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# Review of correlations between SPT *N* and shear modulus: A new correlation applicable to any region

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A low strain shear modulus plays a fundamental role in earthquake geotechnical engineering to estimate the ground response parameters for seismic microzonation. A large number of site response studies are being carried out using the standard penetration test (SPT) data, considering the existing correlation between SPT *N* values and shear modulus. The purpose of this paper is to review the available empirical correlations between shear modulus and SPT *N* values and to generate a new correlation by combining the new data obtained by the author and the old available data. The review shows that only few authors have used measured density and shear wave velocity to estimate shear modulus, which were related to the SPT *N* values. Others have assumed a constant density for all the shear wave velocities to estimate the shear modulus. Many authors used the SPT *N* values of less than 1 and more than 100 to generate the correlation by extrapolation or assumption, but practically these *N* values have limited applications, as measuring of the SPT *N* values of less than 1 is not possible and more than 100 is not carried out. Most of the existing correlations were developed based on the studies carried out in Japan, where *N* values are measured with a hammer energy of 78%, which may not be directly applicable for other regions because of the variation in SPT hammer energy. A new correlation has been generated using the measured values in Japan and in India by eliminating the assumed and extrapolated data. This correlation has higher regression coefficient and lower standard error. Finally modification factors are suggested for other regions, where the hammer energy is different from 78%.



## 1. Introduction

Many countries have initiated seismic microzonation studies with emphasis on site effects around the world, because of the increasing earthquake damages due to ground motion/site effects. Researchers are trying to develop regional level hazard maps considering different earthquake effects. Earthquake damages are mainly because of the changes in the seismic waves and soil behavior during dynamic loading. These are called as site effects and induced effects, which are primarily based on geotechnical properties of the subsurface materials. Site effects are the combination of soil and topographical effects, which can modify (amplify and deamplify) the characteristics (amplitude, frequency content and duration) of the incoming wave field. Induced effects are liquefaction, landslide and Tsunami hazards. Amplification and liquefaction are the major effects of earthquake that cause massive damages to infrastructures and loss of lives. Recent study by USGS revealed that among deadly earthquakes reported for the last 40 years, loss of lives and damages caused by ground shaking hazard was more than 80% of the total damages [24]. Subsurface soil layers play a very important role in ground shaking modification. Most of the earthquake geotechnical engineers are working to estimate and reduce the hazards due to geotechnical aspects.

Site specific response and seismic microzonation studies are carried out by considering the local geotechnical properties of subsurface layers. Dynamic shear modulus of subsurface layer is the most important geotechnical property used in the site specific response analysis. The shear modulus of subsurface layers are usually measured in situ by means of seismic exploration and sometimes by the dynamic triaxial compression test or the resonant column test of undisturbed soil samples in the laboratory [28]. A large number of researchers have presented the laboratory based shear modulus studies. Even though SPT *N* data are widely used for site response and seismic microzonation, very few studies are available for in situ correlation between shear modulus versus standard penetration test (SPT) *N* values using the field experiments [5,9]. Seismic microzonation requires soil parameters in the form of shear wave velocity for site classification and shear modulus to estimate the site specific ground

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response parameters [6–8,38,4]. The input soil parameters required essentially are thickness ($h$), density ($\rho$), and shear modulus ($G_{max}$) for each subsurface layer. The soil type and thickness of each layer are generally obtained by drilling boreholes and logging the borehole information (bore log). The in-situ density of each layer is usually obtained from the undisturbed soil samples collected from boreholes. However, such measuring techniques are expensive, time consuming, and require specialized techniques [28]. Borelogs with SPT $N$ values are widely used in most of the microzonation studies. Shear modulus ($G_{max}$) for site response analysis is evaluated by using the existing correlations between SPT $N$ values and shear modulus. The SPT is one of the oldest, popular and most common in situ tests used for soil exploration in soil mechanics and foundation engineering. This test is being used for many geotechnical projects because of the simplicity of the equipment and test procedure. In particular SPTs are used for seismic site characterization, site response and liquefaction studies for seismic microzonation [2,5].

This paper reviews available correlations between SPT $N$ and shear modulus. The existing correlations were developed by Imai and Yoshimura [17], Ohba and Toriumi [27], Ohta et al. [29], Ohsaki and Iwasaki [28], Hara et al. [16], Imai and Tonouchi [18], Seed et al. [34,36] and Anbazhagan and Sitharam [5]. Most of the old correlations are listed in the popular textbook of Ishihara [20] and Kramer [23]. Ishihara [20] has presented the summary of SPT $N$ values and $G_{max}$ correlations based on the above first five research works. Kramer [23] has modified the correlation developed by Imai and Tonouchi [18] for a sandy soil by replacing the measured $N$ values with energy corrected $N$ values [$N_{60}$]. Seed et al. [34] presented the correlation based on their previous studies. Seed et al. [36] have presented $G_{max}$ correlation based on the Ohta and Goto [30] data. Correlation proposed by Seed et al. [34,36] and Kramer [23] is being used in SHAKE2000 site response software to estimate the shear modulus from the SPT $N$ values. A correlation by Anbazhagan and Sitharam [5] is a recently developed one, after 27 years of gap. This paper presents the summary of the above correlations and comparisons. A new correlation has been developed considering the measured old and new data from Japan and India, where $N$ values are measured with a hammer energy of 78%. The modification factor for old and new correlations is suggested for other regions, where the SPT $N$ values are measured with different hammer energies.

## 2. Existing correlations between SPT $N$ and $G_{max}$

Many regression equations of SPT $N$ versus shear wave velocity are available in the literature for different soils by many researchers. Among these correlations few were developed considering corrected SPT $N$ and shear wave velocities. But few regression equations are available for SPT $N$ versus shear modulus when compared to SPT $N$ versus shear wave velocity relation. Summary of SPT $N$ versus shear modulus correlation in original form and converted in SI units is presented in Table 1 and discussed below.

Imai and Yoshimura [17] presented the very first correlation based on downhole shear wave velocity measurements in various soil layers. Here authors calculated shear modulus by assuming a unit weight of 1.7 t/m$^3$ (16.67 kN/m$^3$ or 1.7 g/cm$^3$) and highlighted that their correlation is valid for different soil types (see Eq. (1) in Table 1), provided that the small changes are needed in the numerical value of Poisson's ratio.

In the same year Ohba and Toriumi [27] have also given a correlation based on their experimental study at Osaka. The authors have estimated the shear wave velocity by manipulation of measured Rayleigh wave velocities and have assumed a unit weight of 1.7 t/m$^3$ (see Eq. (2) in Table 1).

**Table 1**
Existing correlations between SPT $N$ and $G_{max}$.

| Correlations available in literature | | | | Converted in SI units (MPa) | No. of data sets | N value used | | Remarks |
|---|---|---|---|---|---|---|---|---|
| Authors | Original Eq. no | Eq. no. | Unit | | | Min | Max | |
| Imai and Yoshimura [17] | $G_{max}=1000N^{0.78}$ | (1) | t/m$^2$ | $G=9.81N^{0.78}$ | | | | Mixed soil type |
| Ohba and Toriumi [27] | $G_{max}=1220N^{0.62}$ | (2) | t/m$^2$ | $G=11.96N^{0.62}$ | | | | Alluvial sand, clay |
| Ohta et al. [29] | $G_{max}=1390N^{0.72}$ | (3) | t/m$^2$ | $G=13.63N^{0.72}$ | 100 | 0.5 | 150 | Tertiary soil, diluvial sandy and cohesive soil |
| Ohsaki and Iwasaki [28] | $G_{max}=1218N^{0.78}$ | (4) | t/m$^2$ | $G=11.94N^{0.78}$ | 220 | 0.5 | 100 | All soil types |
| Ohsaki and Iwasaki [28] | $G_{max}=650N^{0.94}$ | (5) | t/m$^2$ | $G=6.374N^{0.94}$ | – | – | – | Sandy soil |
| Ohsaki and Iwasaki [28] | $G_{max}=1182N^{0.76}$ | (6) | t/m$^2$ | $G=11.59N^{0.76}$ | – | – | – | Intermediate soil |
| Ohsaki and Iwasaki [28] | $G_{max}=1400N^{0.71}$ | (7) | t/m$^2$ | $G=13.73N^{0.71}$ | – | – | – | Cohesive soil |
| Ohsaki and Iwasaki [28] | $G_{max}=1200N^{0.8}$ | (8) | t/m$^2$ | $G=11.77N^{0.8}$ | – | – | – | All soil types |
| Hara et al. [16] | $G_{max}=158N^{0.668}$ | (9) | kg/cm$^2$ | $G=15.49N^{0.668}$ | 25 sites data | | | Alluvial, diluvial and tertiary deposit |
| Imai and Tonouchi [18] | $G_{max}=176N^{0.607}$ | (10) | kg/cm$^2$ | $G=17.26N^{0.607}$ | 325 | 0.2 | 40 | Alluvial clay |
| Imai and Tonouchi [18] | $G_{max}=125N^{0.611}$ | (11) | kg/cm$^2$ | $G=12.26N^{0.611}$ | 294 | 1 | 70 | Alluvial sand |
| Imai and Tonouchi [18] | $G_{max}=251N^{0.555}$ | (12) | kg/cm$^2$ | $G=24.61N^{0.555}$ | 222 | 1.5 | 170 | Diluvial clay |
| Imai and Tonouchi [18] | $G_{max}=177N^{0.631}$ | (13) | kg/cm$^2$ | $G=17.36N^{0.631}$ | 338 | 2 | 300 | Diluvial sand |
| Imai and Tonouchi [18] | $G_{max}=144N^{0.68}$ | (14) | kg/cm$^2$ | $G=14.12N^{0.68}$ | 1654 | 0.2 | 300 | All soil types |
| Seed et al. [34] | $G_{max}=65N$ | (15) | t/ft$^2$ | $G=6.22N$ | Not available | | | |
| Anbazhagan and Sitharam [5] | $G_{max}=24.28N^{0.55}$ | (16) | MPa | $G=24.28N^{0.55}$ | 215 | 2 | 109 | Silty sand with less percentage of clay |
| Kramer [23] | $G_{max}=325(N_{60})^{0.68}$ | (21) | kips/sqf | $G=15.56(N_{60})^{0.68}$ | Modified from Imai and Tonouchi [18] | | | Sandy soil |

Eq.—equation, $G$—low strain measured shear modulus and $N$ is the measured SPT "$N$" value.

Ohta et al. [29] have presented the correlation between SPT *N* versus shear modulus using 100 sets of data from 18 locations (see Eq. (3) in Table 1). Data are derived from Tertiary soil, Diluvial sandy and cohesive soil, and Alluvial sandy and cohesive soil. The authors observed that the sandy soil possessed a little lower shear modulus than the cohesive soils for the same values of *N*, but the difference was not so definitive.

Ohsaki and Iwasaki [28] presented a summary of all the above equations and proposed new correlations from well shooting and SPTs. The authors and Evaluation Committee collected these data jointly on High Rise Building Structures. The authors developed this correlation by considering the SPT *N* value of 0.5 instead of zero, also by considering the different soil category and soil types. These data sets contain the data from Tertiary soil, Diluvial sandy soil, Diluvial cohesive soil, Alluvial Sandy soil and Alluvial cohesive soil. Correlations were developed based on soil category (Tertiary, Diluvial and Alluvial) and soil type (Sandy, intermediate and cohesive). The authors have observed that based on soil categories there was no appreciable difference between the coefficients of correlation. The correlation considering all the data sets is given in Eq. (4) in Table 1 and correlation for each soil type is given in Eqs. (5)–(7) in Table 1. The authors have highlighted that among the above correlations, the correlation obtained for cohesive soils (Eq. (7)) is well correlated and correlation for intermediate soils (Eq. (6)) is fairly correlated since soils of too much variety are incorporated in this category. In order to use a correlation regardless of soil type and geological age, authors rounded up Eq. (4) as given in Eq. (8) (see Table 1).

Fig. 1 shows the comparison of correlation developed by Ohsaki and Iwasaki [28]. The figure clearly shows that up to the *N* values of 30 all correlations give similar shear modulus, beyond that value the shear modulus of cohesive (Eq. (7)) and intermediate soil (Eq. (6)) are less than that of the sandy soil (Eq. (5)). The rounded correlation (Eq. (8)) and correlation for sandy soil (Eq. (5)) match closely for the values of *N* above 40, which may be due to a large number of data sets for sandy soil than cohesive soil. The correlation considering all the data sets (Eq. (4)) is in-between the Eq. (5) and Eqs. (6) and (7). Cohesive data sets are clustered in between SPT *N* value of 2 and 20, and the *N* value of less than 2 is found only in cohesive soils.

Hara et al. [16] have developed a correlation using the data set of 25 sites, which consisted of 15 Alluvial deposits, 9 Diluvial deposits and 1 Tertiary deposit. Cohesive soil data were only considered to develop correlation between $G_{max}$ and SPT *N* value. Shear wave velocity was measured by the well-shooting test, and the developed correlation is Eq. (9) in Table 1.

Imai and Tonouchi [18] developed correlations between SPT *N* with shear wave velocity and shear modulus and presented them

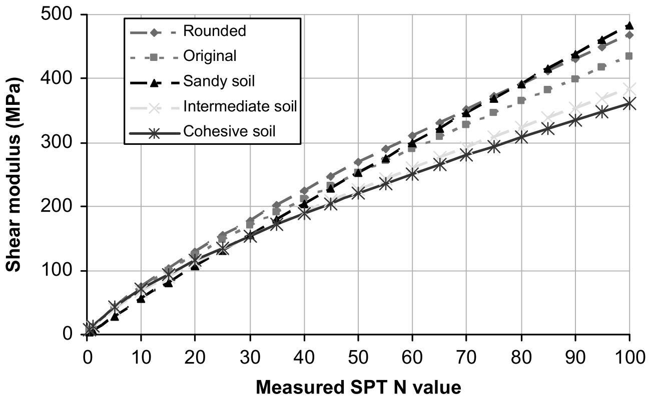


**Fig. 1.** Comparison of correlations developed by Ohsaki and Iwasaki [28] for different soils.

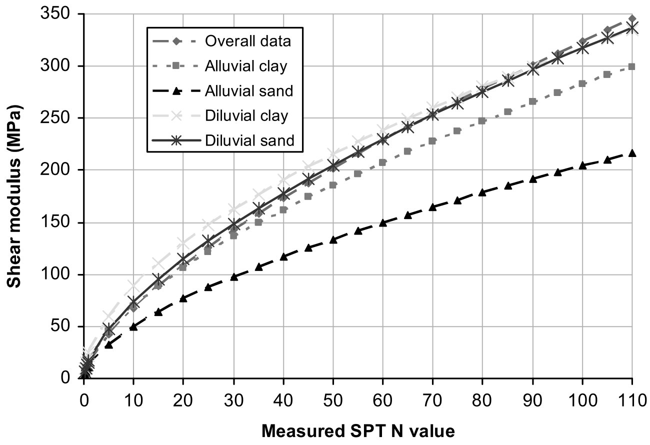


**Fig. 2.** Comparison of correlations developed by Imai and Tonouchi [18] for different soils.

in the Second European Symposium on Penetration Testing. The authors have accumulated the above data in the year 1967, which contains 400 boreholes data throughout Japan. They have measured S wave and P wave velocity separately, considering average *N* values for single velocity layer and have presented the correlation for different soil geological categories and soil types. The *N* values of less than 1 and above 50 are substituted for the number of blows required to achieve a penetration depth of 30 cm from the actual amount of penetration achieved in blows. Data set includes alluvial peat, clay, sand and gravel, diluvial clay, sand and gravel, Tertiary clay and sand, Fill clay and sand, and Special soil of loam and Sirasu. A large number of data are from alluvial clay and sand, diluvial clay and sand. Eqs. (10)–(14) in Table 1 give the correlation developed for different soil types with a number of data sets considered along with their range *N* values.

Fig. 2 shows the comparison of correlation developed by Imai and Tonouchi [18] (Eqs. (10)–(14)). It is interesting to note that the correlation for all the soil types (Eq. (14)) matches with the correlation for Diluvial sand (Eq. (13)) and clay (Eq. (12)). The correlation for alluvial clay (Eq. (10)) is comparable with the correlation for all the soil types (Eq. (14)) up to the SPT *N* value of 40. The alluvial sand correlation (Eq. (11)) is not comparable with the correlation for all the soil types (Eq. (14)) for any *N* value.

Seed et al. [34] developed a correlation based on their previous studies. The correlation is available, but other information regarding the number of points, data sets and soil types is missing. Co-author Arango (personal e-mail communication, October 2009) has also confirmed that the above details are not available. The correlation presented by Seed et al. [34] is given by Eq. (15).

Review shows that Eqs. (1) and (2) were developed by assuming uniform density. Remaining equations were developed assuming SPT *N* values less than 1 and extrapolating SPT *N* values more than 50 using shear wave velocity measured by well shooting. These studies were carried out in Japan except by Seed et al. [34]. Recently, Anbazhagan and Sitharam [5] developed a correlation between measured SPT *N* and shear modulus values using data generated for seismic microzonation study of Bangalore, India.

## 3. SPT and MASW comparison and correlation

Shear wave velocity used for old correlations is obtained from well shooting tests. The recent and very popular method for computation of shear wave velocity is Multichannel Analysis of Surface Wave (MASW). This method is widely used for seismic microzonation. A MASW is a seismic surface method, widely used

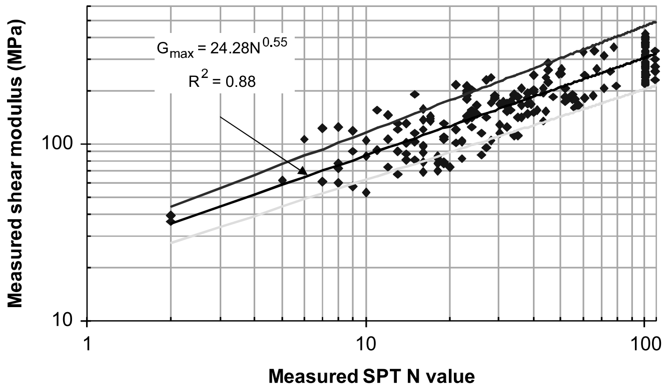


**Fig. 3.** Correlation developed by Anbazhagan and Sitharam [5] with data and upper and lower sides on 95% confidence interval.

for subsurface characterization and is increasingly being applied for seismic microzonation and site response studies [6]. It is also used for the geotechnical characterization of near surface materials [31,41,25,21,7]. MASW is used to identify the subsurface material boundaries, spatial and depth variations of weathered and engineering rocks [3], and also used in railway engineering to identify the degree and types of fouling [10]. MASW generates a $V_s$ profile (i.e., $V_s$ versus depth) by analyzing Raleigh-type surface waves recorded on a multichannel. Anbazhagan and Sitharam [3,5] have used the MASW system consisting of 24 channels Geode seismograph with 24 vertical geophones of 4.5 Hz capacity and have carried out a number of field experiments close to SPT borehole locations. The authors compared soil layers and rock depth using their experimental data. It is found that the shear wave velocities using MASW match well with soil layers in the boreholes.

Anbazhagan and Sitharam [5] selected 38 locations MASW and SPT results and generated 215 data pairs of SPT $N$ and $G_{max}$ values, which they have used for the regression analysis. Fig. 3 shows the shear modulus correlation recently developed by Anbazhagan and Sitharam [5] with data. The shear modulus corresponding to SPT $N$ value was estimated using measured shear wave velocity and density from the in-situ samples [5]. The correlation developed between $G_{max}$ and $N$ is given by Eq. (16). The correlation between SPT $N$ and $G_{max}$ presented in log–log plot and the best-fit equation has the regression coefficient of 0.88. In addition 95% confidence bands enclose the area that one can be 95% sure of the true curve gives a visual sense of how well the data define the best-fit curve [26]. Regression equations corresponding to 95% confidence intervals are given in Eqs. (16a) and (16b), respectively.

Upper side on 95% confidence interval

$$G_{max} = 29.12N^{0.60} \tag{16a}$$

Lower side on 95% confidence interval

$$G_{max} = 19.43N^{0.51} \tag{16b}$$

These $N$ values are measured values and no extrapolation or assumptions were made. The authors have compared newly developed correlation with widely used correlations and also developed correlation between corrected SPT $N$ with measured and corrected shear modulus [5].

## 4. SPT *N* values and corrections

The Standard Penetration Test (SPT) is one of the oldest and most common in situ tests used for soil exploration in soil mechanics and foundation engineering, because of the simplicity of the equipment and test procedures. Standard Penetration Test $N$ values become very important in earthquake geotechnical engineering because of a good correlation with an index of soil liquefaction and also provides the basis for site response and microzonation studies. Many researchers have published site-specific response parameters and liquefaction maps using the SPT data. This test is quite crude and depends on many factors due to the test procedure and some equipment used in the test. Many factors include the drilling methods, drill rods, borehole sizes and stabilization, sampler, blow count rate, hammer configuration, energy corrections, fine content and test procedure [33,22,15,39]. The combined effect of all these factors can be accounted by applying the correction factors separately or together. The SPT $N$ values may vary even for identical soil conditions because of the sensitivity to operator techniques, equipment malfunctions and boring practice. So the SPT $N$ based correlations may be used for projects in preliminary stage or where there is a financial limitation [5].

SPT data are most likely to be used in case of seismic microzonation and related site response and liquefaction studies. SPT data can be used effectively if proper corrections are applied to $N$ values based on field record and lab results. Detailed SPT corrections and range of correction values followed for microzonation and liquefaction study are given in Youd et al. [43], Anbazhagan [1], and Anbazhagan and Sitharam [8,5]. Most of the shear modulus correlations are developed using the measured SPT $N$ values. But Kramer [23] has given the correlation between corrected $N$ values for hammer energy [$N_{60}$] and shear modulus. In order to account this correlation, a brief summary of hammer energy correction is discussed here and more details can be found in Seed et al. [35] and Youd et al. [43]. The actual energy delivered to the drill rods while performing the SPT is different from the theoretical energy, which varies from region to region depending on the procedure and equipment used. Hammer energy generally varies from 40% to 90% of theoretical free-fall energy. The main reason for this variation is the use of different methods for raising and then dropping the hammer [22,33,35]. The widely used SPT hammers are Donut hammer, Safety hammer and Automatic trip donut type hammer. Seed et al. [35] have reviewed different hammers used in practice in Argentina, China, Japan and the United States with their energy measurement. The authors have considered 60% hammer energy as a base (safety hammer—most commonly used in the United States) and have produced correction factors. Corrected $N$ value considering hammer energy can be calculated as follows [35]:

$$N_{60} = N_m \frac{ER_m}{60} \tag{17}$$

where $N_{60}$ is the corrected $N$ value for 60% energy delivery, $N_m$ is the measured SPT $N$ value, and $ER_m$ is the hammer energy ratio for the method used in the investigation. The safety hammer with rope and pulley is mostly used in the US, where $N_{60}$ for the same is equal to $N_m$. Hammer used in Japan is Donut type, Seed et al. [35] have highlighted that rope and pulley with special throw release was followed in Japan in the year around 1983. Previously the free fall hammer release was practiced in Japan; hence, SPT $N$ values used for correlation before 1983 were measured by the free fall hammer release. The $G_{max}$ correlation papers do not have any information about hammer energy. So the SPT $N$ value measured using the Japan Donut hammer with the free fall energy release is 1.30 times ($ER_m$=78) greater than US safety hammer with rope and pulley release ($ER_m$=60). Hence an energy correction factor of 1.30 is applicable only for the data measured before 1983. Similarly, the SPT $N$ values measured using the Japanese Donut hammer with rope and pulley with a special throw release is 1.12 times ($ER_m$=67) greater than US safety hammer with rope and pulley. So, an energy correction factor of 1.12 is applicable for $N$ values measured around 1983 and later. These SPT $N$ value differences between the Japan and US practices are also highlighted in [20].

Correlation developed by Anbazhagan and Sitharam [5] is based on the SPT $N$ value measured in Bangalore, India. The procedure and hammer used in India are in concord with BIS 2131 [19] standard, which are similar to international specifications regarding weight and height of fall. Donut hammer is widely used in India, but limited information is available regarding hammer energy measurement. Personal discussion with leading geotechnical consultants reveals that the SPT $N$ values are measured using the Donut hammer with free fall release manually (pulling hammer rope by hand and dropping them after reaching marked height) or Donut hammer with pulley and rope release (pulling hammer by machine with operator). These are similar to Japanese practice to measure the SPT $N$ value before 1983. No record is available for SPT energy measurement in India. However, leading geotechnical consultant Mr. Anirudhan (personal communication, December 2009) has measured energy release by Donut hammer in 2000. He has found that energy varies from about 70% to 86%, which is similar to Japanese Donut hammer and hence $N$ values in India are almost similar to Japanese $N$ values.

## 5. Converted and modified correlations

Most of the correlations were developed in Japan and the related articles were published in Japanese. These correlations have come to light through a standard textbook of Soil Dynamics, Earthquake Engineering by Ishihara [20] and Geotechnical Earthquake Engineering by Kramer [23]. Few $G_{max}$ and SPT $N$ based correlations are also listed in SHAKE2000 software [37]. The very first converted correlation was presented by Seed et al. [36]. The authors have presented a correlation between corrected $N$ considering effective vertical stress and shear modulus based on the Ohta and Goto [30] studies. Ohta and Goto [30] developed correlation between measured $V_s$ and Japanese SPT $N$ values with depth by including soil factors. Seed et al. [36] have simplified original correlation by averaging soil factors and replacing Japanese $N$ value by US $N$ values with depth. Further Seed et al. [36] have assumed a unit weight of 1.92 g/cm$^3$ (120 pcf) and converted depth in effective stress by assuming water table is relatively shallow. Final correlation derived by above assumptions by Seed et al. [36] is given below:

$$G_{max} = 35 \times 1000 N_{60}^{0.34} (\sigma'_0)^{0.4} \text{(psf)} \tag{18}$$

where $N_{60}$ is the $N$ value measured in SPT delivering 60% of the theoretical free fall energy to the drill rods and $\sigma'_0$ is the effective vertical stress. Seed et al. [36] further modified Eq. (18) by considering $N = N_1/C_N$ and for normally consolidated deposits $\sigma'_m = 0.65\sigma'_0$. Final correlation proposed by Seed et al. [36] is given below:

$$G_{max} = 20 \times 1000 (N_1)_{60}^{1/3} (\sigma'_m)^{1/2} \text{(psf)} \tag{19}$$

where $(N_1)_{60}$ is the $N$-value measured in SPT delivering 60% of the theoretical free fall energy to the drill rods, and corrected for an effective overburden pressure of 1 t/sft and $\sigma'_m$ is the effective confining pressure.

The summary and compilation of relations between SPT $N$ values and $G_{max}$ was presented by Ishihara [20]. The author has plotted the summary of relations developed by others using a straight line log–log plot and have tabulated the constants "$a$" and "$b$" for the equation given below:

$$G_{max} = aN^b \tag{20}$$

The coefficient of "$a$" takes a value between 1.0 and 1.6 kPa and the exponent of $N$ takes the value between 0.6 and 0.8. Table 2, columns 1 and 2 shows the "$a$" and "$b$" values presented by Ishihara [20] and respective references. This is the first textbook which summarizes many SPT $N$ versus shear modulus relations developed by others. In this book, the author has also highlighted that the SPT $N$ value in Japanese practice is approximately 1.2 times [$\approx(1.3+1.12)/2$] greater than the $N_{60}$ values used in the US practice [20]. Fig. 4 shows the correlation presented by Ishihara [20] considering the Japanese SPT $N$ values. Anbazhagan et al. [11] had noticed that $G_{max}$ values vary from 1.2 to 2.5 kPa for the SPT $N$ value of 1 and 21–48 kPa for the $N$ value of 100, which are very less. This has been brought to the notice of Ishihara by the first author and had requested clarification for the same (e-mail communication with Ishihara on June 2009). Ishihara has given the clarification by e-mail that the constant "$a$" presented in column 3, Table 2 (Table 6.4, p. 119 in [20]) should have values of 10, 12.2, 13.9, … with the unit MPa. This means that the shear modulus correlation given by Ishihara [20] in Table 6.4, p. 119 is 9810 times less than the actual values reported by the original researchers. Hence the modified '$a$' values based on this study are given in Table 2 column 4.

Another SPT $N$ based correlation given by Kramer [23] textbook of Geotechnical Earthquake Engineering (p. 235, SPT Eq. (2))

**Table 2**
Coefficient of constants for $N$ versus $G_{max}$ correlations given in Ishihara [20] and revised constants of "$a$" value.

| Value of "$a$" as per Ishihara [20]. (kPa) | Value of $b$ | Modified "$a$" value suggested by Ishihara on Sep 28, 2009[a] (MPa) | Suggested "$a$" value by authors in this paper (MPa) | References and respective equations in this paper |
|---|---|---|---|---|
| 1 | 0.78 | 10 | 9.81 | Imai and Yoshimura [17] and Eq. (1a) |
| 1.22 | 0.62 | 12.2 | 11.96 | Ohba and Toriumi [27] and Eq. (2a) |
| 1.39 | 0.72 | 13.9 | 13.63 | Ohta et al. [29] and Eq. (3a) |
| 1.2 | 0.8 | 12 | 11.77 | Ohsaki and Iwasaki [28] and Eq. (8a) |
| 1.58 | 0.67 | 15.8 | 15.49 | Hara et al. [16] and Eq. (9a) |

[a] By e-mail personal communication on September 2009.

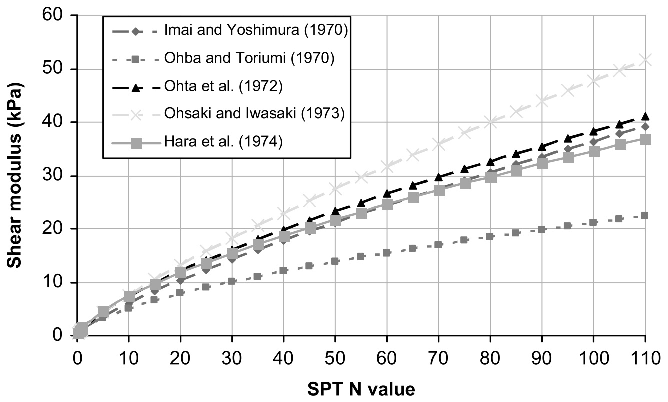


**Fig. 4.** Plot of correlations given in Ishihara [20] (Table 6.4) (modified after Anbazhagan et al. [11]).

is given by Eq. (21) in Table 1. This correlation was cross referred by the original authors Imai and Tonouchi [18] for sandy soil, but SPT *N* values were replaced by hammer energy corrected *N* values in the original correlation. Personal communication with Kramer confirms that $N_{60}$ is the hammer energy corrected *N* value for 60% energy release. It can be noticed that no information is available regarding hammer type, energy level and releasing mechanism in Imai and Tonouchi [18]. Kramer [23] has not highlighted how $N_{60}$ was estimated. According to Seed et al. [35], two types of hammers were used in Japan with different hammer energies. Hammer used before 1982 had the energy release of 78% of theoretical values, which is 1.3 times larger than that of 60% hammer release in the US [35].

In order to compare, the original correlation developed by Imai and Tonouchi [18] and reproduced sand correlation by Kramer [23], *N* values in the original correlation for alluvial clay and sand, diluvial sand and all soils (Eqs. (10), (11), (13) and (14)) are multiplied by 1.3 (i.e. $N_{60}=1.3N$). Fig. 5 shows the comparison of reproduced correlation by Kramer [23] (Eq. (21)) for sand with original Imai and Tonouchi [18] correlation for alluvial clay and sand, diluvial sand and all the soil types (Eqs. (10), (11), (13) and (14)). Similar to Fig. 2, correlations of diluvial sand and all the soil types (13 and 14) are comparable for hammer energy corrected *N* values. It can be easily observed that the reproduced correlation (Eq. (21)) is not comparable with Imai and Tonouchi [18] correlations applicable for alluvial and diluvial sand or all the soil types for any *N* value. But the reproduced correlation by Kramer [23] is well comparable with alluvial clay (Eq. (10)) for all the *N* values. Kramer [23] has suggested the correlation (Eq. (21)) for sand, but which closely matches with alluvial clay.

SHAKE2000 is a widely used ground response software, which is used by many researchers for site specific response studies and microzonation mapping. Correlations given in Eqs. (15), (18), (19) and (21) (Eqs. (3), (5), (6) and (13) in SHAKE2000) are inbuilt in SHAKE2000 to calculate the shear modulus using SPT *N* values. Eqs. (18) and (19) require the effective vertical and mean stress and hence these are not considered for comparison in this paper with other correlations. Eqs. (15) and (21) are compared by considering $N_{60}$, and *N* values measured in the US are the same [35]. Fig. 6 shows the comparison of Seed et al. [34] correlation (Eq. (15)) and reproduced Kramer [23] correlation (Eq. (21)). Two correlations are comparable up to the SPT *N* values of 25, beyond which both correlations are not compatible.

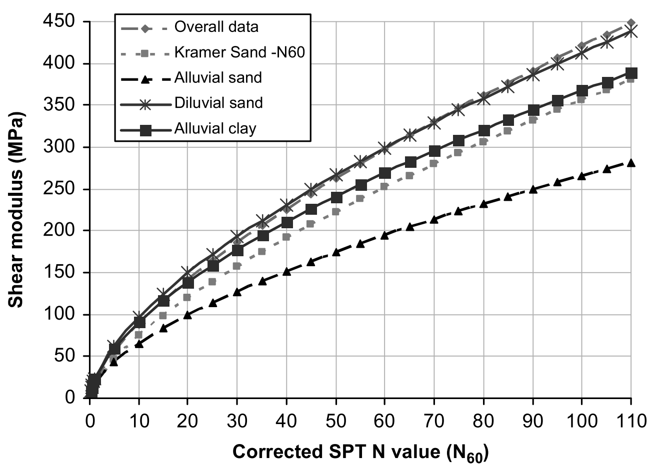


**Fig. 5.** Comparison of original correlations developed by Imai and Tonouchi [18] for corrected *N* values for 60% hammer energy and reproduced correlation given in Kramer [23].

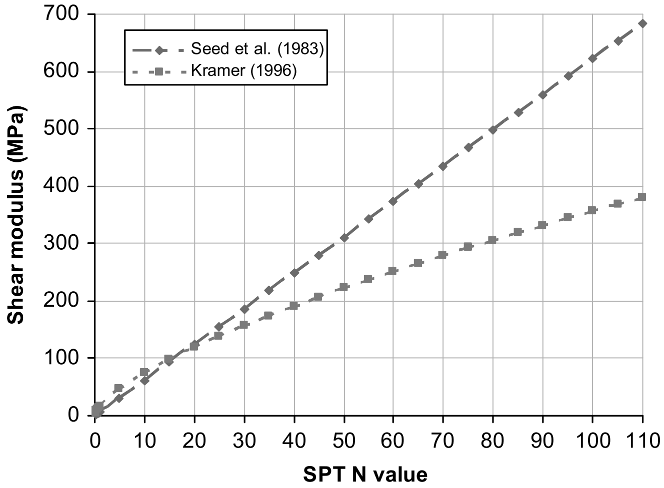


**Fig. 6.** Comparison of correlation developed by Seed et al. [34] and reproduced by Kramer [23], these are also used in SHAKE2000.

## 6. Comparison of existing correlations

Review of shear modulus correlations clearly shows that limited study has been carried out in this area. Most of the studies were carried out during the 1970s and 1980s using the well shooting technique except that by Anbazhagan and Sitharam [5]. A few correlations were developed by assuming the density. Rest of them has assumed *N* values less than 1 and has extrapolated *N* value more than 100 or 50 to estimate the shear modulus. One similarity is that the above correlations were developed between measured SPT *N* values and shear modulus, except that Kramer [23] and Seed et al. [36] reproduced correlations between the corrected *N* values to measured shear modulus. It is also observed that these correlations are based on the experimental studies carried out in Japan, the United States and India. In Japan and India the hammer energy is almost same because of similarities in hammer type and releasing mechanism. In the US the hammer energy is 0.77 times that of the Japanese and Indian hammer energy.

Seed et al. [34] have not given any information about *N* values (corrected or measured) and hammer energy. In order to compare Seed et al. [34] correlation (Eq. (15)) with other correlations, Eq. (15) is considered two cases, (a) assuming *N* value is similar to other correlations and (b) *N* values are 0.77 times less than the other correlations and similar to US measured values (called as Eq. (15) modified). Fig. 7 shows the comparison of final correlations proposed by different researchers (Eqs. (1)–(4), (8), (9), (14)–(16) and (15) modified).

Fig. 7 shows that the shear modulus is almost same for all the correlations for *N* value up to 20, beyond which shear modulus is inconsistent. The correlation proposed by Ohba and Toriumi [27] [Eq. (2)] gives the least shear modulus for all the values of *N* when compared to other correlations. Similarly the correlation proposed by Seed et al. [34] [Eq. (15) and (15) modified] gives the highest shear modulus for the entire values of *N* when compared to other correlations. The shear modulus obtained from correlations proposed by Imai and Yoshimura [17] [Eq. (1)], Ohta et al. [16] [Eq. (3)], Hara et al. [29] [Eq. (9)], Imai and Tonouchi [18] [Eq. (14)] and Sitharam and Anbazhagan [38] [Eq. (16)] is comparable. The shear modulus obtained from Ohsaki and Iwasaki [28] [Eqs. (4) and (8)] is comparable with the above correlations up to SPT *N* value 60 and for *N* value above 60, it gives slightly higher shear modulus. Among the Ohsaki and Iwasaki [28] correlations, the original correlation [Eq. (4)] is closer to

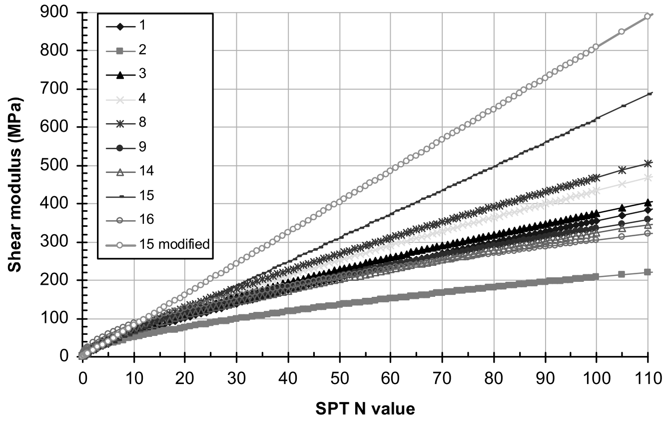


Fig. 7. Comparison of final correlations developed by different researchers.

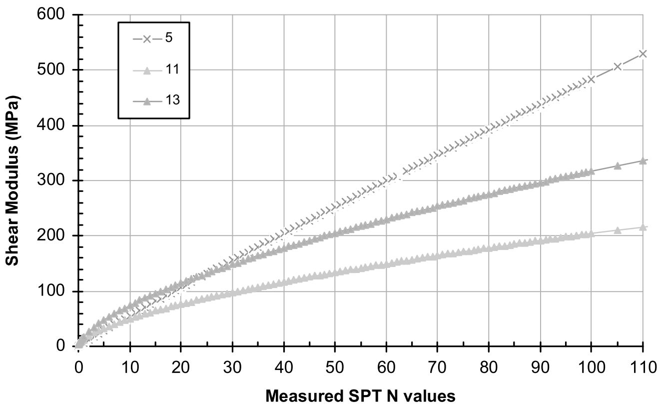


Fig. 9. Comparison of correlations developed using the sandy soil.

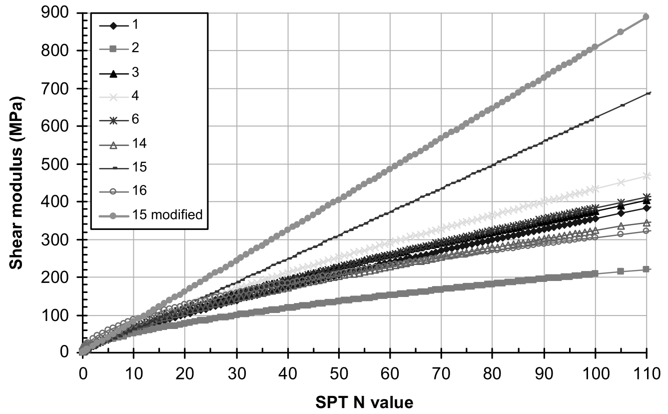


Fig. 8. Comparison of correlations developed using all the soil types.

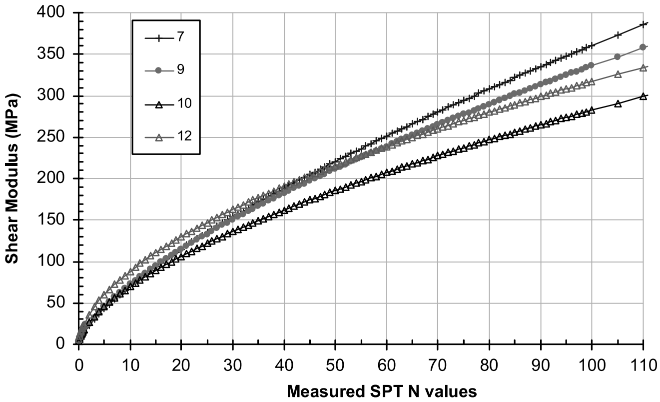


Fig. 10. Comparison of correlations developed using the cohesive soil.

other five correlations and rounded correlation [Eq. (8)] gives slightly higher shear modulus when compared to Eq. (4). Correlations developed by Imai and Yoshimura [17] [Eq. (1)] and Ohba and Toriumi [27] [Eq. (2)] have a similar density assumption to estimate the shear modulus, but Eq. (1) matches closely with other four correlations. Out of five comparable correlations, correlation developed by Hara et al. [16] [Eq. (9)] has considered data from cohesive soil, but it matches well with the other four correlations developed for all soil types.

In order to discuss the correlations developed for specific soil type, the above correlations are broadly divided as three groups applicable to (a) all the soil types, (b) sandy soil and (c) cohesive soil. Final correlation and correlation developed for intermediate soil are included in the first group. Fig. 8 shows the comparison of correlations coming under the first group. Here similar to Fig. 7, Eqs. (2) and (15) give lesser and higher shear modulus when compared to other correlations. The correlation given for intermediate soil (Eq. (6)) by Ohsaki and Iwasaki [28] matches closely with other correlations (Eqs. (1), (3), (14) and (16)). The correlation proposed by Ohsaki and Iwasaki [28] considering all the soil types (Eq. (4)) shows the higher shear modulus for the SPT *N* value of above 60. Correlations developed by Imai and Yoshimura [17] [Eq. (1)], Ohta et al. [29] [Eq. (3)], Ohsaki and Iwasaki [28] [Eq. (6)], Imai and Tonouchi [18] [Eq. (14)] and Sitharam and Anbazhagan [38] [Eq. (16)] show comparable shear modulus for all the soil types irrespective of the *N* values. However, slight difference can be observed for the *N* value of above 80, which might be due to data variations.

Fig. 9 shows correlations for sandy soil. Ohsaki and Iwasaki [28] [Eq. (5)] and Imai and Tonouchi [18] [Eq. (11) for Alluvial and Eq. (13) for Diluvial] have developed correlation considering sandy soil data. These three correlations show similar shear modulus up to the *N* value of 20, beyond which Eqs. (5) and (13) are comparable up to the *N* value of 50. For *N* values above 50, correlation developed by Imai and Tonouchi [18] [Eqs. (11) and (13)] shows the lower shear modulus when compared to Eq. (5), which may be attributed by the data. Imai and Tonouchi [18] have considered more data points of *N* value 50 and below, and Ohsaki and Iwasaki [28] have considered more data points of *N* value 50 and above. *N* values above 50 were extrapolated by Imai and Tonouchi [18], but the same might be measured by Ohsaki and Iwasaki [28].

Group three correlations are developed using the cohesive soil and are shown in Fig. 10. Ohsaki and Iwasaki [28] [Eq. (7)], Hara et al. [29] [Eq. (9)] and Imai and Tonouchi [18] [Eq. (10) for Alluvial and Eq. (12) for Diluvial] developed the correlation applicable to cohesive soil. These four correlations give similar shear modulus up to the *N* value of 40, beyond which the correlation developed by Imai and Tonouchi [18] [Eq. (10)] gives the lower shear modulus when compared to the other three correlations. This may be attributed by data set used by Imai and Tonouchi [18], which contains a maximum *N* value of 40. Other three correlations are comparable for all the *N* values. This comparison shows that correlations developed by different researchers are unique and have limited applications for other region-based SPT procedures and soil types. A new correlation considering the measured data and which is applicable to all types of soils and regions will be appropriate for practical application. Many researchers are using single or textbook cited correlations worldwide for site response and microzonation studies without realizing its suitability for their region.

## 7. New correlations based on two data set combinations

This study shows that about 10 independent publications were given SPT *N* versus shear modulus correlations. The correlation given by Seed et al. [36] and Kramer [23] was reproduced the correlations from other researcher's data with required assumptions. Among the remaining eight correlations, five correlations are comparable to each other's, one correlation is partially comparable and two correlations are not comparable. Among these five comparable correlations, the correlation by Imai and Yoshimura [17] [Eq. (1)] has developed by assuming the density to calculate the shear modulus. Among the remaining four correlations, three were developed in Japan and one was developed in India. Even though these correlations are comparable, they may not be directly applicable to other regions because of different SPT practice and extrapolated data. Hence, new correlations have been attempted in this section by combining the authors data with the available old data. Most of the earlier correlations were developed including the SPT *N* value of less than 1 and more than 100. Researchers have assumed the SPT *N* values of less than 1 and extrapolated the SPT *N* values of more than 100. Data set used by Anbazhagan and Sitharam [5] has a measured *N* value of up to 109 and assumed the *N* value of 100 for rebound corresponding to rock. In few locations the *N* value of more than 100 was also recorded.

In this study eight combinations have been attempted to develop new SPT N versus $G_{max}$ correlations. Shear modulus reported by other researchers is converted to SI units of MPa and used for regression analysis. Two correlations have been developed for each combination, the first one is considering all the data sets and the second one is eliminating the assumed data sets, i.e. considering the SPT *N* value of 1–100 with 10% error. The *N* values from 0.9 (10% less than 1) to 110 (10% more than 100) are considered in the second

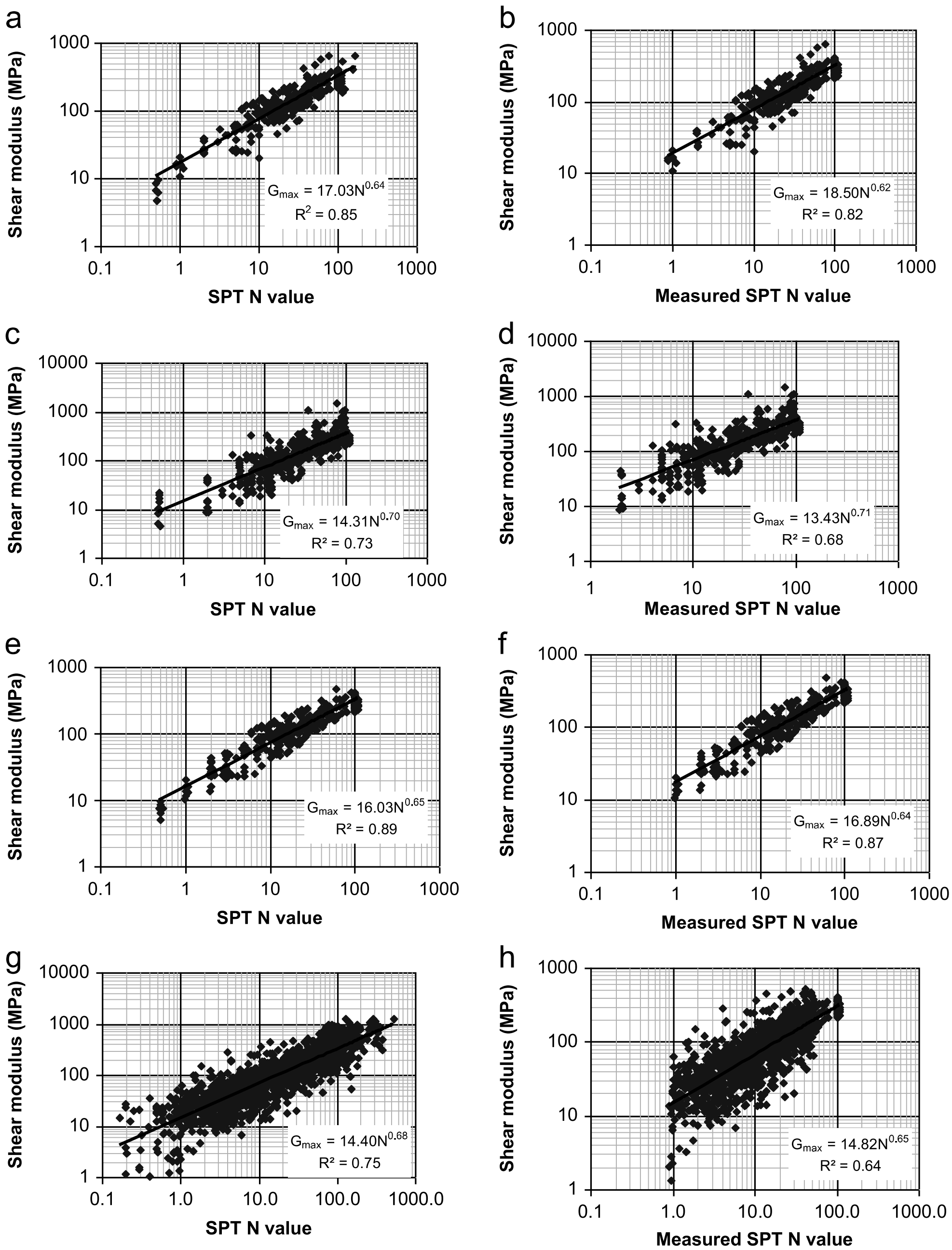


**Fig. 11.** New correlations by combining Anbazhagan and Sitharam [5] and others data. (a), (c), (e) and (g) are considering all the data and (b), (d), (f) and (h) are considering the SPT *N* value of 1–100 with 10% error.

combination to account the digitalization error. Fig. 11a–h, shows the combination of author data with other researchers data and resulted best fit correlation. Fig. 11a, c, e and g for all the data sets with correlation and Fig. 11b, d, f and h for measured data set with correlation. Details of each combination and resulting correlations are given in Table 3.

**Table 3**
New correlations based on two, three or more data set combinations.

| Case | Correlations | | | Remarks |
|---|---|---|---|---|
| | Authors data are combined with | Eqs. in (MPa) | Eq. no. | |
| I | Ohta et al. [29] | $G_{max}=17.03N^{0.64}$ | (22) | 100% data give $R^2$ value 0.85 |
| | Ohta et al. [29] | $G_{max}=18.5N^{0.62}$ | (23) | 96.77% data give $R^2$ value 0.82 |
| II | Ohsaki and Iwasaki [28] | $G_{max}=14.31N^{0.70}$ | (24) | 100% data give $R^2$ value 0.70 |
| | Ohsaki and Iwasaki [28] | $G_{max}=13.43N^{0.71}$ | (25) | 97.85% data give $R^2$ value 0.68 |
| III | Hara et al. [16] | $G_{max}=16.03N^{0.65}$ | (26) | 100% data give $R^2$ value 0.89 |
| | Hara et al. [16] | $G_{max}=16.89N^{0.64}$ | (27) | 98.14% data give $R^2$ value 0.87 |
| IV | Imai and Tonouchi [18] | $G_{max}=14.40N^{0.68}$ | (28) | 100% data give $R^2$ value 0.75 |
| | Imai and Tonouchi [18] | $G_{max}=14.82N^{0.65}$ | (29) | 77.44% data give $R^2$ value 0.64 |
| V | Ohta et al. [29] and Hara et al. [16] | $G_{max}=15.43N^{0.67}$ | (30) | 100% data give $R^2$ value 0.88 |
| | Ohta et al. [29] and Hara et al. [16] | $G_{max}=16.40N^{0.65}$ | (31) | 96.17% data give $R^2$ value 0.85 |
| VI | Ohta et al. [29], Hara et al. [16] and Ohsaki and Iwasaki [28] | $G_{max}=14.12N^{0.7}$ | (32) | 100% data give $R^2$ value 0.80 |
| | Ohta et al. [29], Hara et al. [16] and Ohsaki and Iwasaki [28] | $G_{max}=14.10N^{0.70}$ | (33) | 95.98% data give $R^2$ value 0.76 |
| VII | Ohta et al. [29], Hara et al. [16] and Imai and Tonouchi [18] | $G_{max}=14.38N^{0.68}$ | (34) | 100% data give $R^2$ value 0.76 |
| | Ohta et al. [29], Hara et al. [16] and Imai and Tonouchi [18] | $G_{max}=14.83N^{0.66}$ | (35) | 79.16% data give $R^2$ value 0.66 |
| VIII | Ohta et al. [29], Hara et al. [16], Ohsaki and Iwasaki [28] and Imai and Tonouchi [18] | $G_{max}=14.15N^{0.69}$ | (36) | 100% data give $R^2$ value 0.76 |
| | Ohta et al. [29], Hara et al. [16], Ohsaki and Iwasaki [28] and Imai and Tonouchi [18] | $G_{max}=14.12N^{0.68}$ | (37) | 80.88% data give $R^2$ value 0.67 |

*G*—low strain measured shear modulus and *N*—measured SPT "*N*" value.

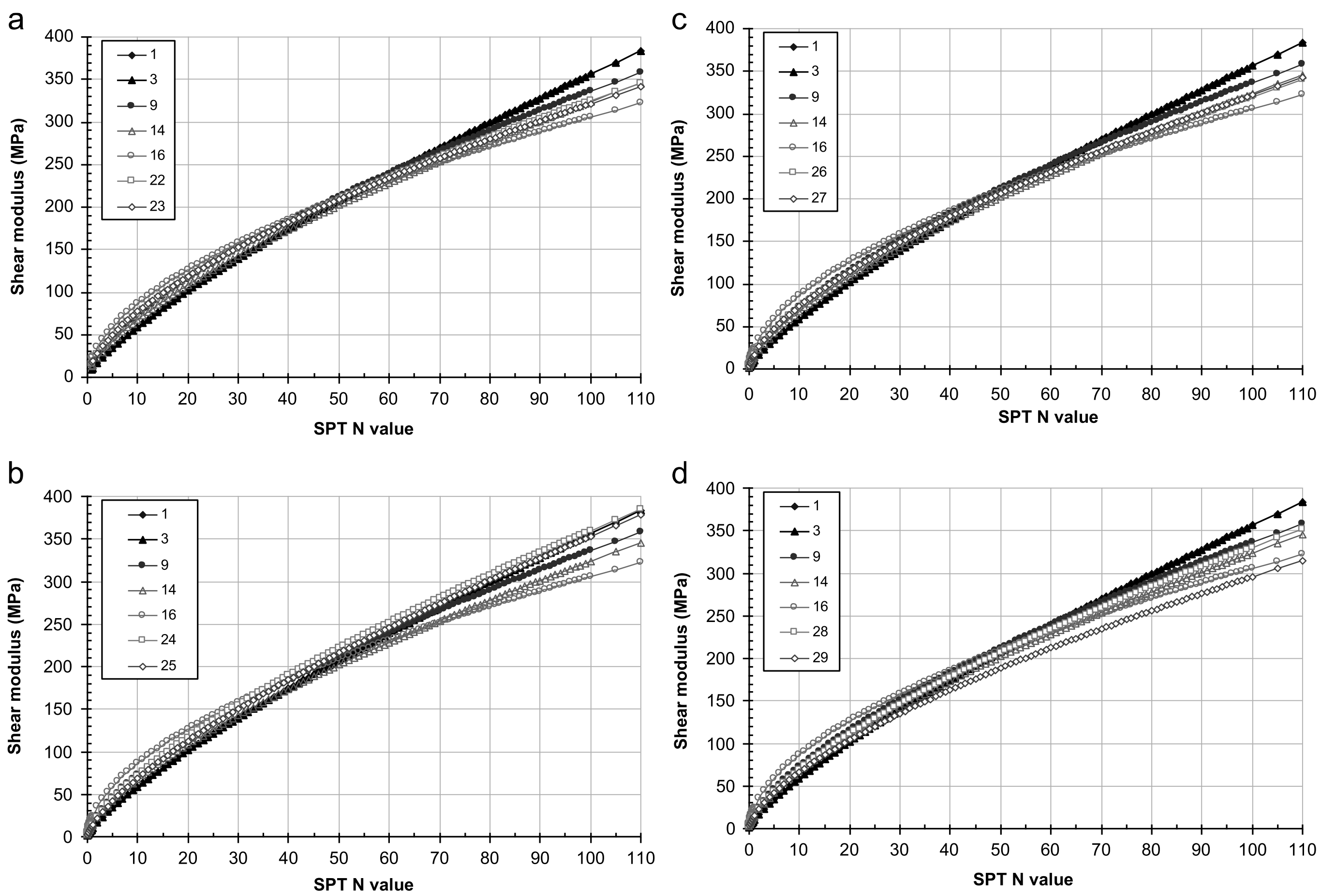


**Fig. 12.** Comparison of newly developed correlation by combining authors data and others data with five comparable old correlations: (a) case I, (b) case II, (c) case III and (d) case IV.

The authors data have been combined with the Ohta et al. [29] data and two correlations have been generated. Fig. 11a and b shows a typical plot for the correlations using the data from [5,29]. The first combination of 100% data set gives Eq. (22) and the second combination of 96.77% total data set gives Eq. (23) (see Table 3). Developed correlations (Eqs. (22) and (23)) are compared with the original five comparable correlations (Eqs. (1), (3), (9), (14) and (16)) in Fig. 12a. These two correlations matches well with the five correlations when compared to the original correlations developed by Ohta et al. [29] and [5]. Eq. (22), i.e. first combinations resulting lesser shear modulus for *N* values less than 50 and higher shear modulus for *N* values more than 50 when compared to Eq. (23), i.e. second combinations. The authors data are combined with Ohsaki and Iwasaki [28] and two correlations have been generated and presented as Eqs. (24) and (25) in Table 3. Fig. 12b shows the comparison of new correlations (Eqs. (24) and (25)) with five original correlations. Both the correlations give similar shear modulus for all the *N* values. These new correlations give comparable shear modulus up to the *N* value of 50 and higher modulus shear modulus for the *N* value of above 50. Data used by Hara et al. [16] is combined with the authors data and new correlations have been generated and presented as Eqs. (26) and (27) in Table 3. These two new correlations (Eqs. (26) and (27)) give similar shear modulus for all the values of *N* and match well with the correlation developed by Imai and Tonouchi [18]. Fig. 12c shows the comparison of two new correlations with the old five correlations. The authors data are combined with the Imai and Tonouchi [18] data and two new correlations have been generated. Imai and Tonouchi [18] have used the extrapolated *N* values of less than 1 and more than 50, for the second combinations these data are removed (Fig. 11h). The comparison of these two new correlations (Eqs. (28) and (29)) with five correlations is shown in Fig. 12d. The first combination gives slightly lesser shear modulus when compared to the second one up to the *N* value of about 20, beyond which the first correlation gives the higher shear modulus. The first correlation (Eq. (28)) is comparable with five correlations, but the second correlation (Eq. (29)) by eliminating extrapolated data (*N* values less than 1 and more than 50) from Imai and Tonouchi [18] is not comparable. The second correlation (Eq. (29)) shows the least shear modulus for the *N* value of more than 50.

Newly developed eight correlations for four cases are compared in Fig. 13. Five correlations (Eqs. (22), (23), (26)–(28)) match closely for all the values of *N*. Two correlations (Eqs. (24) and (25)) obtained by the combination of the Anbazhagan and Sitharam [5] and Ohsaki and Iwasaki [28] data give higher shear

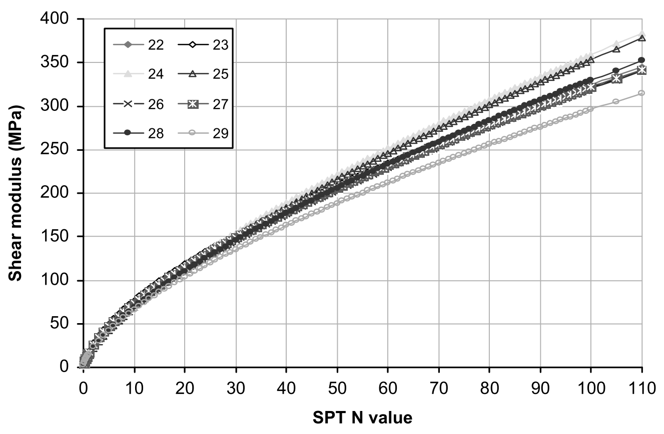


**Fig. 13.** Comparison of newly developed correlation by considering two data combinations.

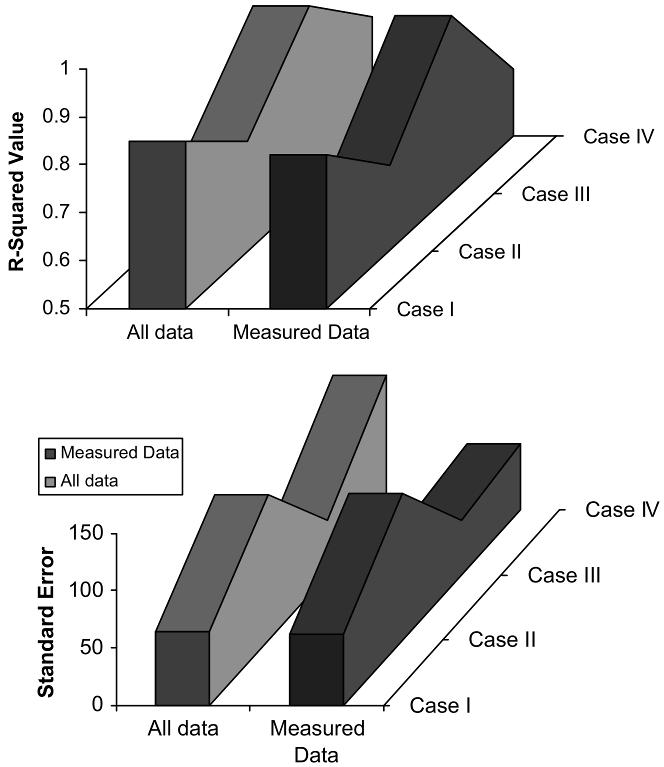


**Fig. 14.** Comparisons of *R*-squared value and standard error of correlations developed considering the four cases.

modulus when compared to the other five correlations for the SPT *N* value above 60. The correlation (Eq. (29)) obtained considering measured data of Anbazhagan and Sitharam [5] and Imai and Tonouchi [18] gives lesser shear modulus when compared to the other correlations for the SPT *N* value of above 50. Standard error of each case has been estimated and the correlations fitness is compared. The standard error is a measure of the amount of error in the prediction of $G_{max}(y)$ for an individual $N(x)$.

Fig. 14 shows the *R*-squared values and standard error of the first four cases. The measured data standard errors are slightly lower than all the data standard errors. Differences in standard error for cases I–III are negligible. The measured data are 50% less when compared to all the data for case IV. *R*-squared values of all the data combinations are slightly higher than the measured data combinations. *R*-squared value for case III shows the highest and case IV is the least among the four cases. Difference in *R*-squared value is negligible for cases I and III and is considerable for cases II and IV. Data combination of cases I and III show relatively less standard error and higher *R*-squared values. Data combinations cases II and IV shows relatively higher standard error and lesser *R*-squared values. Further cases I and III data sets are combined together and are used to generate new correlations.

## 8. New correlations based on three and more data set combinations

The first four cases with two combinations have resulted in eight correlations, among which cases I and III, i.e. author data combined with Ohta et al. [29] and Hara et al. [16] give correlations with less standard error and higher *R*-squared values. In order to improve the correlations these three data sets, Anbazhagan and Sitharam [5], Ohta et al. [29] and Hara et al. [16], are combined together to develop the correlations which is callused as case V. Case V data set is combined with Ohsaki and Iwasaki

[28] [case VI] and Imai and Tonouchi [18] [case VII] and used to generate two correlations. Further, Anbazhagan and Sitharam [5], Ohta et al. [29], Hara et al. [16], Ohsaki and Iwasaki [28] and Imai and Tonouchi [18] data sets are combined (case VIII) to generate the correlations. In each case two correlations have been developed by considering all the data sets and measured data set (SPT *N* value of 1–100 with 10% error) separately. The summary of these combinations is given in the first three columns in Table 3. Fig. 15a, c, e and g and Fig. 15b, d, f and h show data set with a correlation for all data and measured data. Newly developed correlations by combining three and more research works are compared with the original five comparable correlations (Eqs. (1), (3), (9), (14) and (16)) in Fig. 16a–d. Newly developed correlations by combining three and more research works are compared with new five comparable correlations (Eqs. (22), (23), (26)–(28)) developed in the previous sections in Fig. 17a–d. Fig. 15a and b shows combined data from Anbazhagan and Sitharam [5], Ohta et al. [29] and Hara et al. [16] and newly arrived Eqs. (30) and (31) (see Table 3). These two correlations (Eqs. (30) and (31)) match well with original five correlations (Fig. 16a). Fig. 17a shows that correlation considering all the data (Eq. (30)) matches with new five comparable correlations up to the *N* value of 60, beyond which it gives slightly higher shear modulus. The correlation considering the measured data (Eq. (31)) matches well with five old and five new comparable correlations for all the values of *N*. Case VI gives two new correlations (Eqs. (32) and (33) in Table 3) and which are shown in Fig. 15c and d. These two correlations are compared with the old, and new five comparable correlations are shown in Figs. 16b and 17b. These correlations are comparable with the original old five correlations (Fig. 16b). Fig. 17b shows that these two correlations are comparable with five new correlations up to the *N* value of 50, beyond which both the correlations give higher shear modulus. Anbazhagan and Sitharam [5], Ohta et al. [29] and Hara et al. [16] data are combined with Imai and Tonouchi [18] data and generated Eqs. (34) and (35) (Fig. 15e and f). These two correlations are comparable up to the SPT *N*

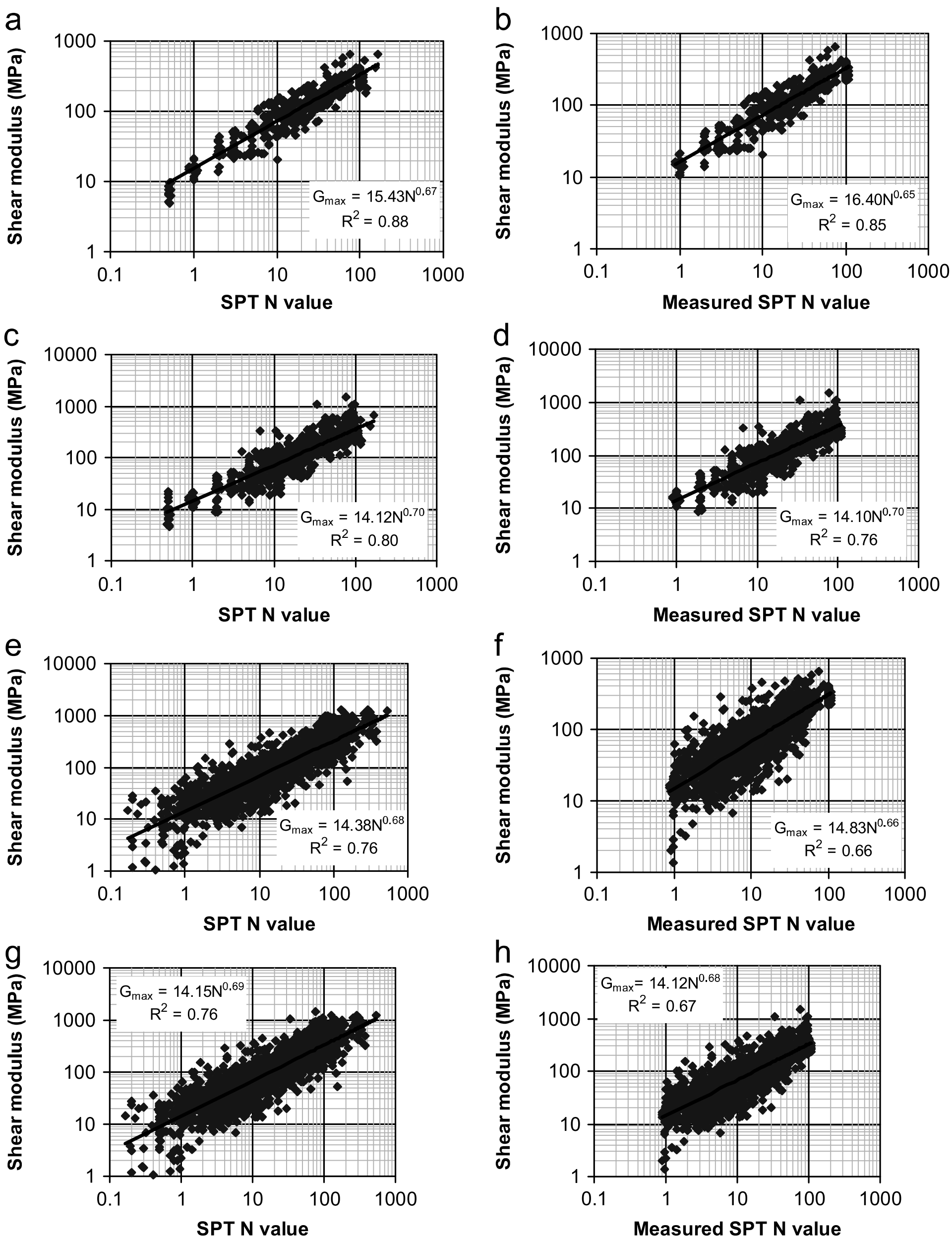


**Fig. 15.** New correlations by combining three and more researchers data: (a), (c), (e) and (g) are considering all the data and (b), (d), (f) and (h) are considering the SPT *N* value of 1–100 with 10% error.

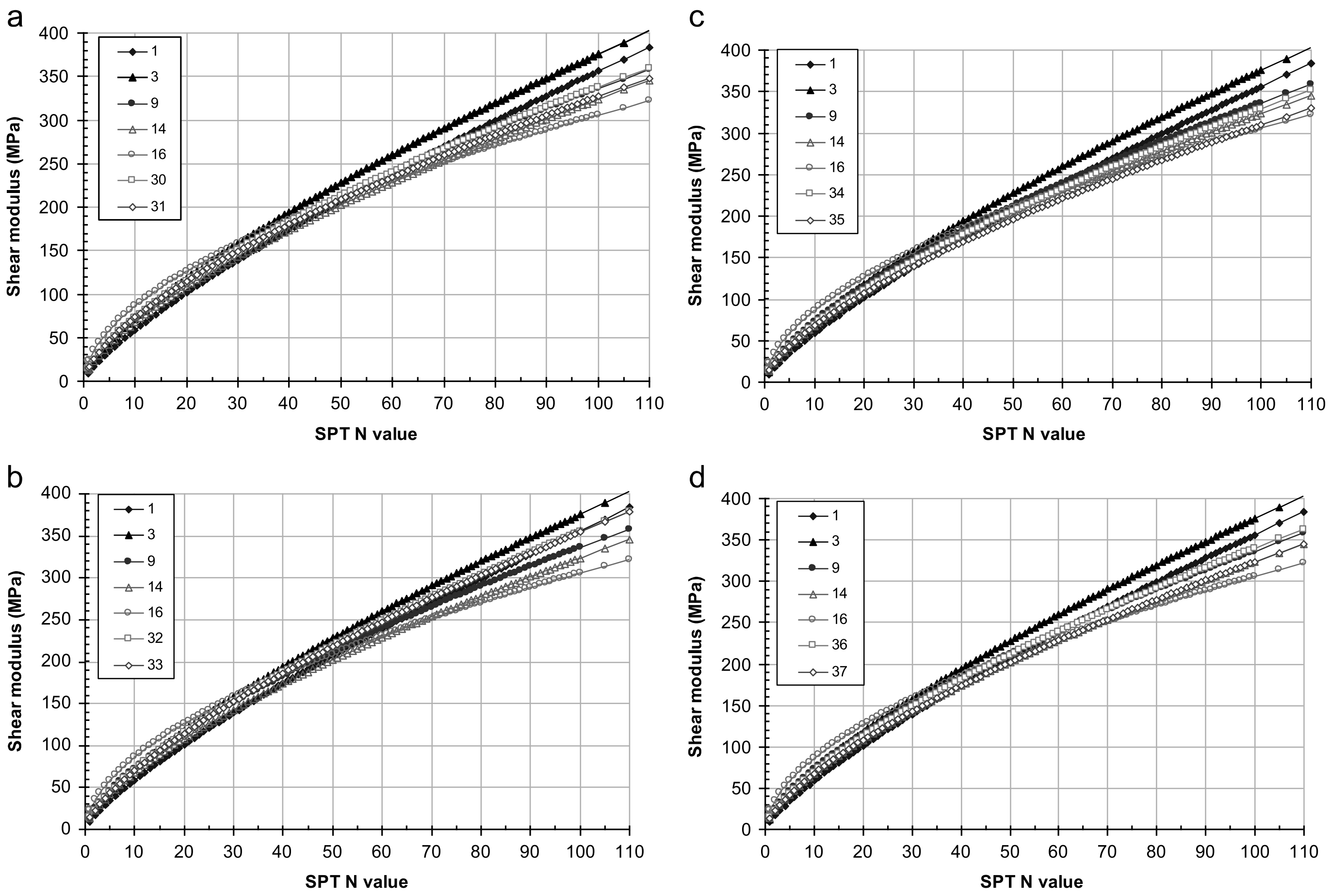


**Fig. 16.** Comparison of newly developed correlations with five original comparable correlations: old correlations and new correlations from (a) Anbazhagan and Sitharam [5], Ohta et al. [29] and Hara et al. [16]; (b) Anbazhagan and Sitharam [5], Ohta et al. [29], Hara et al. [16] and Ohsaki and Iwasaki [28]; (c) Anbazhagan and Sitharam [5], Ohta et al. [29], Hara et al. [16] and Imai and Tonouchi [18]; and (d) Anbazhagan and Sitharam [5], Ohta et al. [29], Hara et al. [16], Ohsaki and Iwasaki [28] and Imai and Tonouchi [18].

value of 50, beyond which the measured data correlation gives the lesser shear modulus. Fig. 16c shows the comparison of these two correlations with the original five comparable correlations. These two correlations reasonably match with five original correlations (Fig. 16c). Fig. 17c shows the comparison of these two correlations with the new five comparable correlations. Correlation using all the data (Eq. (34)) is well comparable with these new five correlations. Correlations considering the measured data (Eq. (35)) are comparable up to the *N* value of 50, beyond which it gives the lower shear modulus. Case VII data sets are combined with the Ohsaki and Iwasaki [28] data, and two new correlations have been generated. This is called as case VIII and data set with correlation is shown in Fig. 15g and h. Both the correlations (Eqs. (36) and (37)) are comparable with the five original correlations (Fig. 16d). A comparison with the new five correlations (Fig. 17d) shows that the correlation using all the data (Eq. (36)) gives higher shear modulus for the value *N* above 70 and measured data correlation match with others correlations.

Fig. 18 shows the correlations developed in this section considering data from three data sets and more research works. From Fig. 18, it can be observed that combining more data reduces the differences in estimating the shear modulus and improves the correlations coefficient, i.e. two data combined correlation shows larger difference in the shear modulus for the same values of *N* when compared to three or more data combinations. Fig. 19 shows the *R*-squared values and standard error of four cases discussed above. The highest *R* squared value of 0.88 and lower standard error were obtained for case V all data and measured data combinations. The *R* squared value and standard error of measured data correlation are very close to all the data correlations. In general measured data correlations are having less standard error when compared to all the data correlations.

## 9. Result and discussion

Eight independent correlations are developed between shear modulus and measured SPT *N* values by various researchers. Five of them are comparable and rest of them are not. Each equation has its own limitations with respect to the data distribution and density assumptions. In order to find a good correlation applicable for all the regions, different combinations are attempted. This study shows that correlations resulting by adding the Ohsaki and Iwasaki [28] data to any other data give higher predication of shear modulus, particularly for the SPT *N* value of above 50. Similarly resulting correlation by adding the Imai and Tonouchi's [18] measured data to any other data gives lower predication of shear modulus for any *N* value. Correlations obtained by combination of any other data with Imai and Tonouchi [18] are very close to Imai and Tonouchi [18] original correlation. This is attributed by a large number of data points in Imai and Tonouchi [18] when compared to others.

A comparison of *R* squared value and standard error of all the data and measured data combinations shows that the correlation developed by using Anbazhagan and Sitharam [5], Ohta et al. [29] and Hara et al. [16] data having higher *R* squared value and less

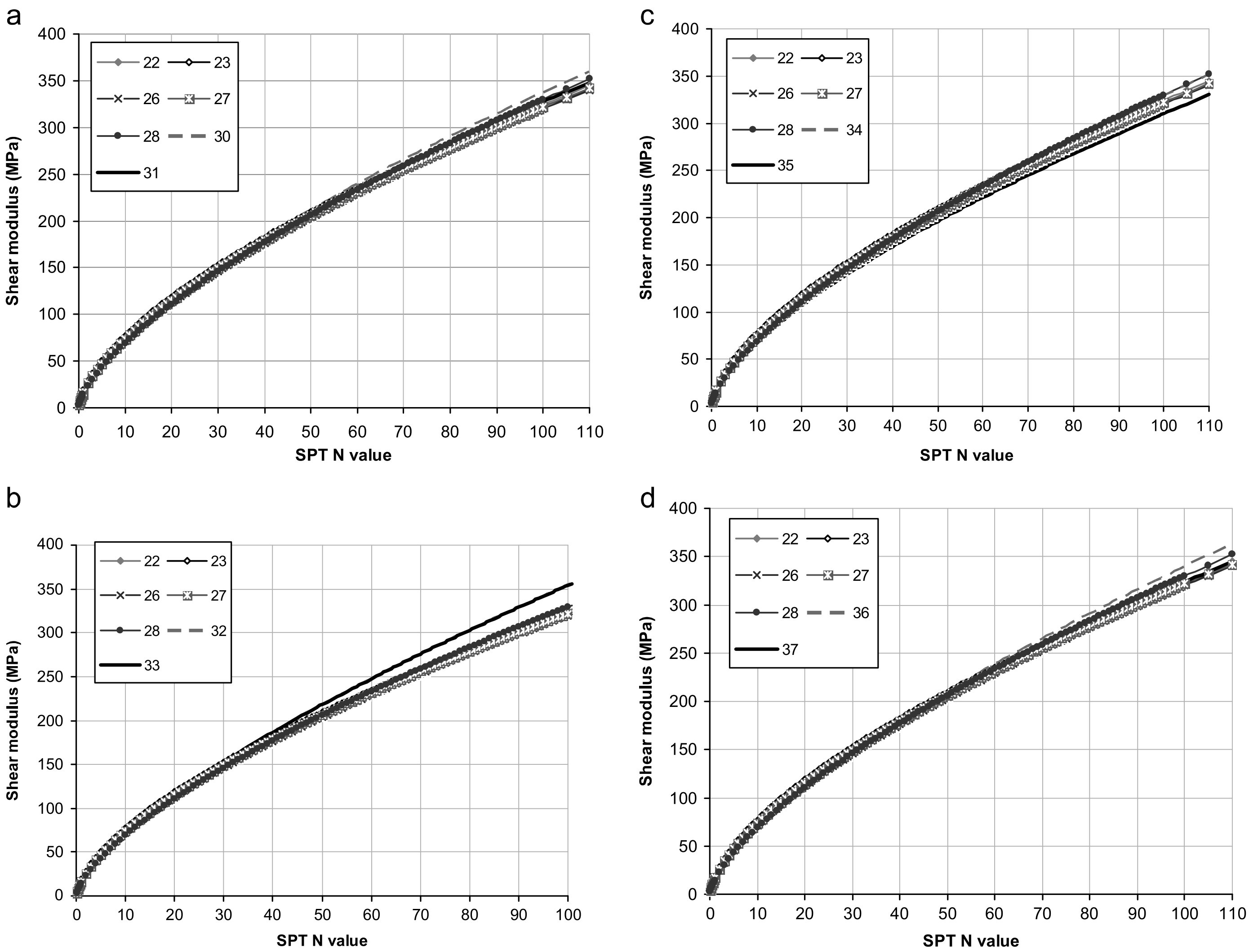


**Fig. 17.** Comparison of newly developed correlations with five comparable correlation developed by combining authors data with others data (a) Anbazhagan and Sitharam [5], Ohta et al. [29] and Hara et al. [16]; (b) Anbazhagan and Sitharam [5], Ohta et al. [29], Hara et al. [16] and Ohsaki and Iwasaki [28]; (c) Anbazhagan and Sitharam [5], Ohta et al. [29], Hara et al. [16] and Imai and Tonouchi [18]; and (d) Ohta et al. [29], Hara et al. [16], Ohsaki and Iwasaki [28] and Imai and Tonouchi [18].

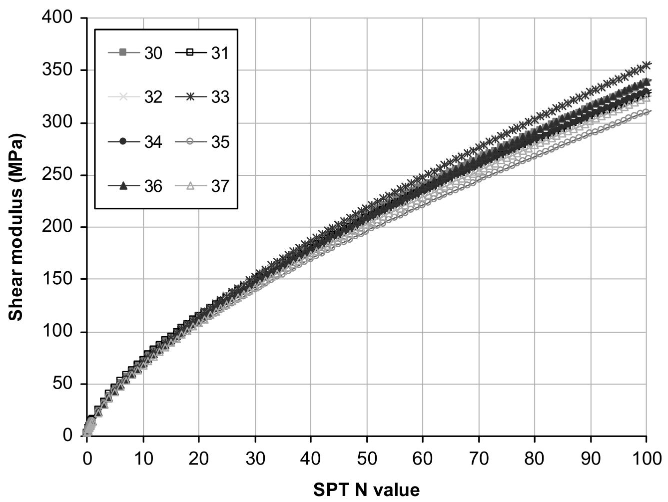


**Fig. 18.** Comparison of correlations developed considering the three and more data sets.

standard error. All the data correlations have slightly higher *R* squared value and lower standard error when compared to the measured data correlation. Both correlations are comparable, and measured data correlation matches very well with the original old and new comparable correlations. This correlation (Eq. (31)) has been considered as a reference to compare other correlations in terms of percentage of $G_{max}$ error (PGE). Typical PGE is calculated according to the relation given below:

$$\text{PGE for correlation 1} = \frac{G_{max}\text{ from correlation 1}-G_{max}\text{ from correlation 31}}{G_{max}\text{ from correlation 31}} \times 100\,(\%) \tag{38}$$

Percentage error in between correlations 30 and 31 is very less, about 5% up to the *N* value of 5 and less than 3% for the *N* value of above 5 (see Fig. 20a). Percentage error in between correlation 15 [34] and 31 is very high (more than 300 and above). Hence this is removed from the comparison plot. Fig. 20a shows the PGE for the original old correlations with new correlation (Eq. (31)). PGE is reduced up to a certain value of *N* and

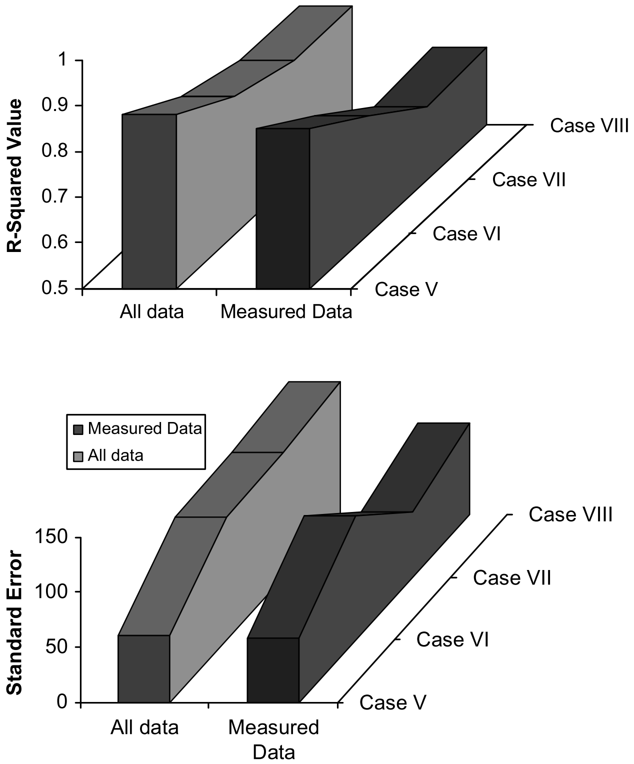


**Fig. 19.** Comparisons of standard error and $R$ squared value of correlations developed by considering the three and more data sets.

increased or constant for all the correlations except the correlations by Ohba and Toriumi [27] [Eq. (2)] and Kramer [23] [Eq. (21)], where PGE increases with increasing $N$ value. PGE is less than 20% for the correlations developed by Ohta et al. [16] [Eq. (3)], Hara et al. [29] [Eq. (9)] and Imai and Tonouchi [18] [Eq. (14)]. PGE is more than 20% up to the $N$ value of 8 and gradually decreases, approaching zero and less than 10% for rest of the $N$ values in the correlation developed by Imai and Yoshimura [17] [Eq. (1)] and Anbazhagan and Sitharam [5] [Eq. (16)]. PGE is less than 15% for the $N$ value of 3–30, and more than 15% for rest of the $N$ values for the correlation given by Ohsaki and Iwasaki [28] [Eq. (4)]. PGE is more than 15% for all the $N$ values for correlations presented by Ohba and Toriumi [27] [Eq. (2)] and Kramer [23] [Eq. (21)].

Fig. 20b shows the PGE for correlations developed considering two data combinations (cases I–IV). PGE for the correlation considering the measured data (Eqs. (23), (25), (27), and (29)) are less when compared to correlations (Eqs. (22), (24), (26), and (28)) considering all the data. PGE is less than 5% for correlations developed combining the authors data with Ohta et al. [29] and Hara et al. [16] [Eqs. (22), (26) and (27)]. A correlation considering the measured data of the author and Ohta et al. [29] [Eq. (23)] shows a PGE of more than 5% up to the $N$ value of 10 and PGE approaches less than 5 for rest of the $N$ values. A similar trend is also observed up to the value of $N$ of 15 for correlations developed using all the data of the author and Imai and Tonouchi [18] [Eq. (28)]. The same combinations have constant PGE for all the $N$ values using the measured data. The correlations developed considering the author data and Ohsaki and Iwasaki [28] show large variations in PGE. In general PGE is reduced considerably for new correlations developed considering the two data combinations.

Fig. 20c shows the PGE for correlations developed considering the three and more data combinations (cases V–VIII). Fig. 20c shows the similar trend and pattern like Fig. 20b, but PGE values decrease considerably when compared to new correlations by two data combinations. PGE values for the correlations considering all the data are relatively more up to the SPT $N$ value of 10 and beyond which PGE is reduced to about 3% except for correlations 32, 33 and 35. These three correlations have PGE more than 3% for all the values of $N$ due to adding Ohsaki and Iwasaki [28] data and removing extrapolated data from Imai and Tonouchi [18].

## 10. Correlations for all regions

Proposed correlations with high $R^2$ and less standard error match well with the originally proposed correlations and are lower in percentage of $G_{max}$ error for all the $N$ values. This correlation cannot be directly applicable to other regions because the SPT $N$ values used for correlations are measured in Japan and India with a hammer energy of 78%. Hammer energy and other parameters control the SPT $N$, which is region specific and vary from region to region. The SPT $N$ values depend on drilling methods, drill rods, borehole sizes and stabilization, sampler, blow count rate, hammer configuration, energy corrections, fine content and test procedure [33,22,15,39,5]. These correlations can be used for other regions if proper correction factors are applied to the SPT $N$ values.

The first and foremost correction factor is the hammer energy correction factor, which depends on the energy applied to count $N$ values. The SPT $N$ values used for correlations were measured by applying average 78% of theoretical energy. If the SPT $N$ values measured other than 78% theoretical energy, the corrections factor has to be applied, so that these shear modulus correlation can be used in any region.

Hammer energy correction factor $C_{ES}$ can be calculated using the below equation:

$$C_{ES} = \frac{ER_U}{ER_M} = \frac{78}{ER_M} \tag{39}$$

where $ER_U$ is the hammer energy used for $G_{max}$ correlations, i.e. 78% and $ER_M$ the average measured hammer energy applied in the region (percentage with respect to theoretical energy). This factor can be multiplied with measured $N$ value in the region and used in the correlation (Eq. (31)). Energy level in different regions and respective correction factor is given in Table 4. Table 4 also shows energy corrected correlation constant '$a$' corresponding to Eq. (31), here constant '$b$' remains same as 0.65. By considering the average reported energy in different regions, correlation constant can be modified. This constant can be directly used with the measured value of $N$ in the respective region. Based on hammer energy, one can choose the constant '$a$', for example if the correlation is used in the United States (60% hammer energy), the value of '$a$' can be taken as 21.23 with measured $N$ values. Similarly for other regions based on the energy measurements, value of "$a$" can be obtained from Table 4. Fig. 21a shows the hammer energy corrected $N$ value for the hammer energy of 70%, 65%, 60%, 55%, 50% and 45% with respect to measured $N$ values (hammer energy of 78%) used for $G_{max}$ correlations. Fig. 21b shows the $G_{max}$ variation for the hammer energy of 70%, 65%, 60%, 55%, 50% and 45%.

In addition to hammer energy variations other factors also affect $N$ count, which are listed in the beginning of this section. These factors can be accounted by applying necessary corrections. Widely applied correction factors in addition to the hammer energy ($C_E$) are (a) overburden pressure ($C_N$), (b) borehole diameter ($C_B$), (c) presence or absence of liner ($C_S$), (d) rod length ($C_R$) and (e) fines content ($C_{fines}$) [34,35,40,43,12,32,5]. Daniel et al. [14] reviewed SPT short rod length correction and suggested detailed investigation for rod length corrections. Youd et al. [42]

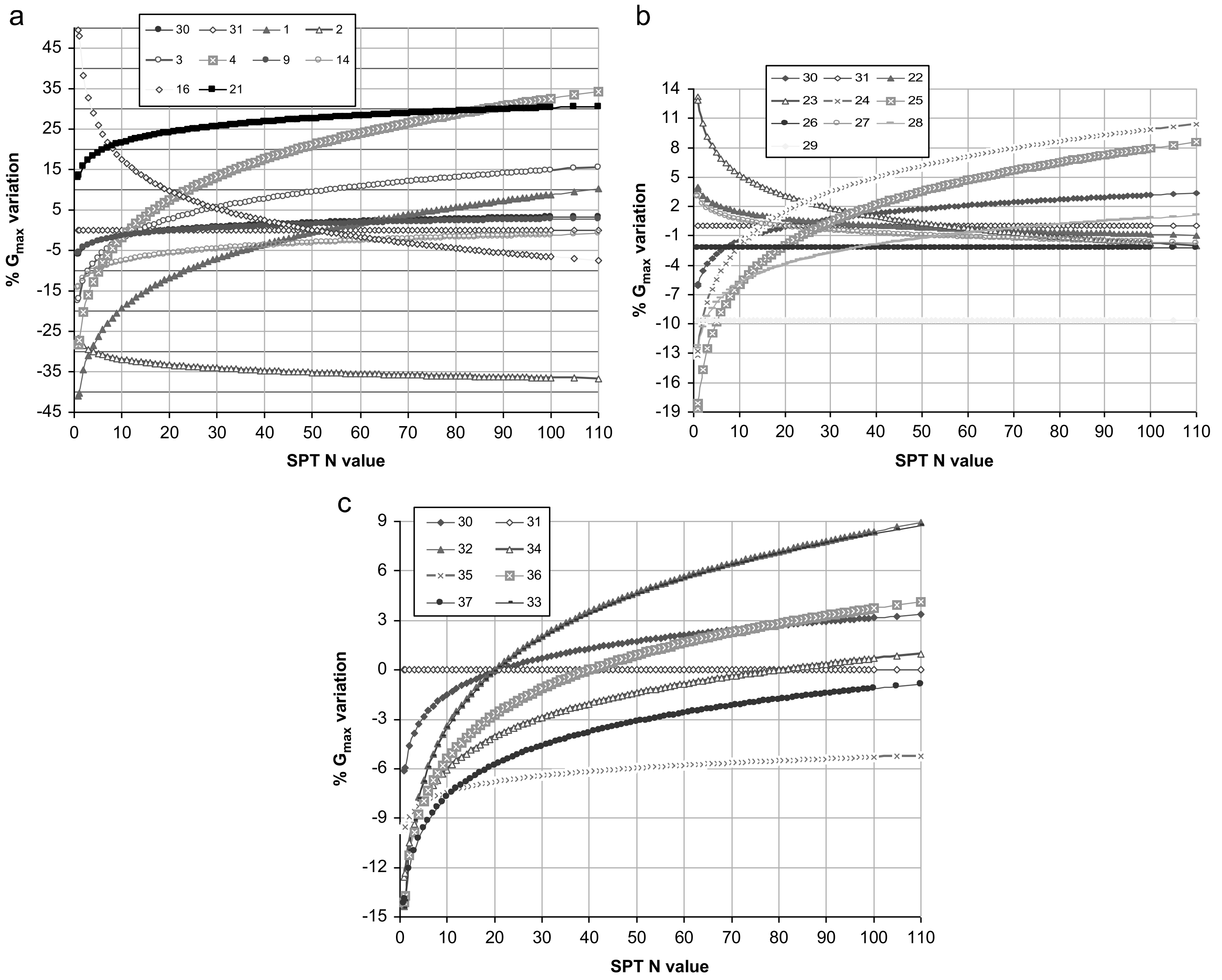


**Fig. 20.** Percentage of $G_{max}$ error reference to new correlation Eq. (31) developed in this study with other correlations: (a) original old correlations, (b) correlations developed by considering the two data combinations and (c) correlations developed by considering the three and more data sets combinations.

**Table 4**
Energy correction factor for shear modulus correlations.

| Average measured energy[a] (%) | Hammer type and release | Country | Correction factor with respect to original correlations | Modified constant of 'a' corresponding to Eq. (31) |
|---|---|---|---|---|
| 78 | Donut—free fall | Japan and India | 78/78 = 1.00 | 16.40 |
| 67 | Donut—rope and pulley | Japan after 1982 | 78/64 = 1.219 | 19.99 |
| 60 | Donut—Free fall | China | 78/60 = 1.30 | 21.32 |
| 60 | Safety—rope and pulley | United States | | |
| 50 | Donut—rope and pulley | China | 78/50 = 1.56 | 25.58 |
| 45 | Donut—rope and pulley | United States | 78/45 = 1.733 | 28.43 |
| 45 | Donut—rope and pulley | Argentina | | |

[a] Measured the hammer energy values after Seed et al. [35].

have carried out field experiments and have concluded that the correction factor for rod length is increasing with the length of rod as given in Youd et al. [43]. Changho et al. [13] have studied the secondary impacts on SPT rod energy and sampler penetration.

Anbazhagan and Sitharam [5] have applied all the corrections and developed correlation between measured and corrected $N$ values. The authors have used the hammer energy correction factor of 0.7 for 60% hammer energy, but in this study it can be noticed that the hammer energy correction factor should be 0.77. Hence correlations developed by Anbazhagan and Sitharam [5] are modified and presented with data in Fig. 22a and b. Modified correlations between measured $N$ values and corrected $N$ values [$(N_1)_{60}$ and $(N_1)_{60cs}$] are given below:

$$(N_1)_{60} = 1.05(N)^{0.90} \quad (40)$$

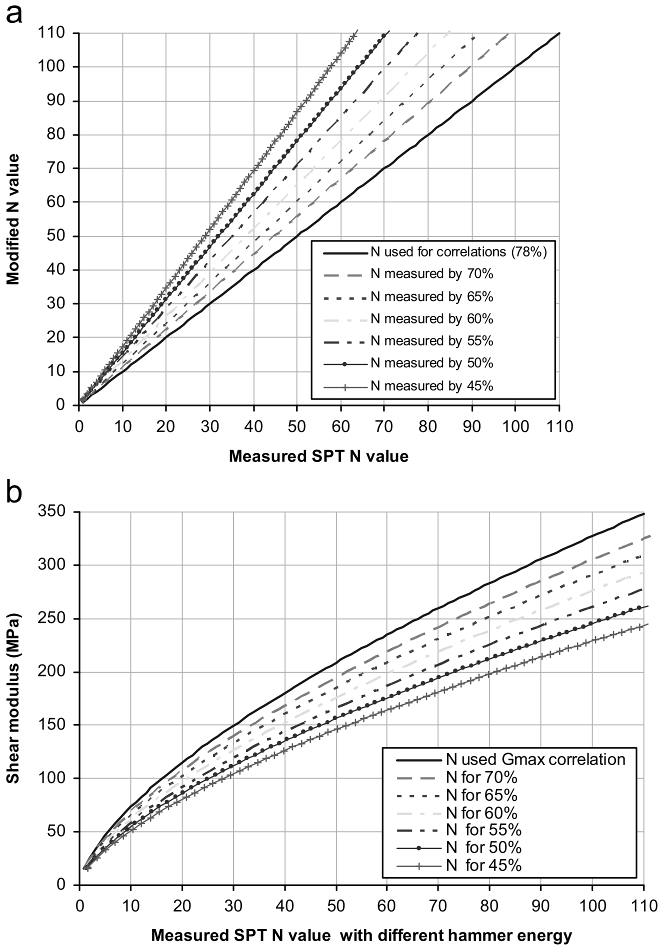


**Fig. 21.** (a) Plot of measured and corrected SPT *N* values for different hammer energies and (b) comparison of shear modulus variation for measured and different hammer energies corrected *N* values considering correlation 31.

$$(N_1)_{60cs} = 2.86(N)^{0.68} \tag{41}$$

where $(N_1)_{60}$ is the corrected *N* value for 60% hammer energy and other corrections excluding fines content correction and $(N_1)_{60cs}$ is the corrected *N* value for 60% hammer energy and other corrections including fines content correction. Fig. 22a and b also shows the presently developed correlation between measured and corrected *N* values with old correlations proposed by Anbazhagan and Sitharam [5] considering $C_E$ as 0.7. This variation is considerable for *N* values corrected without considering fines correction and negligible by considering fines content corrections. $G_{max}$ correlation (Eq. (31)) is also modified with respect to the above two corrected *N* values considering 60% hammer energy. Fig. 23a and b shows correlations between corrected *N* values and shear modulus for data used in correlation 31. The regression coefficient of $R^2$ values does not vary for measured or corrected values of *N*. Correlations for corrected values of *N* are given below:

The correlation for corrected *N* value for 60% hammer energy and other corrections excluding fines content correction $[(N_1)_{60}]$

$$G_{max} = 15.09[(N_1)_{60}]^{0.74} \tag{42}$$

The correlation for corrected *N* value for 60% hammer energy and other corrections including fines content correction $[(N_1)_{60cs}]$

$$G_{max} = 6.03[(N_1)_{60cs}]^{0.95} \tag{43}$$

These correlations can be directly used in Japan and India. In other regions based on hammer energy, the value of *N* should be modified, and $(N_1)_{60}$ or $(N_1)_{60cs}$ can be evaluated using Eqs. (40)

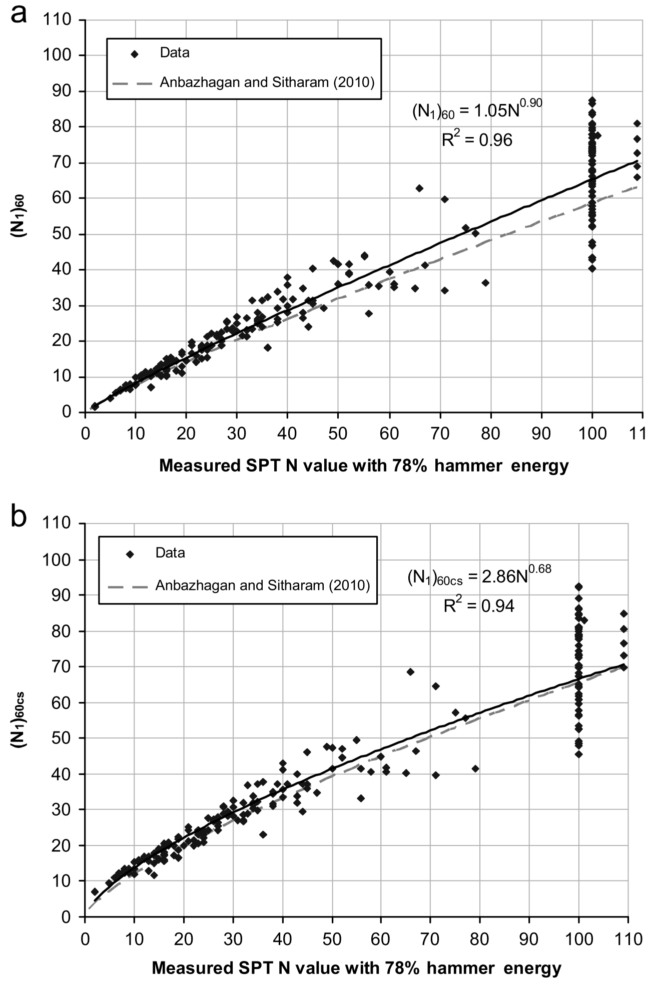


**Fig. 22.** Correlation between measured and corrected SPT *N* values: (a) *N* versus corrected *N* value for 60% hammer energy and other corrections excluding fines content correction $[(N_1)_{60}]$ and (b) *N* versus corrected *N* value for 60% hammer energy and other corrections including fines content correction $[(N_1)_{60cs}]$.

and (41) and correlations (42) and (43) can be used. Before using $(N_1)_{60}$ or $(N_1)_{60cs}$ the researcher should take into account the parameters suitable for their region.

## 11. Conclusions

This paper presents a review of available correlations between SPT *N* values and shear modulus. Eight independent and two reproduced correlations are published till date. The following observations have been made while analyzing these correlations in this study:

(1) Reproduced $G_{max}$ correlations given in Ishihara [20] is not comparable with the original published correlations. Correlation coefficient of constant "*a*" values given in Ishihara [20] are 9810 times less than the actual value. The authors have identified this and suggested modified constant "*a*" values (in Table 2) for the correlation given in Ishihara [20] after personal communication with Ishihara (e-mail from Ishihara in 2009).
(2) The reproduced correlation given by Kramer [23] for sandy soil with a corrected *N* value of 60% hammer energy is comparable with Imai and Tonouchi [18] alluvial clay correlation with corrected *N* value.

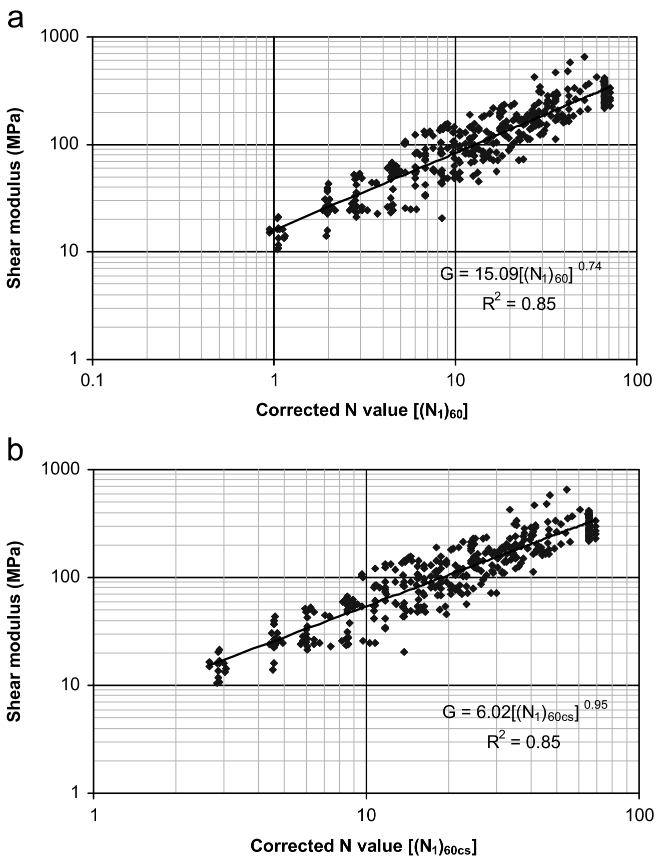


**Fig. 23.** Correlation between shear modulus and corrected *N* values: (a) corrected *N* value for 60% hammer energy and other corrections excluding fines content correction [$(N_1)_{60}$] and (b) corrected *N* value for 60% hammer energy and other corrections including fines content correction [$(N_1)_{60cs}$].

(3) The two correlations proposed by Seed et al. [34] and Kramer [23] and used in site response program SHAKE2000, are not comparable even though Seed et al. [34] have developed correlation considering the US data. These data were measured using 60% hammer energy and Kramer [23] has modified the Imai and Tonouchi [18] equation for similar 60% hammer energy.
(4) Eight independent researchers have developed SPT measured *N* versus $G_{max}$ correlations. The comparison shows that the correlation proposed by Ohba and Toriumi [27] [Eq. (2)] gives the least shear modulus for all the values of *N* when compared to the other correlations. Similarly correlation proposed by Seed et al. [34] [Eq. (15)] gives the highest shear modulus for all the values of *N* when compared to the other correlations.
(5) Correlations proposed by Imai and Yoshimura [17] [Eq. (1)], Ohta et al. [29] [Eq. (3)], Hara et al. [16] [Eq. (9)], Imai and Tonouchi [18] [Eq. (14)] and Sitharam and Anbazhagan [38] [Eq. (16)] are comparable. These correlations may be used by knowing the limitations with respect to hammer energy, soil types and extrapolated SPT N values.
(6) Correlation proposed by Ohsaki and Iwasaki [28] [Eqs. (4) and (5)] is comparable with the above five correlations up to the SPT *N* value of 60 and beyond which it gives slightly higher shear modulus.
(7) Grouping of correlations based on soil type shows that correlation proposed by Imai and Yoshimura [17] [Eq. (1)], Ohta et al. [29] [Eq. (3)], Ohsaki and Iwasaki [28] [Eq. (6)], Imai and Tonouchi [18] [Eq. (14)] and Sitharam and Anbazhagan [38] [Eq. (16)] may be applicable to all types of soil.
(8) The correlations proposed for sandy soil by Ohsaki and Iwasaki [28] [Eq. (5)] and Imai and Tonouchi [18] [Eq. (11) for Alluvial and Eq. (13) for Diluvial] are not comparable.
(9) The correlations proposed for cohesive soil by Ohsaki and Iwasaki [28] [Eq. (7)], Hara et al. [16] [Eq. (9)] and Imai and Tonouchi [18] [Eq. (10) for Alluvial and Eq. (12) for Diluvial] are comparable up to an *N* value of 40 and the first three correlations (Eqs. (7), (9) and (10)) are comparable for all the values of *N*.

New correlations are proposed by combining the authors data with available old data from each researcher separately in two ways (a) using all the data and (b) eliminating assumed and extrapolated data, i.e. measured data. This study shows that correlations using measured data are better than correlations using all the data (including extrapolated). Further, another set of correlations is developed by combining three and more data sets by considering all the data and measured data separately. Three and more data combinations give the best correlation when compared to the original independent correlations and two data combined correlations. Correlation obtained by combining Anbazhagan and Sitharam [5], Ohta et al. [29] and Hara et al. [16] measured data shows less standard error and highest *R* squared value. Existing correlations and new correlations are developed using the SPT *N* values measured by the hammer energy of 78% in Japan and India. This correlation can be directly used in other regions, where hammer energy is same. For regions with different hammer energies, correction factors and modified coefficient of constant values of '*a*' for $G_{max}$ correlation are suggested based on this study. Correction factors are obtained considering the widely available hammer energy measurement of 45–70%. Correlation between uncorrected and corrected SPT *N* values for 60% hammer energy is studied and presented in this paper. Correlation between measured shear modulus and corrected 60% hammer energy *N* values is also presented. The proposed correlations are new and applicable to all types of soils. This correlation can be used in other regions with different hammer energies by applying the necessary correction factor suggested in this study based on the available hammer energy measurement.

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