Soil Dynamics and Earthquake Engineering 150 (2021) 106925

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Technical Note

Shear modulus from SPT N-values with different energy values

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ARTICLE INFO

Keywords:
Shear modulus
SPT N-Values
SPT Correlations
Hammer energy
Downhole
Crosshole

ABSTRACT

It is essential to determine low strain shear modulus (G_{max}) to model dynamic soil response and estimate the site effects due to earthquakes. Several correlations have been developed between dynamic soil properties and soil penetration resistance values such as N-values from Standard Penetration Test (SPT). However, only a few of the established correlations are often used because of uncertainty over applied hammer energy (E_H) and applicability in different regions. Hence, this study aims to signify the importance of E_H in N-value corrections, its influence on G_{max} estimation, to suggest modification factor for an existing correlation and validate with Downhole and Crosshole measurements. Different SPT corrections are studied besides the energy measurements in the analysis of the correlation between the N-value and G_{max}. A previously proposed correlation between measured N-value and G_{max} is improved to account for in-situ E_H measurement, and the correction factors to account for different hammer energy ratios (ER) are suggested. Modified correlations compared well and agreed within the 95 % confidence bound with the freshly acquired seismic borehole tests data.

1. Introduction

Estimating local site effects during the earthquake helps produce reliable design criteria for the upcoming infrastructure in any region. Seismic waves may get strongly amplified or attenuated just before reaching the surface. Hence, site effects such as amplification have prompted many microzonation studies which improved understanding of the local site conditions, ground response analysis, and liquefaction estimation. The dynamic response of the soil under cyclic loading depends on the nature of the earthquake source, wave travel path and local subsurface properties such as G_{max}, S-wave velocity (V_s), sediment depth (h) and in-situ density (ρ). These properties can be estimated from in-situ sampling and laboratory tests. However, the dynamic laboratory tests of soils are often time-consuming, expensive and require specialised monitoring of the specimen properties [1]. Since most designs in geotechnical engineering such as bearing capacity calculation, stiffness, site characterization, in-situ density estimation and safety against liquefaction are predominantly based on N-values, several attempts were made to correlate N-value with properties like G_{max}, P-wave velocity (V_p), V_s and other dynamic or static properties.

Many of these correlations with in-situ dynamic properties are defined for a specific E_H value. Change in energy delivered to the sampler from the hammer will lead to different measured N-values at the same depth and location [2,3]. Thus, it is necessary to measure E_H and correct the measured N-values before using these in any calculation. A review of the existing literature indicated that there is a lack of studies that included the effect of E_H in SPT correlations. Variation of estimated G_{max} with E_H is not well discussed in the literature, except for some work by Anbazhagan et al. [4]. Since a wide variation in applied E_H during SPT tests is reported throughout the world (Electronic Table ET1), energy-adjusted G_{max} correlations are necessary to obtain reliable dynamic properties. A previously proposed correlation [4]. has been analyzed, and the effect of E_H on SPT N-values has been studied. Based on the analysis, correction factors and the modified values for the constant “a” have been proposed considering different E_H values. The newly revised correlation is validated by comparing the G_{max} estimated from N-values at 26 locations (with E_H measurement) with G_{max} from Crosshole and Downhole seismic tests.

2. Correlations of SPT N with G_{max}

Several researchers have evaluated the low strain dynamic proper-

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https://doi.org/10.1016/j.soildyn.2021.106925
Received 31 May 2021; Received in revised form 22 July 2021; Accepted 23 July 2021
Available online 3 August 2021

ties (V_s and G_{max}) for different soils by empirically correlating them with indirect methods such as SPT N-values. Schmertmann [5] observed that G_{max} depends on the dynamic stress-strain properties of the soil and the level of strain in the soil due to the travelling shear waves. As SPT sampler penetration involves dynamic soil shear behaviour at the failure reference level of shear strain and modulus; it would be reasonable to expect a correlation between N-values and G_{max} at low strains [5]. These two parameters can be interrelated because they are both influenced by effective confining pressure, stress state, mineralogy, ageing and bonding. Over the years, SPT has been improved through standardization and E_H measurement, which is now compulsory in the design codes of developed countries [6,7]. However, it is still not included in the design codes of many developing countries, including Indian standards [8]. As a result, E_H measurement in SPT is still not practised in India despite N-value being widely used geotechnical design input.

Anbazhagan et al. [4] reviewed SPT N - G_{max} correlations and observed that most of the correlations were obtained based on the studies in Japan, thus limiting their applications elsewhere. By eliminating the assumed and extrapolated data, they developed a set of new correlations which can be directly applied in any region using correction factors for different E_H values. In this study, correction factors for different E_H values are updated, with further validated with G_{max} measurement from in-situ seismic tests.

2.1. Provisions for SPT N correction

In early studies, Schmertmann and Palacios [2] showed experimentally that the measured blow count was inversely proportional to the energy delivered to the drill rods. Later, Seed et al. [9] proposed E_H standardization at 60 % ER after studying for liquefaction potential using data from different SPT equipment. They observed that most of the SPT data was obtained using the safety hammer, with average 60 % Energy Ratio (ER) (actual delivered energy/theoretical maximum energy). However, a generalised approach to account for energy variations is debatable as E_H is highly dependent on local practice (e.g., method of release), type of equipment and subsoil. ET1 presents the energy correction factors for equipment in different countries, as reported previously [4,8,10].

The standard corrected blow count $(N_1)_{60}$ is calculated using the relation [3] below

$$(N_1)_{60} = E_h C_2 C_3 C_4 C_N N \tag{1}$$

where E_h = energy correction factor ((measured E_H)/60) [9], C_2 = borehole diameter correction, C_3 = sampler correction, C_4 = rod length correction and C_N = overburden pressure correction. Bowles [3] suggested that for the case of a small borehole, no sampler liner and for drill rod length more than 10 m, it is acceptable to assume correction factors C_i~1.0. For validation during this study, a soil column was considered, first with all the corrections, and second with only E_h and C_N. The distribution of corrections factors along with mean was found to change little when considering only E_h and C_N (Electronic Figure EF1). Thus, overburden pressure and E_H are observed to be the major factors affecting N-values.

3. Effect of E_H on G_{max} and correction factor for different energy values

Studies [4,5,11] have shown that the most important factor influencing the N-values is the amount of energy delivered to the drill rods. For the same soil conditions, N-values will vary with the efficiency of the SPT equipment. Thus, N-value should be standardized to a site-specific E_H measurement. If E_H measurement is not carried out during SPT, error in N-values because of energy difference will propagate to the correlated dynamic properties.

Based on previous studies [4,8,10], it can be noted that E_H ranges from 25 % to 85 %. Since the energy delivered itself is not constant, assuming E_H to be constant based on the widely used hammer type in a region may often lead to error in the assessment of in-situ properties. Therefore, a study on the effect of E_H on N-G_{max} correlation is discussed here. A correlation to estimate G_{max} for all soils from N-value at any E_H was proposed earlier [4] by combining SPT data (with 78 % E_H) with over ten existing correlations. The previous correlation [4] can be rewritten by introducing corrected N-value as

Table 1
Correction factors and coefficient 'a_m' value from Equation (4) and Equation (6).

ER, %	80	70	60	50	40	30	20
$CF_{ERmto78}$	1.03	0.90	0.77	0.64	0.51	0.38	0.26
a_m	16.67	15.29	13.83	12.28	10.62	8.81	6.77

$$G_{max} = 16.40 {N_{78}}^{0.65} \tag{2}$$

where N_{78} is the SPT blow count for 78 % E_H. It is to be noted that N_{78} is used in the above correlation because it was developed based on the previous correlations and majority of the data from Japan where N-values were reported with 78 % E_H. For the more popular N_{60}, a correction factor can be used. To use equation (2), we note the measured energy value and then convert the measured N-value to N_{78}. However, this conversion is not practiced often [4] due to the unavailability of E_H data.

Hence, it is necessary to discuss correction factors for the appropriate use of the correlations. Considering measured ER as ER_m, G_{max} can be estimated as

$$G_{max} = 16.40 {N_{78}}^{0.65} = 16.40 \times \left(CF_{(ER_m \text{ to } 78)} \times N_{ER_m}\right)^{0.65} \tag{3}$$

Here N_{ER_m} is measured N-value under ER_m, and $CF_{(ER_m \text{ to } 78)}$ is the correction factor given by

$$CF_{(ER_m \text{ to } 78)} = \frac{ER_m}{78} \tag{4}$$

Alternatively, modified coefficient a_m can be used for different ER as given below

$$G_{max} = 16.40 \times \left(\frac{ER_m}{78}\right)^{0.65} \times {N_{ER_m}}^{0.65} \tag{5}$$

$$a_m = 16.40 \times \left(\frac{ER_m}{78}\right)^{0.65} \tag{6}$$

This modified coefficient. 'a_m' can be multiplied with $(N_{ER_m})^{0.65}$, and G_{max} can be estimated at the given ER_m. The a_m values for different ER_m are presented in Table 1. As an example, for ER_m = 60%, the following equation shall be used to estimate G_{max}

$$G_{max} = 13.83 {N_{60}}^{0.65}$$

Similarly, for ER_m = 50%, the equation will be $G_{max} = 12.28 {N_{50}}^{0.65}$. Thus, with an increase in ER for a constant N-value, a_m also increases. a_m values for different ER_m for Equation (5) along with $CF_{(ER_m \text{ to } 78)}$ are tabulated in Table 1 (also refer to EF2). It is evident from equation (4) and equation (6) that $CF_{(ER_m \text{ to } 78)}$ varies linearly with ER_m, while a_m varies nonlinearly with ER_m.

Fig. 1(a) presents the variation of G_{max} with N-value at different ERs. The graph is exponential and shows large differences in G_{max} for same N-values at different ER. Thus, E_H measurement is essential for proper use of correlation without which the estimated parameter values will not be reliable. Fig. 1(b) shows the variation in G_{max} with ER at different N-values. From this graph, it can be observed that the slope of the curve increases with an increase in N-value. This increase implies that the change in G_{max} with E_H would be significant at the higher range of N-values than the lower N-values.

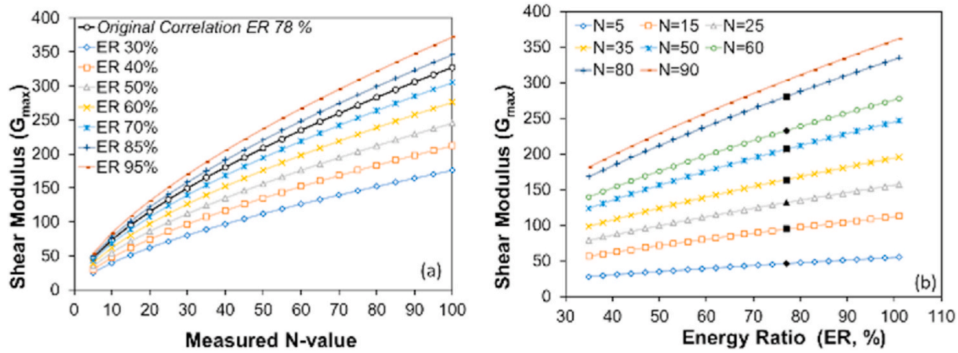

Fig. 1. (a). G_{max} vs. measured N-value for different E_H, **(b).** G_{max} vs. Energy Ratio (ER) for measured N-values with N-values being kept constant, with G_{max} for 78 % ER highlighted in black.

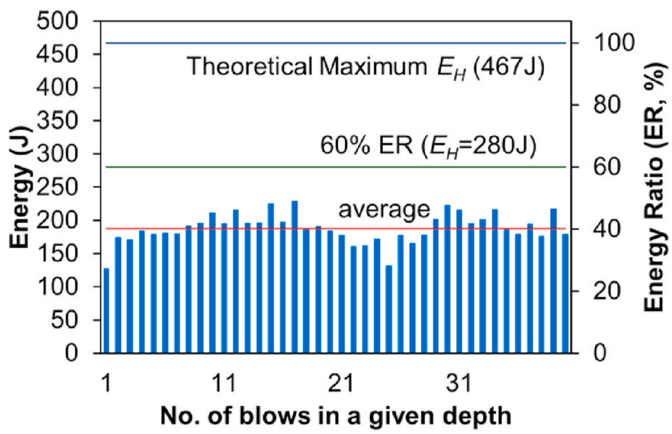

Fig. 2. Typical energy data recorded in SPT-HEMA during the test at 4 m depth at site Test_B10, total blows = 41, N = 29.

4. G_{max} based on field measurements

To validate the correction factors for different E_H values (Table 1), detailed field experiments have been carried out at 26 test locations in the cities of Chennai, Bangalore and Tumkur in Southern India. Boreholes were drilled by rotary wash boring methods and SPT was carried out using a Donut hammer with energy measurement apparatus attached below the anvil [6]. Crosshole and Downhole tests were conducted at 9 and 17 test locations in total respectively. In-situ bulk densities at different depths were calculated using undisturbed sampling and density correlations.

4.1. E_H Measurement in SPT

Several correlations of N-values with Bearing capacity and the other soil properties [3,12] have been developed using standard SPT corrections with standard ER in the correlations. In-situ E_H measurement is necessary for correct use of these correlations. For the first time in India, the Indian Institute of Science (IISc) Bangalore developed SPT Hammer Energy Measuring Apparatus (SPT-HEMA) and carried out energy measurements in Bangalore and Chennai in Southern India [8]. Recent studies reported ER for three types of SPT setups used in India, with mean ER ranging from 15 to 80 % [11].

To measure E_H, SPT-HEMAhttps://www.iisc.ac.in/better-soil-investigation-by-energy-measurement-during-spt measures the impact energy delivered by the hammer below the anvil and above the sampler using the Force-Velocity method [6]. N-values at 26 borehole locations were measured at 1 or 1.5 m interval along with E_H measurement below anvil [6]. For comparison, SPT-HEMA was used along with SPT Analyzer from Pile Dynamics, Inc. and the E_H measurements were found to differ by

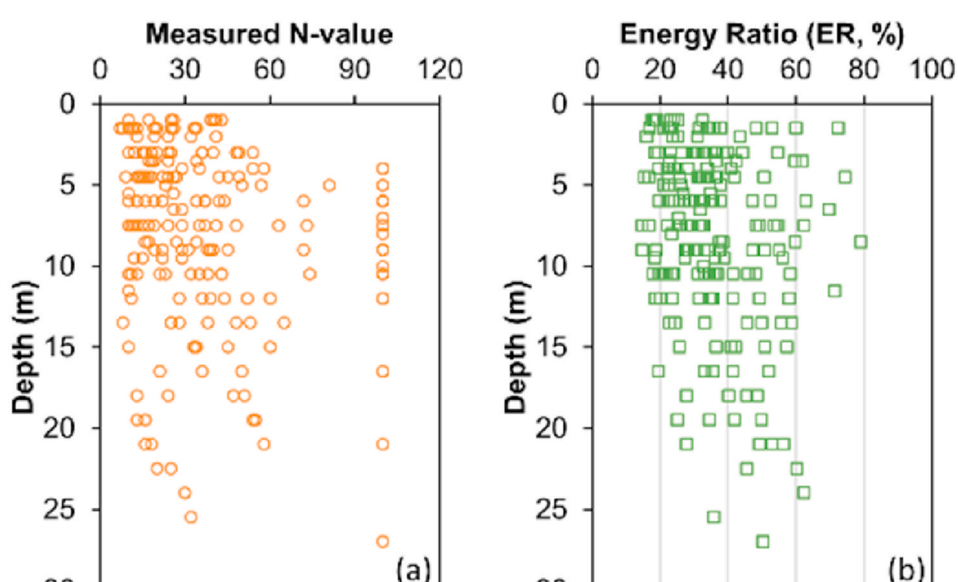

Fig. 3. (a). Distribution of N-values with depth for test locations, **(b).** Distribution of Hammer Energy Ratio (ER, %) delivered with depth.

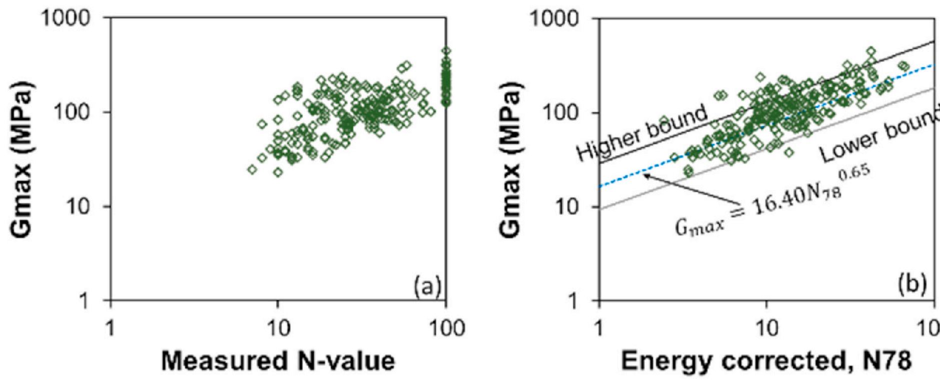

Fig. 4. G_{max}^{test} plotted against **(a).** Uncorrected measured N-value **(b).** Energy corrected N-value (N_{78}) with 95 % confidence bound from Equation (7) & Equation (8).

6–8%, with SPT-HEMA on the lower side. The average E_H values at the test sites (ET2) present a broader spectrum of measured E_H values than previous studies [8]. Around 77 % of the measured E_H values fall in the range of 15–45 %. Such low E_H values are often a result of non-standard drop weight and height, lifting mechanism, anvil size and inclination of guide rods, e.g., higher inclinations of guide rod cause friction between guide rod and hammer [8,11]. Anbazhagan and Ingale [11] measured E_H for each blow during SPT and reported considerable variation of energy during test at any particular depth (Fig. 2, EF3), which has not been reported earlier. Thus, it would be incorrect to select average E_H or ER for any site or equipment solely based on the previous studies.

The efficiency of energy transfer of each blow (ER) can be calculated by taking the ratio of E_H and theoretical potential energy for the standard hammer of 63.5 kg dropped by 760 mm. The combined Distribution of N-values and ER (%) with depth at all the test locations are shown in Fig. 3.

4.2. Borehole seismic tests

Borehole seismic tests CH and DH are low-strain seismic tests commonly used to obtain V_s and V_p profiles. These tests have been used previously up to a depth of 100 m and more to estimate G_{max} and the Poisson's ratio (ν) from V_p and V_s although caution should be exercised while estimating poisson ratio in the field as saturation of soil significantly changes V_p. The source-receiver spacings and acquisition parameters were selected as per ASTM standards [13,14]. Data acquisition was carried out using a 24-channel Geode (Geometrics) seismograph, BGK5 borehole receiver and BIS-SH sparker source from Geotomographie. At selected test locations, the Multichannel Analysis of Surface Waves (MASW) method was also used to validate the V_S profiles.

5. Results and discussion

To study how well the acquired data validates the correlation in equation (2), a 95 % confidence bound for individual data points was obtained from the original data [4].

$$\text{Higher bound:}\quad G_{max} = 28.89N_{78}^{0.648} \tag{7}$$

$$\text{Lower bound:}\quad G_{max} = 9.31N_{78}^{0.646} \tag{8}$$

The SPT N-values in the study range from 7 to 100 (assuming N = 100 for refusal). Dense silty sand, silty sand along with fine gravel particles, and weathered Charnockite rock are reported as refusal layers at the test locations. Different G_{max} values estimated from DH and CH tests for similar refusal conditions may be attributed to different deposition and stratification of soil, varying stress conditions and overburden pressure. G_{max} is calculated using $G = \rho V_s^2$, hereafter called as G_{max}^{test}. Fig. 4(a) and (b) show the G_{max}^{test} values estimated from the field tests in the current study plotted separately against N (Fig. 4(a)) and N_{78} (Fig. 4 (b)) along with the 95 % confidence bound from Equation (7) and Equation (8). It was observed that ~84 % of the G_{max}^{test} data lies within the 95 % confidence bound.

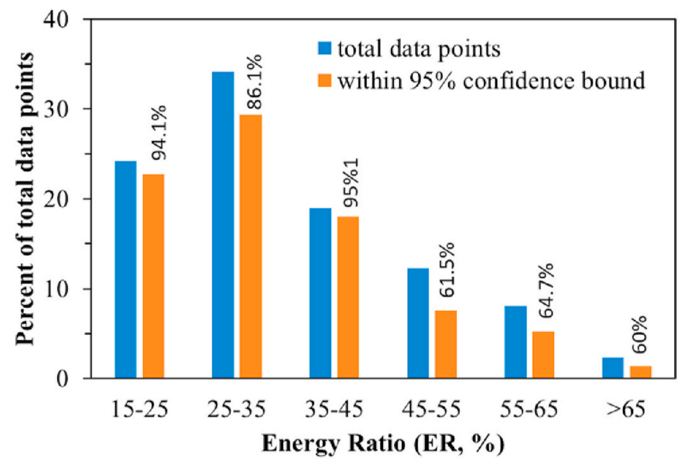

Fig. 5. Distribution of acquired data in ER bins showing % of total data in the bins as well as % of G_{max}^{test} points that fall within the confidence bound.

G_{max}^{test} data from Fig. 4 has been divided into bins of width 10 % ER ranging from 15 to 75 %. The percentage of G_{max}^{test} data lying within the confidence bound is shown in Fig. 5. Fig. 5 also shows the number of G_{max}^{test} data points within the confidence bound in each bin as a percent of the number of total data points as well as percent of the number of data points in the respective bin. It is observed that data in the selected E_H bins satisfy the proposed correlation well within the confidence bound.

The majority of ER data (~77 %) lies within the range of 15–45 %, with ~91 % of the G_{max}^{test} data lying within the defined confidence bound (Fig. 5). Therefore, 15–45 % could be the ER range in which the majority of SPT equipment in this region generally operate. G_{max}^{test} data from Fig. 4 (a) is plotted in Fig. 6, with uncorrected N-values in the same ER bins from Fig. 5. Using Equation (5) and Table 1, G_{max}^{test} is compared with theoretical plots for G_{max} for mean ER value of the bins and presented in Fig. 6. It was observed that the acquired data in the selected ER range (15–45 %) fits well with the theoretical plots, and hence, validate the application of correction factors. It can thereby be ascertained that all the SPTs should be accompanied with energy measurement, and a common energy correction should be avoided. In the higher ER ranges, i.e., 45–75 %, a similar fit is not so prominent. This may imply that apart from E_H correction, other site parameters like effective overburden pressure may play a role in SPT and E_H correlations for higher E_H values and need to be accounted for in the development of energy-based N-value-G_{max} correlations in further studies.

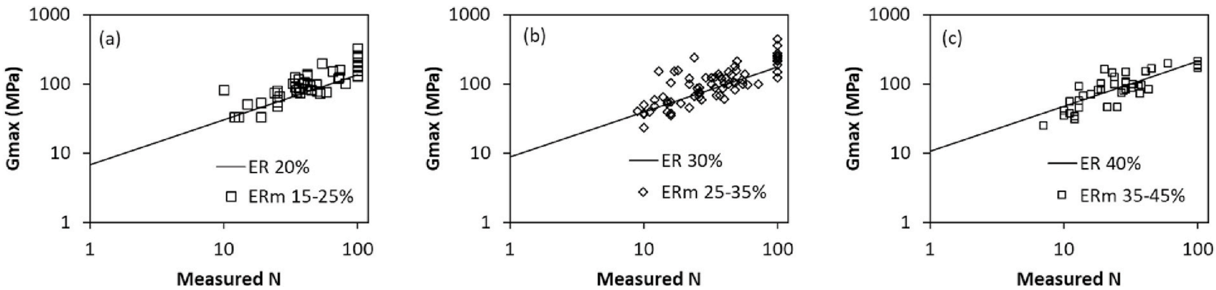

Fig. 6. G_{max}^{test} plotted against measured N-values, compared with theoretical plot (equation (5), Table 1) for ER 15–45 %.

6. Conclusions

This note presented a study on the importance of E_H measurement for SPT on estimated low strain shear modulus. E_H is found to be a governing factor with the overburden pressure affecting the measured N-values at any given depth for different SPT equipment. An improvement to a previously proposed correlation between SPT N-values and G_{max} for all soil types has been discussed in this paper. The original equation has been modified, and correction factors have been proposed to extend its use beyond the standard ER used for a given SPT equipment. Corrections have been proposed in two ways. First to use the corrected N-values for measured ER and then use it in the correlation for N_{78}. Second, to use the correction factors for coefficient "a", and directly use the measured N-value. For validation, CH and DH tests after E_H measurement during SPT were conducted. G_{max}^{test} estimated from CH and DH tests were compared with the modified $N - G_{max}$ correlation and are found to be in good agreement for the measured $E_H$values within the 95 % confidence bounds.

Author statement

Anbazhagan P: Conceptualization, Methodology, Validation, Resources, Writing - Review & Editing, Visualization, Supervision. **Ayush Kumar**: Methodology, Software, Validation, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization. **Sagar G Ingale**: Software, Formal analysis, Resources. **Sanjay K Jha**: Validation. **Lenin K R**: Investigation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Dam Safety (Rehabilitation) Directorate, Central Water Commission, Government of India for funding the project entitled "Capacity Buildings in Dam Safety" under "Dam Rehabilitation and Improvement Project". Authors also thank SERB, DST for funding project "Development of correction factors for standard penetration test N-values in India through energy measurement and field experiments – Step towards a reliable Liquefaction Potential Assessment" Ref: SERB/F/198/2017-18 dated May 11, 2017 and M/s Secon for funding Project "Effect of shear wave velocity calibration on Amplification of shallow and deep soil sites" Ref: SECON/IISc/MoES/WO/07-18/0079 date. August 14, 2018. The authors also thank Mr. Ravinesh Kumar, Research Associate, IISc for his valuable assistance in field tests and processing of field data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.soildyn.2021.106925.

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