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Significance of Energy Transfer Ratio in Standard Penetration Test and its Influence on Foundation Design

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Abstract. The majority of the cost and time over-runs in infrastructural projects are due to concerns related to substructures. Every project needs a detailed geotechnical investigation for cost economics, safety and to arrive at a competent load bearing stratum for construction of foundation. The Standard Penetration Test is an in-situ method which measures penetration resistance of a standard split spoon sampler to dynamic impacts by a standard hammer and involves several corrections to arrive at the corrected N value. Energy correction factor is a field correction tool to arrive at a normalized N value for 60% energy transfer ratio (N60) from the SPT hammer to the drill rods. IS 2131 mentions hammer drop to be a free-fall but doesn't emphasize the need for energy measurement. It is a standard practice and quality control procedure to calibrate every geotechnical SPT drilling rig to measure the energy transfer ratio (ETR). In the present study, ETR data of 40+ geotechnical drilling rigs with different driving systems across India are presented. Consequences of over-prediction and under-prediction of bearing capacity for different cases are briefly discussed. The importance of the measurement of ETR is appraised and its influence on foundation design, cost economics and safety are explored along with case studies.

Keywords: Geotechnical Investigation, Energy Transfer Ratio, Standard Penetration Test, Drilling rig.

1 Introduction

Geotechnical site characterization is an essential task for every project to ensure economics and safety. Geotechnical investigation in every sense aids the necessary information to characterize the site using different methods based on practical feasibility of the site. It is a sophisticated method of determining the sub-soil stratification and properties by using standard equipments and procedures. Every site on earth is unique in its own way. Two sites can never have same sub-soil profile with similar properties. In an engineering point of view, it is essential to conduct the geotechnical investigation at any site where a structure is being erected. Mentality of many stakeholders across different projects to neglect geotechnical investigation is not un-common. Likewise, failure of a structure with a history of irregular ground characterization is seen day-in day-out and always lead to serious consequences. Detailed laboratory testing program is an added advantage and needs to be carried out to determine engineering properties of soil which will aid further to characterize the ground. A Structure built in a standard engineering way will not fail even during seismic excitations.

Major benefits of performing a geotechnical investigation with some important observations are listed below.

- **Cost Economics**: In case where an investigation program is not planned, engineer may design the footings by under estimating the soil properties (assumed) which may lead to cost-overrun. With proper investigation, if soil has competent strength than the assumed, dimensions of foundation will be much smaller which would save building materials and related costs.

- **Safety:** Either way if it is found that sub-soil is weak, considerable size of foundations can be designed which would otherwise lead to a potential disaster due to over estimation of soil properties.
- **Seismic Behavior:** In case, loose sand or silty sands exist beneath a structure in seismic vulnerable zones, an event of earthquake may lead to differential settlements and associated risks induced by liquefaction. A proper geotechnical investigation right at the first place may safeguard the structure and livelihood of people.
- **Settlement:** In case of soft clays like bentonite and black cotton soils, consolidation behaviour is to be properly addressed. If investigation is skipped, it may lead to consolidation settlement in the foundation and may further lead to failure of the structure.

Ample number of methods are available at the discretion of every stakeholder to carry out geotechnical investigation. Standard Penetration test is one of them. It is most-used and proven method worldwide.

1.1 Standard Penetration Test

SPT is common knowledge for any civil engineer. The test estimates the soil resistance to penetration. A hammer in free fall applies an impact load onto a rod setup of necessary depth up to a total penetration of 45cm. The first 15cm is disregarded citing inconsistencies during the seating period. Further, The N value is the number of blows it takes for the final 30cm penetration. This N value is standardized and then used as input quantities for the design of foundations. The split-spoon sampler attached to the bottom of the rod setup collects a disturbed sample as well.

In the Indian context, the major scope of geotechnical investigation comprises conducting SPT at necessary depths in the borehole. The collected samples are further evaluated at the laboratory. At present, in certain projects calyx & hydraulic semi-automatic/automatic rigs are being utilized for geotechnical investigation activity as shown in Fig 1. Multi-purpose hydraulic drilling rigs does have in house automatic hammer, anchoring system, CPT unit and auger facility. They have a mast to maintain verticality of drilling operation while Tripod system is used in other type of rigs. Rate of drilling is 3 times faster than ordinary rigs and creates the difference by reducing the time run of the projects and adding value. In mega projects like high speed rails and metros, these specialized rigs are being deployed considering the cutting-edge technology and progress of work.

Fig 1. Different Geotechnical Rigs with different Hammers

Ground characterization using Standard Penetration test data is followed around the globe and the foundations designed using standard practices with incorporation of recent advancements are sound to present date. Although, this test is supposed to have a standardized test procedure, there is a wide variability in equipment and test procedures encountered in practice throughout the world. It has been shown that, in different parts of the world, the Standard penetration resistance is conventionally measured using different kinds of hammers, different energy delivery systems with different degrees of efficiency, different borehole fluids, and different kinds of sampling tubes. (Yimsiri S, 2012)

2 Energy Transfer Ratio

Numerous corrections for measured N values are illustrated in the literatures, IS 2131:1981 & IS 1896:2016. Corrections for overburden, dilatancy, rod length, non-standard borehole diameter and liners are listed in the literatures with range of site-specific values to be adopted.

Anbazhagan et al, 2022 studied the energy measurement of SPT hammer for instrumented rods and provided comparison between SBC values with and without considering energy correction factors. Anbazhagan et al, 2022 opined that 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. The influence of considering proper in-situ hammer energy is not clearly understood yet and thus, it is still not practised in many developing countries. Panjamani et al., 2022 highlighted the importance of hammer energy in N-value corrections and studied the effect of hammer energy on soil properties like low strain shear modulus and SBC values and further integrated with the subsurface imaging methods to determine spatial variation of these parameters.

Indian Standards need to incorporate correction for energy transfer ratio in line with ASTM D4633 which provides procedures, guidelines and importance of ETR test. Energy correction to SPT N value is a field correction to normalize N value to 60% energy transfer. The direct impact of not using an energy correction factor leads to inconsistency on geotechnical design quality and cost which has sparked significant research on the factors that affect the N values. (Sherif et al, 2001). Any design estimates made without the consideration of energy correction may overestimate or underestimate the corresponding values. The calibration of the SPT hammers for each rig is to be performed prior to utilizing it on the field. The Energy Transfer Ratio (ETR) test is performed for this purpose. The ETR test estimates the energy efficiency of the SPT hammer. The energy ratio is the actual energy measured upon the initial impact of the hammer as compared to the theoretical maximum potential energy of the hammer.

$$ETR = (Kinetic\ Energy/Potential\ Energy) * 100\ \%$$

For an ideal SPT hammer designed in accordance to **IS 2131 - 1981** is as follows,
Potential Energy (PE) = mgh = 63.5kg x 9.81m/s^2 x 0.75m = 467J
Where,
m = mass of the hammer, kg
g = acceleration due to gravity, m/s^2
h = height of fall, m

Energy losses may occur due to multiple reasons such as friction, impact on the anvil, type of machine, and the skills of the operator. To ensure good measurement of data, the weight of the hammer and the height of fall is measured prior to the first ETR test before sanctioning of the drilling rig. The following factors are also kept in observation during the conduct of the tests.

· Condition of Guide rod
· Condition of SPT drill rods (AW/NW rods)
· Tightness of joints between the SPT rods
· Verticality of the SPT setup,
· Controlled engine speed of the machine,
· Proper winch control, and
· Blows per minute.

The reasons for the conduct of the test would be obsolete if the above-mentioned factors are not controlled within ideal conditions. The energy ratio is measured for each blow and the energy ratio values corresponding to the N value are averaged to obtain the ETR value of the rig for that particular depth.

2.1 Instrumentation

Theory of wave propagation is the basis of this test where accelerometers and strain gauges are fixed to a calibrated AW SPT rod of 1m length (Fig 2). During ETR test, calibrated rod is attached to the driving system as shown in Fig 3 and SPT is conducted. Energy is computed as integration of Force and Velocity. Strain gauges measure the strain and calculates force, as elasticity modulus of the steel material and rod area are known parameters. Similarly, accelerometer obtains velocity by integrating the captured accelerations during the test. Thus, maximum energy is obtained (EMX) which attributes to the Kinetic energy transferred from the SPT hammer to the drill rods. EMX obtained from data acquisition device divided by the Potential energy is ETR (%). The data acquisition system as shown in Fig 2. captures and records measured force and velocity and computes ETR for every blow. Average of all blows for 3 consecutive SPT tests is used and further averaged to obtained ETR for that driving system.

Fig 2. Instrumented AW rod and Data Acquisition System

Fig 3. ETR Test Set-up

2.2 Scope and importance of Measurement of Energy Transfer Ratio

Consider two rigs of different energy efficiencies are performing an SPT at the same depth of an identical location, the rig with higher energy efficiency shall take a lesser number of blows for the 30cm penetration as compared to the rig with lower energy efficiency. Alternatively, in the case of two calibrated rigs of identical energy efficiency, the N values shall be comparable. **BS EN ISO 22476 Part 3: 2005** suggests that in conditions where several rigs are to work on a project, assessment of ETR of the hammer holds significance. Frequent equipment checks also ensure good quality of investigation. Thus, for a project of such humungous scale as High-Speed Rail, Metro, Power and other infrastructural projects where over 50 rigs are in operation, the calibration of rigs makes it imperative. It would make it effortless to compare the N values across the complete scale of the project. Hence, ETR calibration is mandatory for sanctions on rigs for geotechnical investigation operations. Furthermore, the calibration of the sanctioned rigs is to be re-verified after the completion of every set of ten boreholes.

3 Energy Transfer Ratio of different Driving systems

ETR can vary with type of hammer and type of drilling rig (shown in Fig 1) used to perform geotechnical investigation. As stated above, various quality checks shall be effectively ensured before conduction of ETR test. ETR data of more than 40+ geotechnical drilling rigs across the length and breadth of India with different driving systems have been compiled and a summary of the available data is presented in Table 1.

Table 1. Summary of ETR data of 40+ Geotechnical drilling rigs

Type of Rig	**Type of Hammer**	**ETR (%)**
Calyx Rig	Donut Hammer – Rope-drop (7+ Nos, 33+ data sets)	20-40
	Donut Hammer – Hydraulic (6+ Nos, 52+ data sets)	30-50
Hydraulic Model (Ex: TRD-300, TRD-80, Multi-purpose)	Donut Hammer – Rope-drop (5+ Nos, 108+ data sets)	25-40
	Donut Hammer – Hydraulic (12+ Nos, 160+ data sets)	35-40
	Auto-trip Hammer (7+ Nos, 102+ data sets)	60-70
	Automatic Hammer (3+ Nos, 240+ data sets)	80-90

Calyx type of rigs are compact type of geotechnical rig which can work in narrowest of spaces available to perform geotechnical investigation. They are predominantly slow and economical. They are conventional type of rigs which are deployed at majority of the sites in India. The tooling and make of these Calyx rigs attribute for lower energy transfer from SPT hammer to the drill rods. But, recently developed hydraulic model rigs are popular and considered as appropriate to perform geotechnical investigation based on the experience. These rigs can be customized to adopt different driving systems with different hammers.

It is observed that donut hammer with rope drop system only transfers 20-40% as compared to hydraulic drop for the same rig. Manual rope drop or hydraulic drop contains several losses in transfer of available potential energy to kinetic energy. Manual operation of hammers in itself has several limitations where manual effort used to lift the hammer varies from blow to blow. Tension force in the rope is also a prominent factor which accounts for low energy transfer. Hydraulic drop has a better ETR than manual rope drop.

Auto-trip hammers are considered to impart around 60-70% energy transfer. The hammer is lifted hydraulically with a hook and once it reaches an elevation of 760mm the hook releases for free-fall of the hammer. These hammers should be preferably adopted in projects of national importance. The automatic hammer is equipped with an electronic switch. Once the switch is turned on, the hammer free-falls automatically and the engineer can count the number of blows to arrive at N. Blows per minute can be controlled qualitatively and automatic hammers are expected to transfer 80-90% to the drill rods. A sample force velocity time history and ETR (%) of a multi-purpose hydraulic rig with automatic hammer is presented in Figures 4 and 5 respectively. ETR of a rig can be modified by altering the anvil by state-of-art techniques ensuring good quality of SPT data. The automatic release of SPT hammer results in a value of ETR approximately twice the corresponding value of manual release.

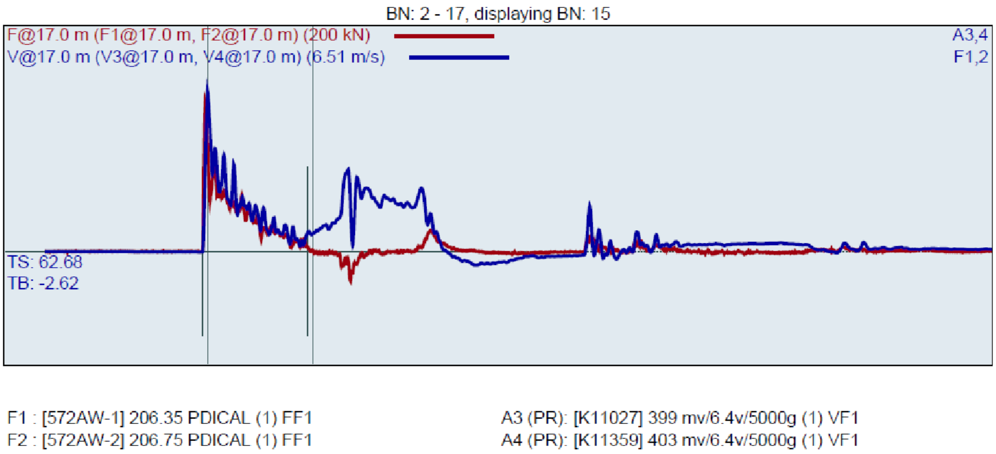

Fig 4. Force Velocity Time-History from a Multi-purpose hydraulic rig with Automatic Hammer

FMX: Maximum Force
VMX: Maximum Velocity
BPM: Blows/Minute
EFV: Maximum Energy
ETR: Energy Transfer Ratio - Rated

BL#	FMX	VMX	BPM	EFV	ETR
	kN	m/s	bpm	J	%
2	121	4.27	32.8	397	84.9
3	124	4.52	32.8	402	86.1
4	124	4.49	32.8	399	85.4
5	126	4.60	32.7	406	86.9
6	127	4.46	32.8	400	85.7
7	127	4.62	32.7	409	87.6
8	129	4.58	32.8	401	85.9
9	127	4.59	32.7	396	84.8
10	129	4.61	32.8	401	85.9
11	130	4.57	32.7	398	85.3
12	132	4.58	32.8	410	87.8
13	132	4.61	32.8	416	89.1
14	132	4.54	32.8	397	85.1
15	132	4.58	32.7	408	87.4
16	132	4.54	32.7	412	88.2
17	133	4.62	32.7	416	89.2
Average	129	4.55	32.8	404	86.6
Std Dev	4	0.09	0.0	7	1.4
Maximum	133	4.62	32.8	416	89.2
Minimum	121	4.27	32.7	396	84.8

N-value: 16

Fig 5. ETR (%) -Multi-purpose hydraulic rig with Automatic Hammer

Depth of measurement of ETR in a borehole has a significant bearing on the correction factor values as observed in the present study. In the literature, Batilas et al, 2016 presents the value of ETR does not depend on depth of measurement. Edgar et al, 2016 illustrates that the influence of rod length produces two opposite effects: wave energy losses increase with increasing rod length and in a long composition of rods the gain in potential energy from rod weight is significant and may partially compensate measured energy. In the present study, it is observed and opined that as number of joints in the drill string increases, losses increase as well. But, the losses are less in automatic hammers as compared to other hammers. Ideally, best estimate of ETR occurs at depths between 10 – 15m for deeper boreholes up to 50m length in silty sand or alluvial deposits. The same shall be calibrated from site to site.

Hydraulic rigs with auto-trip and automatic hammers require minimum 3 trial readings which are consistent to average and obtain ETR (%) as the hydraulic models are efficient and functionality of hammer involves less variations and differences. In case of calyx rigs with donut hammer or manual drop systems ETR varies considerably due to variable nature of energy transfer which includes various factors. In such cases, where the data is not consistent, the tester may opt for additional ETR trial measurements in order to derive the ETR (%) in particular. Use of standard equipment which provides conclusive information will cancel out several future discrepancies and design challenges.

The high-speed railway project (MAHSR) mandated the requirement of geotechnical rigs with automatic hammers to standardize the practice of geotechnical investigation across the country and to obtain good quality geotechnical data. Input parameters for design are very important and doing right things at the first place always produces qualitative engineering analysis. Better the input, reliable is the output. Otherwise with conventional practices, it is always garbage in garbage out.

4 Influence of ETR on Foundation Design

Based on the practical feasibility, super-structure loadings, utility of the structure and many more factors influence the type of foundation. Open foundations like isolated, combined or raft foundations can be employed if competent ground with required safe bearing pressure is available at shallow depth. If competent ground with required bearing pressure is not available at shallow depth, deep foundation elements are required to bypass the weaker soil stratum and install piles bearing on hard soil layer to achieve required bearing capacities. For exceptional cases and critical structures piled raft foundation can also be employed.

Majority of geotechnical computations are correlated with N value and used in design and analysis of geotechnical structures. N value is used to obtain shear strength parameters of soil, liquefaction cyclic resistance ratio, index properties of soil, pile capacity and bearing capacity of shallow foundations. Hence, SPT is an investigation method having more advantages rather than only obtaining N values at different depths. Reliability of the N value becomes very important when the obtained N values are used to correlate different parameters for engineering applications. IS 2131 is yet to be revised to incorporate energy correction factor before normalizing N value to $N_{60.}$ When measured energy is more than 60%, the measured N values are less than the actual N values. Hence, N value is underpredicted. But, when measured energy is less than 60%, measured N values are higher than the actual N values and N value is overpredicted. Correlated parameters with N may also be overpredicted which makes any analysis or design unreliable.

Let us consider SPT data of a hydraulic rig with a donut hammer with N values at every 1.5m intervals. The energy transfer ratio of driving system is measured by averaging ETR for every blow at 4.5m, 6.0m & 7.5m depths and found to be 40% as shown in Table 2. Energy correction factor of 0.67 is multiplied to field measured N values to arrive at N_{60}. Based on experience, 1 N (standard penetration resistance) is equal to 1 ton bearing capacity. If 40 tones is the required bearing pressure, the foundation depth varies from 1.3m for measured N value to 3m for N_{60} (Fig 6). There is a variance of more than 100% in obtaining the founding depth. There is a very likely chance of foundation failure if it is designed with field measured N value which over-predicts the bearing capacity of foundation. Hence, ETR test will ensure safety of structure with a realistic design.

Table 2. Case-1, Hydraulic Rig, Donut hammer

Hydraulic Rig, Donut Hammer, ETR = 42%		
Depth (m)	**Field Measured N value**	**SPT N_{60}**
1.5	43	29
3.0	58	40
4.5	66	45
6.0	27	18
7.5	32	22

9.0	36	25
10.5	25	17
12.0	33	23
13.5	24	16
15.0	39	27

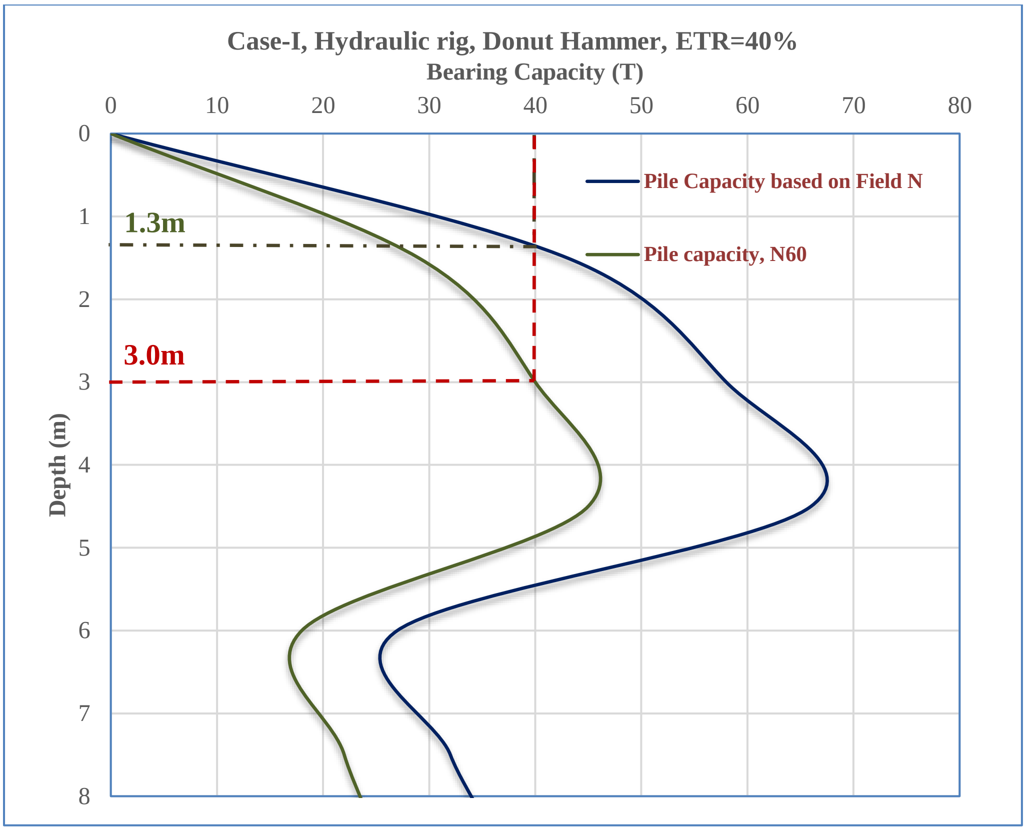

Fig 6. Pile Capacity Curve-I

Further, let us consider the case of a hydraulic rig (multi-purpose) with an automatic hammer and the ETR data at 11m, 12m & 13m is listed as shown in Table 3. EMX values are used to arrive at ETR (%) of 82% and N_{60} values at various depths. Automatic hammers always are bound to impart high energy transfer to drill rods as the energy losses are minimal. State of art techniques like qualitative modification of anvil will vary the ETR values in exceptional cases. ETR will aid in assessment of seismic characteristics of soil. In liquefaction analysis, Cyclic Resistance Ratio has its basis derived from N value. The actual energy transferred plays a very crucial role in assessment of liquefaction and any uncertainty in energy transfer percentage leads to great uncertainties in the liquefaction potential of soil. (Anbazhaghan et al., 2016)

Table 3. ETR Data – Hydraulic rig with Automatic Hammer

Depth (m)	Field Measured N Value	Average Energy Transferred EMX (J)	Average Energy Transfer Ratio ETR (%)	SPT Value
11	24 (7/12/12)	380.92	81.58	33
12	22 (7/10/12)	392.05	83.93	31
13	17 (6/8/9)	382.22	81.83	23

In cases where competent soil stratum is available at deeper depth, variance of pile length with respect to measured N value and N_{60} vary enormously as shown in Fig 7. Field N values are less than N_{60} which underpredicts any design based on measured N values. For illustration a 1000mm diameter pile is chosen and its capacity is derived with N and N_{60} values. Pile length of 35m to 45m is obtained as lower bound and upper bound values for N_{60} values compared to 42m to 48m pile lengths based on N. Cost associated with 10% to 20% extra pile length design can be saved by this method. Considering humongous nature of infrastructural projects in India, a simple ETR test can save lakhs of crores of financial capital in the country.

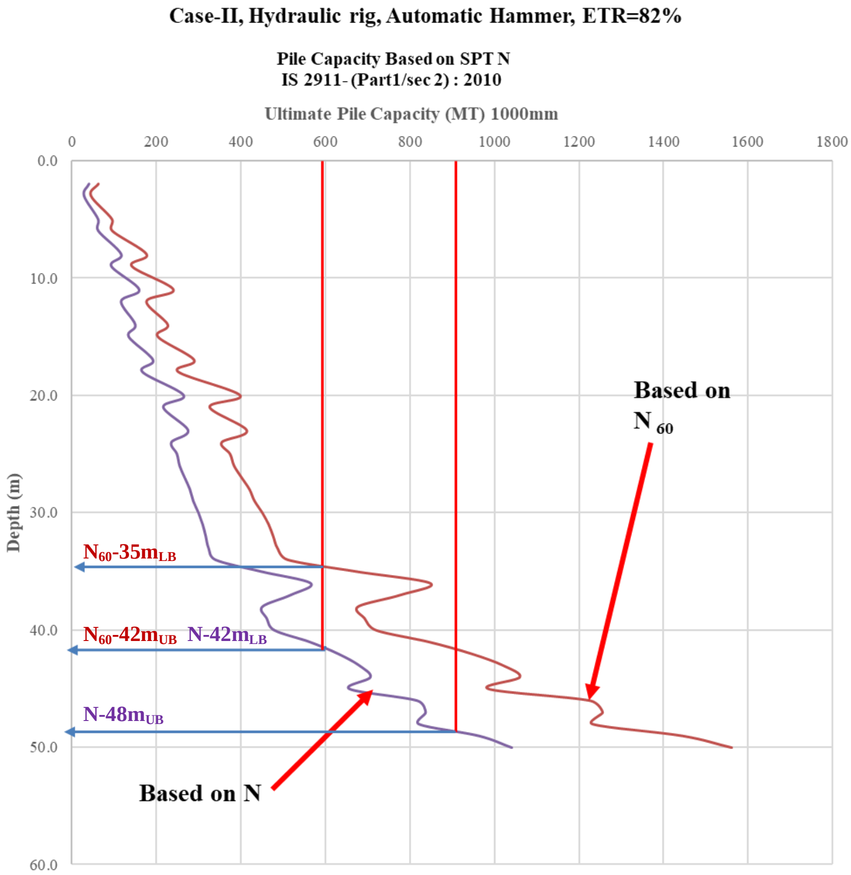

Fig 7. Pile Capacity Curve- II

Regardless of impressive list of shortcomings, SPT is unlikely to be abandoned. The test is very economical in terms of cost per unit of information. The test has advantage over Cone penetration test as it provides soils samples, which can be tested for index properties and visually examined. Long service life of the enormous amount of equipments in use, accumulation of large SPT database that is continually expanding and results of the SPT have been correlated with a number of soil properties makes SPT the most sought method of investigation. The estimated values are often used in the preliminary designs in lieu of values obtained from tests run specifically to determine those properties. N Value shall be standardized to 60% Energy Transfer (N_{60}) in every geotechnical investigation activity, where many correlations will be still valid. IS 2131 and IS 1893 shall be similar while addressing the specifications and corrections.

5 CONCLUSIONS

Based on the present study, the following conclusions are drawn.

- Energy Calibration shall be made for each rig which will have different type of driving systems and skill. Energy Transfer Ratio varies with respect to type of rig and type of hammer. It is imperative to measure ETR (%) to arrive at N_{60} especially in large scale projects which involves operation of several rigs. Standard rig and SPT driving system which produces consistent energy transfer values shall be deployed for good quality geotechnical data which is the basis for basic and advanced engineering analysis of the intended structure.
- When ETR is below 60% (In case of calyx/hydraulic rigs with rope drop/hydraulic drop donut hammers), measured N values are higher than N_{60}. Design with respect to N values will over-predict any design and may further lead to failure of the geotechnical structure. N_{60} values calculated based on ETR test will provide N_{60} values less than measured N and hence ensures safety.
- When ETR is above 60% (In case of hydraulic/multi-purpose high end rigs with hydraulic drop auto-trip/automatic hammers), measured N values are lower than N_{60}. Design with respect to N values will under-predict any design and may further lead to cost-over run of a project and over conservative design of any geotechnical structure. N_{60} values calculated based on ETR test will provide N_{60} values more than measured N and hence ensures economical prospects.
- Ignorance of measuring ETR during geotechnical investigation stage may be detrimental at later stage of a project. A simple ETR test can provide safety, reduce cost and provide more clarity to the designs.

References

1. Anbazhagan P, Aysuh A, Prakash D, "Effect of Energy Efficiency of Hammer on Liquefaction Potential of soil", Indian Geotechnical Conference (2016)
2. Anbazhagan, P., Ayush, K., Yadhunandan, M.E. et al , "Effective Use of SPT: Hammer Energy Measurement and Integrated Subsurface Investigation", Indian Geotech J 52, 1079–1096 (2022). https://doi.org/10.1007/s40098-022-00609-z
3. Anbazhagan, P., Yadhunandan, M.E. & Kumar, A., "Effects of Hammer Energy on Borehole Termination and SBC Calculation Through Site-Specific Hammer Energy Measurement Using SPT HEMA", Indian Geotech J 52, 381–399 (2022). https://doi.org/10.1007/s40098-021-00582-z
4. ASTM D1586-84, "Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils", Annual 36 Book of ASTM Standards, Vol. 04.08, American Society for Testing and Materials, Philadelphia, PA (2011)
5. ASTM D4633-10, "Standard test method for energy measurement for dynamic penetrometers", West 34 Conshohocken, PA (2010)
6. Batilas A V, Athanasopoulos G A, Roussos P G, Pelekis P C " SPT energy measurements: Manual vs Automatic Hammer release".(2016)
7. Edgar O, Fernando S, Marcelo M R, Paula B, "Energy Efficiency for Standard Penetration Tests", Journal of Geotechnical and Geoenvironmental Engineering, ASCE (2005). 10.1061/ASCE1090-02412005131:101252
8. IS 2131, "Indian Standard Method for standard penetration test for soils", First revision, Bureau of Indian Standards, New Delhi (1981)
9. IS 1896-(Part 1), "Criteria for Earthquake Resistant Design of Structures", Bureau of Indian Standard, New Delhi, India. (2016)
10. ISO 22476-3, "Geotechnical investigation and testing- Field testing- Part 3: Standard Penetration test". (2005)

11. Sherif M, Rose W, “Research Report : Standard Penetration Test (SPT) Correcton”, Maryland Department of Transportation State Highway Administration. (2001)
12. Yimsiri S, “Energy ratio of SPT practice performed in Thailand”, Geotechnical and geophysical site characterization 4 : proceedings of the fourth International Conference on Site Characterization, ISC-4, Porto de Galinhas, Pernambuco, Brasil, 17-21 September 2012. CRC Press. (2012)