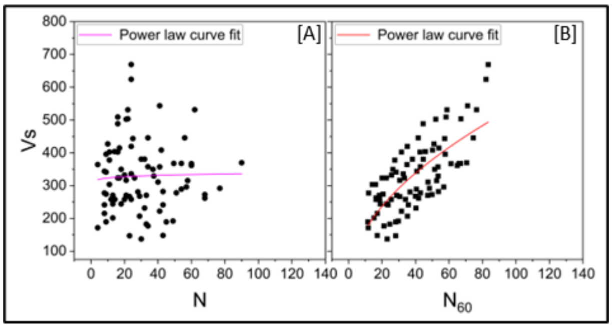

Figure 15. Comparative analysis of N and N_{60} with Vs relationships for ETR 70-90 %

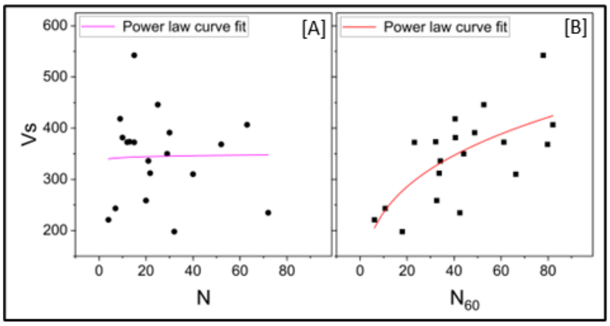

Figure 16. Comparative analysis of N and N_{60} with Vs relationships for ETR above 90 %

Table 2. Comparison of Regression parameters for ETR subranges

ETR (%)	Equation	N versus Vs			N_{60} versus Vs		
		a	b	R-Square (COD)	a	b	R-Square (COD)
15-30	$y = ax^b$	139.37 ± 83.06	0.16 ± 0.17	0.06	75.73 ± 21.91	0.45 ± 0.1	0.6
30-50	$y = ax^b$	155.06 ± 23.77	0.11 ± 0.05	0.05	65.20 ± 8.28	0.41 ± 0.04	0.47
50-70	$y = ax^b$	337.06 ± 67.21	-0.07 ± 0.06	0.02	20.44 ± 6.51	0.74 ± 0.09	0.52
70-90	$y = ax^b$	310.23 ± 53.63	0.02 ± 0.05	0.001	50.75 ± 10.74	0.51 ± 0.056	0.52
> 90	$y = ax^b$	336.37 ± 83.79	0.008 ± 0.08	0.0006	123.34 ± 38.14	0.28 ± 0.08	0.46

Rather than assuming an arbitrary N value correction value of 60%, site-specific ETR is more reliable. For instance, every hammer mechanism or SPT rig operates at varying ETR. If using site-specific ETR for existing correlations (mentioned in "Table 1"), correction factors for a range of ETR are provided in "Table 3". N values are recommended to correct by applying the corresponding correction factor for reliable results.

Table 3. N value correction factor for corresponding ETR bin

ETR (%)	N value Correction factor
15-30	0.33
30-50	0.66
50-70	1
70-90	1.33
> 90	1.5

4. Conclusions

In this study, authors simultaneously conducted in-situ measurements of the Standard Penetration Test (SPT) and Multichannel Analysis of Surface Waves (MASW) in 84 boreholes across the Indian Peninsula region. Notably, hammer energy was measured in each SPT, providing valuable data. The study explored correlations between uncorrected (N) and energy-corrected (N_{60}) N values with the Vs value, boasting a more extensive dataset and a broader range of N values for increased reliability. The findings revealed that lower energy values correlated with higher N values and vice versa, while stiffness and Vs values remained consistent. This emphasises the critical role of energy measurement in every SPT test. Moreover, the authors introduced a novel correlation between N_{60} and Vs, incorporating energy measurements to enhance the significance of these connections further. The N_{60} versus Vs trends are more coherent than N versus Vs, again emphasising the importance of ETR. Additionally, correction factors are provided for existing correlations for various ETR ranges.

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