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ORIGINAL PAPER

Quantitative Assessment of Shear Wave Velocity Correlations in the Shallow Bedrock Sites

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Abstract In this study shear wave velocity (V_s) and standard penetration test (SPT) N values up to the bedrock have been measured by multichannel analysis of surface wave and drilling of boreholes at 51 locations in shallow bedrock sites of South India, as part of the intraplate seismic region of India. Testing covers the major cities as Bangalore, Chennai, Coimbatore, and Vizag in South India. Drilling of boreholes in the above locations shows that the top surface consists of soft to very dense soil followed by very hard Granitic rock. N values are measured up to 100 and values beyond 100 were reported as rebound. Soil thickness of these locations varies from 1 m to about 20 m. The measured N and V_s values are used to generate correlations between N and V_s values for each city and also for the combined data by excluding and including SPT N of 100 for rebound layer. Further the applicability of the V_s and N correlations developed for a particular site to other sites in the same region has been studied and it has been found that the site specific correlations are more accurate. The correlations developed for other cities display high percentages of error, even though the sites are similar in geology and soil type. Additionally, the developed empirical correlations have been compared with the existing worldwide correlations using logarithmic Euclidian distance (*logED*). The *logED* value has been estimated between the measured and calculated lower *logED* respectively for different cities and arrived the best suitable predictive equations for the four cities. Lower *logED* value between the measured and calculated V_s corresponds to better empirical relationship.

Keywords Shear wave velocity · Soil depth · N value · Correlation · Euclidian distance

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Introduction

Site effects are a dominant factor that causes damage to many structures during earthquakes. Propagation of seismic waves from source to the site through different layers (having different dynamic properties) of the earth crust are the main cause of modification in seismic wave properties. This results in either amplification or attenuation of the seismic waves, which depends upon the local soil properties i.e. stiffness, density and composition. Subsoil above the bedrock or hard stratum is a main contributor in the modification of seismic waves. Various researchers have reported that site effects are different for deep and shallow soil deposits. Moreover, the design of new structures and performance assessment of existing structures requires the estimation of site effects due to the site specific soil. Special attention has been given in many modern seismic design codes to incorporate site effects and the dynamic properties of the subsurface materials are important to estimate these parameters. Knowledge of shear stiffness of the soil column, expressed in terms of V_s is required to estimate the site effects. Standard geotechnical parameters like standard penetration test (SPT)-N values, undrained shear strength (Su) and average shear wave velocity (V_s) values are being used by Anbazhagan et al. [1] to characterize/classify the sites and further to determine how far a site is susceptible to amplification. The correlation between N and V_s is developed by various researchers India (Hanumanth Rao and Ramana [2]; Anbazhagan and Sitharam, [3]; Maheshwari et al. [4]; Anbazhagan et al. [5]; Chatterjee and Choudhury [6]). These correlations were proposed for different soils such as sand, silt and clay. These correlations are also being used in the sites or study areas where geotechnical materials are similar. In this paper, the correlation developed worldwide has been compiled and compared with presently developed empirical relationship.

In this study, detailed geotechnical and geophysical investigations were carried out at the selected shallow bedrock sites in the cities of Bangalore, Chennai, Coimbatore and Vizag (Vishakhapatnam). Drilling of boreholes with N measurement and seismic surface wave testing using multichannel analysis of surface wave (MASW) testing was carried out at 51 locations in total combining all the four cities. Soil thickness varies from 1 m to about 20 m and all boreholes were drilled up to the hard rock/ engineering bedrock. N and V_s data generated, is further used to develop the correlation between N and V_s values. The correlation considering N value of 100 for rebound layer and excluding rebound layer i.e. SPT N 100 are developed. The correlation between these parameters was developed for each city individually and also for the combined data. Further shear wave velocity corresponding to rebound layer i.e. SPT N value of 100 and effect of including and excluding in the correlation has been discussed in this study. The developed empirical relationships have been compared quantitatively with all existing worldwide relationships for all types of soils using the logarithm of Euclidian distance (*logED*). In this, *logED* has been calculated between the observed and the calculated V_s values and the validity of these equations to the present study area has been evaluated. Using *logED* value, the developed and existing correlations has been compared based on the geological condition and soil type.

Field Experiments

Subsurface geotechnical properties of stiffness, thickness and type of material play an important role in the site response and amplification studies. The SPT is one of the oldest, most popular, and commonly used in situ test for soil exploration in soil mechanics and foundation engineering because of simplicity in the equipment and test procedure. SPT is a widely used in situ test conducted in a borehole to evaluate the geotechnical properties of soil. In the present study, few boreholes are drilled at different sites and others are collected. All boreholes were drilled in shallow bedrock sites where soil thickness is less than 25 m. These boreholes were drilled for 150 mm diameters as per IS: 1892 [7] and N values are measured regularly at 1.5 m interval as per IS: 2131 [8]. Soil samples in disturbed and undisturbed form are collected at possible depths according IS: 2132 [9]. Data corresponding to N values, depth of sample collection and soil type identification, were logged during field testing. Typical borehole of Vizag city with soil description, thickness of soil and N value, is given as Fig. 1. A typical borehole along with soil description, thickness of soil and N value for Chennai, Coimbatore and Bangalore is given as electronic material as Figure EF1, EF2 and EF3 respectively. All the borehole data used in the present study have N values measured up to 100 and boreholes were terminated after reaching rock stratum.

Most of the surface wave tests follow three fundamental steps: Acquisition, Dispersion Analysis and inversion to model the layered-earth model (V_s, V_p, h, r, etc.). Many surface wave methods are attempted for seismic site classification, but the widely used methods are Spectral Analysis of Surface Waves (SASW) and MASW. SASW and MASW are both surface wave methods that are generally used for many civil engineering and earth science applications. The most common application of these tests is to estimate the shear wave velocity of the subsurface layer and further site response parameters such as amplification and predominant frequency of soil can be estimated. In this study, MASW survey has been carried out close to shallow bedrock sites where boreholes with N values are available in the Bangalore, Chennai, Coimbatore and Vizag cities.

MASW system consisting of 24 channel Geode seismograph with 24 numbers of vertical geophones of 4.5 Hz capacity are used to carry out field experiments. All MASW tests have been carried out with geophone intervals of 1 m. The source has been kept on both sides of the spread and the distance between source and the first and last receiver are also varied from 5, 10 and 15 m to avoid the near-field and far-field effect similar to Anbazhagan et al. [5]. The seismic waves are created by an impulsive source of 15 pounds (sledge hammer) with 300 mm × 300 mm size hammer plate with ten shots. These waves are captured by receivers and the data is further used to get dispersion curves, which are used to extract shear wave velocity at the midpoint of the testing locations. Detailed information on the inversion methods, sensitivity parameters and calculation with respective examples are found in Xia et al. [10]. Shear wave velocity obtained from the MASW technique is comparable with the cross hole, up and down hole seismic methods with an error of 8–15 %. A typical dispersion curve along with signal to noise (S/N)

Fig. 1 Typical borehole with SPT N-value for Vizag city

BORE LOG

BH No MBH-75 Date of commencement 03.05.2008

Ground Water Table 3.45m Date of completion 05.05.2008

Depth Below GL(m)	Soil Description	Thickness of layer	Legend
0.65	Light yellowish to dull white sandy to silty clay	0.65	
2.35	Yellowish coloured sandy silty clay	1.7	
6.8	Light yellowish coloured silty to sandy clay	4.45	
9.8	Light yellowish to light reddish sandy to silty clay	3	
11.8	Light reddish coloured sandy soil with few shales	2	
40.0	Greyish white jointed, Fractured slightly to moderately weathered quartzite rock	28.2	

Samples Type	Depth (m)	SPT N values
SPT	0.9	7
SPT	2.4	10
SPT	3.9	12
SPT	5.4	16
SPT	6.9	18
SPT	8.4	23
SPT	9.9	33
SPT	11.4	36
SPT	12.9	42
SPT	14.4	47
SPT	16.5	100
SPT	40	100

Note

Bore hole Terminated at 40m

SPT-Standard Penetration Test

CR-Core Recovery

UDS- Undisturbed Sample

RQD-Rock Quality Designation

GL- Ground level

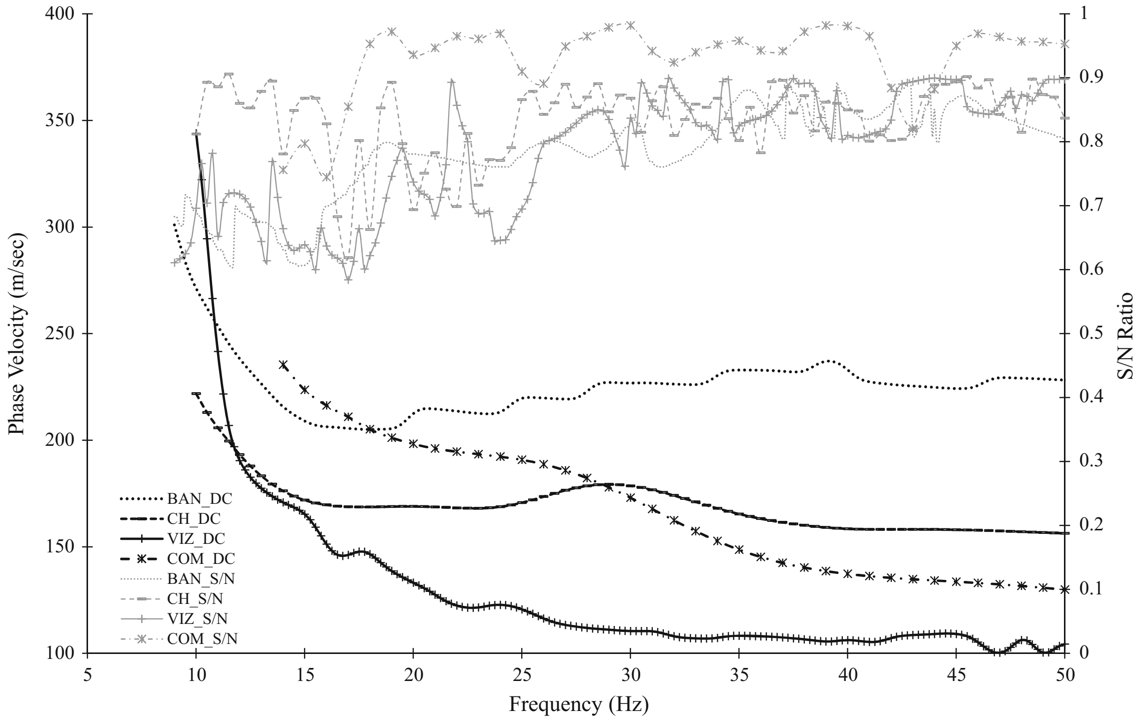


Fig. 2 Typical dispersion curve (DC) and S/N ratio for Bangalore (BAN), Coimbatore (COM), Bangalore (BAN) and Vizag (VIZ)

ratio corresponding to all the four cities are given in Fig. 2. After, inverting all the dispersion curves, it has been observed that layers having V_s of 360 m/s and above lies within 30 m in all the profiles. This layer is considered as a base layer or hard strata for most of the engineering design. Typical variation between V_s and N value with respect to depth has been given in Fig. 3. As the range of V_s and N values would be different for different depths, all values at different depth has been scaled by dividing them with the minimum value of V_s and N. It can be seen from Fig. 3 that V_s and N values are matching well at different depths.

N and V_s Correlations

Empirical relation between N and V_s values would be useful for the sites where it is difficult to conduct surface wave test for determining shear wave velocity value, which would be further useful in determining dynamic properties and site class. There are several such correlations available worldwide in the literature and few site specific correlations were also developed at different cities in the South India. The correlation between N and shear modulus, or density is very limited when compared with correlations between N and V_s values (Anbazhagan et al. [27]). However, several site response and seismic site classification studies were carried out in different cities considering shear wave velocity obtained from existing N versus V_s correlation developed for other sites. In this study, data collected for each city by conducting MASW and SPT test and are used to develop correlation between N and V_s values for respective city. Most of the existing SPT N and V_s correlations were developed considering SPT N value 100 or extrapolated N values for rebound layer. In this study bore log with N values measured up to 100/rebound layer were available. Effect of including and excluding SPT N value of 100 for rebound layer has been studied. Further, an attempt has been made to understand statistically, how accurate it could be to develop a correlation using the combined or site-specific databases for shallow bedrock sites. Summary of the database corresponding to respective cities is given in Table 1. The general form of empirical equation to correlate N and V_s is given below:

$$V_S = aN^b \quad (1)$$

where V_s is shear wave velocity in m/s, 'a' and 'b' are regression coefficients and N is measured/uncorrected N values. Correlation coefficient (R) and regression coefficients corresponds to regression analysis done for respective cites is presented in Table 1.

Generally, researcher capped the N-value either at 50 [2, 5, 16, 25] or 100 [3, 4, 31, 32] for deriving the N versus V_s correlation. Site specific amplification estimation requires shear wave velocity or shear modulus up to input layer i.e. hard rock below rebound layer. Including SPT N value of 100 in the correlation are useful for site

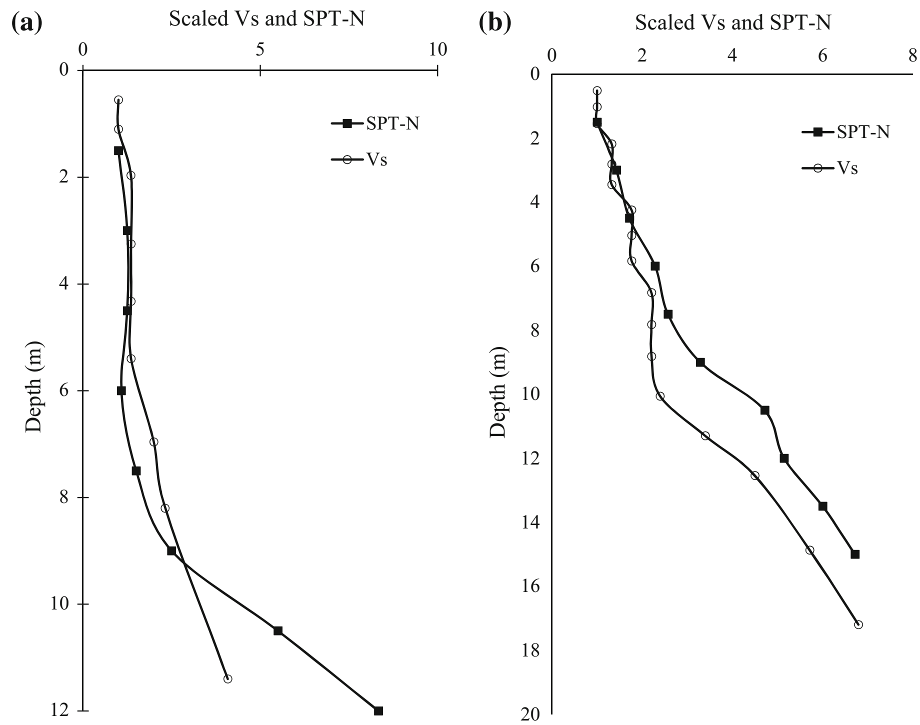


Fig. 3 Typical V_s and SPT-N (both values are scaled by diving each with the minimum value) comparison with respect to different depth

Table 1 Summary of data and shear wave velocity correlation

City	No of borehole	No of data	Minimum SPT N value	Minimum V_s (m/s)	Maximum SPT N value up to rebound layer	V_s (m/s) for maximum N	Range V_s (m/s) for rebound layer	Excluding SPT N value of 100 for rebound layer			Including SPT N value of 100 for rebound layer		
								Correlation coefficient (‘a’ and ‘b’ values)		Correlation coefficient (R)	Correlation coefficient (‘a’ and ‘b’ values)		Correlation coefficient (R)
Bangalore	17	70	6	121.445	77	458.26	337–497	70.71	0.36	0.780	65.67	0.39	0.829
Chennai	5	35	7	125.269	67	252.51	281–502	84.87	0.26	0.740	75.91	0.3	0.822
Coimbatore	9	8	4	214.892	42	241.22	300–424	206.9	0.07	0.520	159.1	0.17	0.826
Vizag	20	115	3	50	92	387.11	375–480	27.37	0.66	0.850	36.68	0.56	0.870
Combined	51	228	3	50	92	458.26	281–502	45.69	0.49	0.770	52.21	0.45	0.823

response studies. Also very limited studies have presented effect of including SPT N value of 100 in correlation for rebound layer. Hence, in the present study, an attempt has been made to derive the N versus V_s correlation with and without including N-value of 100. Power law fit empirical relation and coefficient of determination (R^2) is shown in Fig. 4a–d for each city using respective database. In the figure dotted line shows correlation excluding rebound layer N value and solid lines shows including rebound layer and respective correlation is given in Table 1. From Fig. 4 and Table 1, it can be observed that maximum data points of 115 excluding rebound layer N values are available for Vizag city and minimum data points of 8 are available for Coimbatore city. Lowest SPT-N value of the study is 3 and maximum N value is about 100. Chennai data do not have N values for 70–99 and Coimbatore data do not have N values for 43–99. The average shear wave velocity corresponding to rebound layer for BAN, CH, COM and VIZ are varies from 425 ± 30, 330 ± 40, 350 ± 50 and 410 ± 25 m/s. These correspond to variation in rebound layer property in the four cities. These values can be taken as reference values for the correlation excluding SPT N value of 100 for rebound layer, which will be useful for site response study. Fully weathered rock and clayey silty fine to medium sand

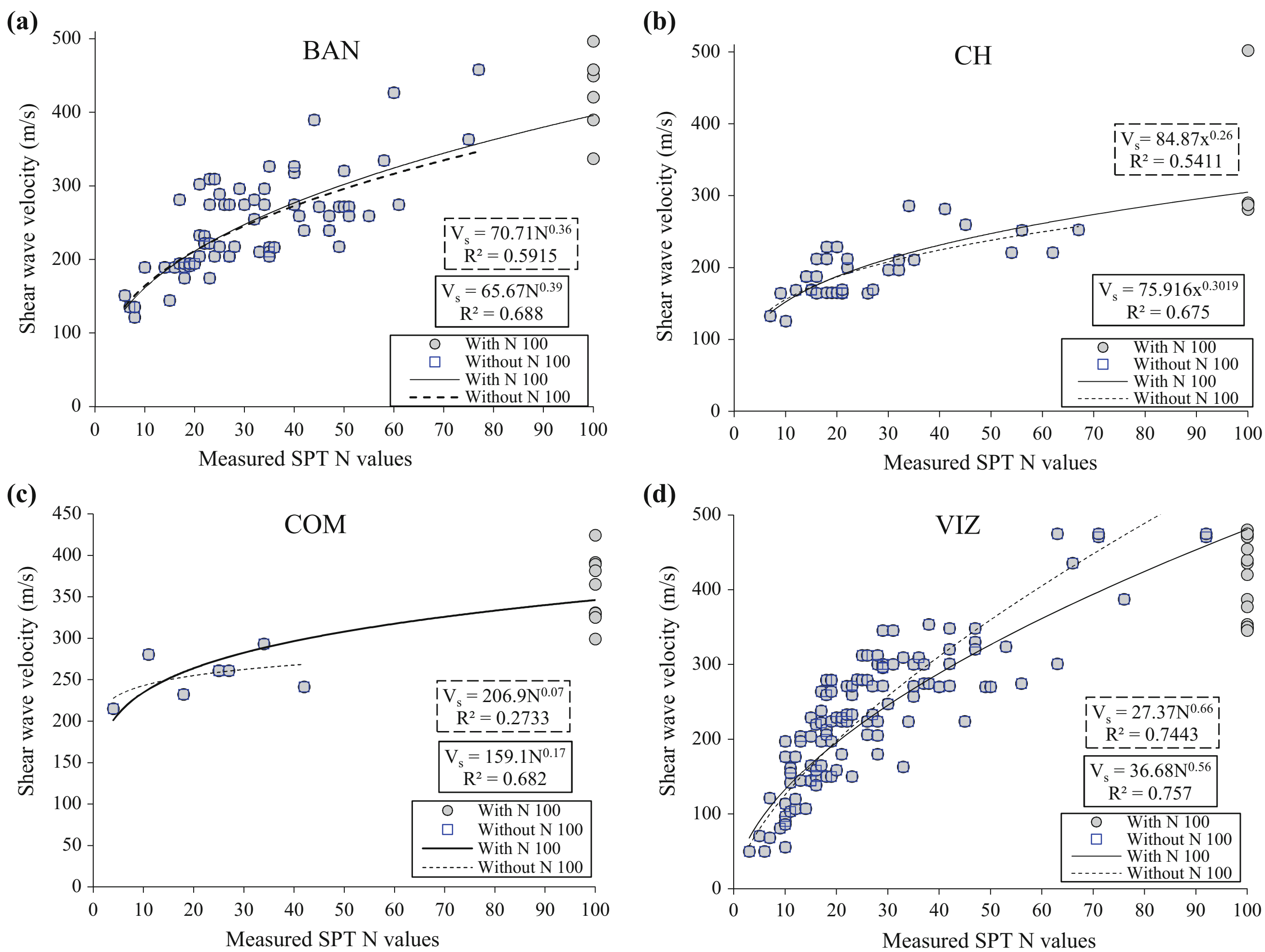


Fig. 4 Shear velocity versus SPT-N data and correlation for four cities **a** Bangalore (BAN), **b** Chennai (CH), **c** Coimbatore (COM) and **d** Vizag (VIZ) with (*solid line*) or without (*dotted line*) including N value 100. *Box* with (*solid line*) and without (*dotted line*) including N value 100 represents regression relationship

with coarse particles are reported for rebound layer i.e. 100 N-value in Bangalore. For Coimbatore and Chennai, grayish brown silt sand and white gravelly silt/sand and coarse sand and weathered rock along with fine to medium sand was reproved as rebound layer. Similarly, for Vizag, rebound i.e. N-value 100 is observed for sandy clay with moorum, yellowish sandy clay and weathered rock. The newly derived empirical correlations for four cities including SPT N value of 100 along with R^2 have been shown in Fig. 4a–d. The empirical correlation has been compared with and without including N-value 100 in figure and respective correlation coefficient (R) is given in Table 1. It has seen that, both relationships are predicting same V_s up to N-value range corresponding to 30–40 as far as Bangalore, Chennai and Vizag are concern. As explained above, the data for Coimbatore is less therefore a wide variation has been seen. Coimbatore correlation may be improved by including more data. Statistically, it can be concluded that, R^2 value of correlation is increased by including the N-value 100 for the same data.

These data are combined to develop combined relation correlation applicable to all cities. Wide variation of shear wave velocity for rebound layer is observed in the combined data and it may be due to variation in dynamic properties corresponds to different locations at these four cities. Higher V_s for similar rebound condition may be due to different decomposition phenomenon of soil in the region and also due to change in stress conditions and overburden pressure at different sites. This could be seen through rebound layer description and a typical dispersion curve given in Fig. 2 that, for the lower frequency that corresponds to deeper depth relatively, phase velocity varies a lot. Shear wave velocity correlation considering all data is shown in Fig. 5 and a summary is given in the last row of Table 1. Combining all database fills the gap in N

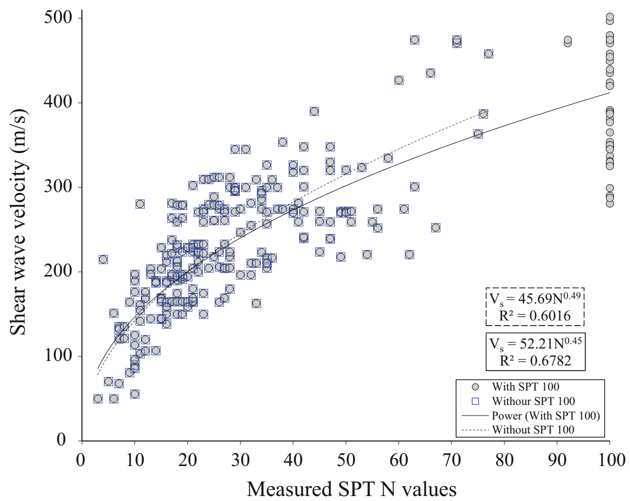


Fig. 5 Combined shear velocity versus SPT N data and correlation excluding (*dotted line* and *box*) and including (*solid line* and *box*) N value of 100. Data from Bangalore, Chennai, Coimbatore and Vizag

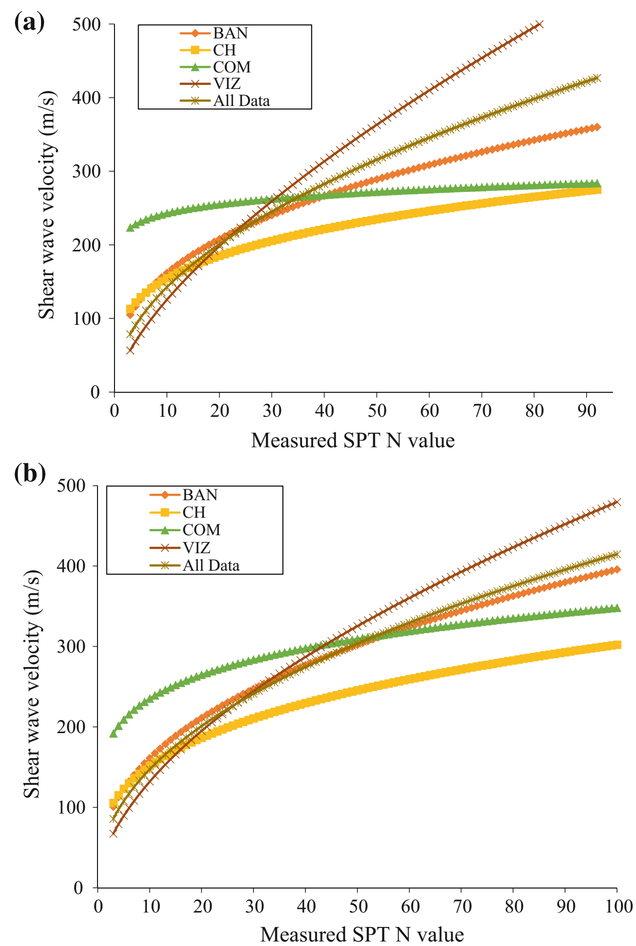


Fig. 6 Comparison of shear wave velocity correlations developed in the study **a** excluding SPT N values 100 and **b** including SPT N values 100

value, however, shear wave velocity corresponding to rebound layer i.e. 100 N value varies from 281 to 502 m/s. The empirical relation along with R^2 developed using combined data of all the cities is given in Fig. 5 with and without SPT N values of 100. The correlation coefficient of relation including 100 N values for Bangalore, Chennai, Coimbatore and combined data is almost similar where in Vizag data has slightly higher values, may be due to large number of data which reduces the variance and improves the correlation. Correlation for Vizag has a high correlation coefficient followed by Bangalore, Coimbatore and Chennai when SPT N of 100 is included. The correlation coefficient for all data is closer to the lowest value, i.e. correlation coefficient for Chennai. Correlation coefficient for all relation excluding 100 is less than relation including 100. Coimbatore relation excluding 100 has lowest correlation coefficient when compared to other relations. Statistically, it can be concluded that, R^2 value has been increased by including the N-value 100. Comparison of these correlations and applicability to other sites is presented in the next section.

Analysis of Predictive Capability

The use of shear wave velocity and SPT-N correlation that has developed for other sites is widely adopted in earthquake geotechnical engineering practices to estimate site specific dynamic properties. Many seismic Microzonation studies follow this procedure because of abundant availability of N values from previous investigations. Many researchers have adopted the existing correlations based on quality judgment i.e. by comparing geological and/or soil type similarities instead of developing a new site specific correlation. However, these properties vary from site to site for shallow depths even though the geological formations are identical. This can be seen clearly from Fig. 2, that for the same frequency, the phase velocity varies a lot even though there is not much variation in the crustal property in Southern part of India. In this study, site-specific V_s shear wave velocity versus N correlation for four South Indian cities viz. Bangalore, Chennai, Coimbatore and Vizag were developed by using individual and combined databases. Figure 6a, b show a comparison of five shear wave velocity versus N correlations developed in this study excluding and including SPT N value of 100 for rebound layer. It can be noted from Fig. 6 that at the lower N values, four correlations predict similar V_s values; at medium N values, three predictions are similar and at higher N values, the predictions are differ. However, Fig. 6 does not give quantifiable values about the predictive capability of the correlation at each site for other sites. Hence, detailed validation and comparison need to be performed to conclude about the applicability of these equations.

All five derived empirical correlations are used to estimate shear wave velocity using available N data for each city and compared with the respective measured shear wave velocity values. Figure 7a–e shows measured velocity of respective city versus predicted velocity by correlation excluding SPT N value of 100 with slopes of 1:1, 1:0.8 and 1:1.2 lines for each city. From Fig. 7, it can be observed that predicted V_s values from correlation for Bangalore data are matching with measured values for Bangalore (Fig. 7a). Predicted V_s values from correlation of Chennai data and Coimbatore data closely matches with measured values for the respective sites (Fig. 7b and c). Predicted V_s values from correlation of Vizag data and combined data are matching and slightly outside boundary lines (Fig. 7d and e). Figure 8a–e shows measured velocity of respective city versus predicted velocity by correlation excluding SPT N value of 100 with slopes of 1:1, 1:0.8 and 1:1.2 lines for each city. From Fig. 8, it can be observed that predicted V_s values from correlation for Bangalore data and combined data are closely matching with measured values for Bangalore (Fig. 8a). Predicted V_s values from correlation of Chennai data and Coimbatore data closely matches with measured values for the respective sites (Fig. 8b and c). Similarly predicted V_s values from correlation of Vizag data and combined data are closely matching with measured values for Vizag (Fig. 8d). None of five correlations are capable of predicting V_s values close to measured values for the combined data within 1.2–0.8 bands. This analysis shows that relations obtained for specified site is more suitable and to some extent, the combined model can be also suitable, but not valid in all the cases. Further, root mean square (RMS) error has been computed between measured and calculated V_s value from different empirical relationships. 3D plot of RMS error values between measured and calculated V_s is given as Fig. 9a and b. It can be clearly seen from Fig. 9 that, RMS error is more if V_s and N empirical relationship derived using database of one site is used for another. Hence, it can be concluded from Figs. 7, 8 and 9 that for the shallow bed rock site, V_s and N should be site-specific as dynamic property may change even though geological formation was same, as density of the deposit plays an important role in that respect.

Further in order to estimate the prediction capability of each V_s relationship with recorded field data, scaled percent error (Dikmen [11]; Anbazhagan et al. [5]) in percent has been calculated using a relationship given below;

$$E_r = 100(V_{SC} - V_{SM})/V_{SC} \quad (2)$$

where, E_r is scaled percent error, V_{SM} is the measured V_s value from MASW for a city and V_{SC} is the predicted V_s value from each correlation. Scaled percent error for each city model has been estimated by calculating V_s values from five correlations and is compared with the measured value for respective city. V_s correlation having more than 75 % of the data within a 20 % error margin is considered as a best predicting correlation for the particular city. Figure 10a–e shows the scaled percent error variation for the five relations developed by excluding SPT N value of 100 for each city. Correlation arrived from Bangalore data, and all data are more suitable for Bangalore city and predict V_s values inside 20 % error margin (Fig. 10a). Correlation arrived from Chennai data, Bangalore data and combined data are suitable for Chennai, and other correlations predict V_s values outside the 20 % error margin (Fig. 10b). Figure 10c shows that correlation developed considering Coimbatore data excluding SPT N value of 100 is predicting V_s values for Coimbatore city within a 20 % error margin and other correlations predict more than 25 % of the data out off 20 % error margin. Correlation developed considering Vizag, Bangalore and combined data predict V_s values for Vizag within a 30 % error margin and other two correlation are having less than 75 % data within 30 % error margin (Fig. 10d). These five correlations are independently used to predict V_s values for the entire data set and compared with the measured V_s values and given as Fig. 10e. Correlation developed considering Bangalore, Vizag and combined data are capable of predicting V_s values of about 65 % of the data within a 20 % error margin and the other two correlations provide even a lesser estimate than this value. Figure 11a–e shows the scaled percent error variation for the five relations developed by including SPT N value of 100 for each city. Correlation arrived from Bangalore data, Vizag data and all data are more suitable for Bangalore and other correlations of Chennai and Coimbatore cities predict V_s values outside 20 % error margin (Fig. 11a). Correlation arrived from Chennai data is more suitable for Chennai and other correlations predict V_s values outside the 20 % error margin (Fig. 11b). Figure 11c shows that correlation developed considering Bangalore and Coimbatore data are capable of predicting V_s values for Coimbatore city within a 20 % error margin and other correlations predict more than 25 % of the data out off 20 % error margin. Correlation developed considering Vizag, Bangalore and all other data predict V_s values for Vizag within a 20 % error margin (Fig. 11d). These five correlations are independently used to predict V_s values for the entire data set and compared with the measured V_s values and given as Fig. 11e. Correlation developed considering Bangalore, Vizag and combined data are capable of predicting V_s values of about 60 % of the data within a 20 % error margin and the other two correlations provide even a lesser estimate than this value. It can be concluded that including N-value 100, statistically improves the correlation and equations become valid for less error margin range. It has also observed that

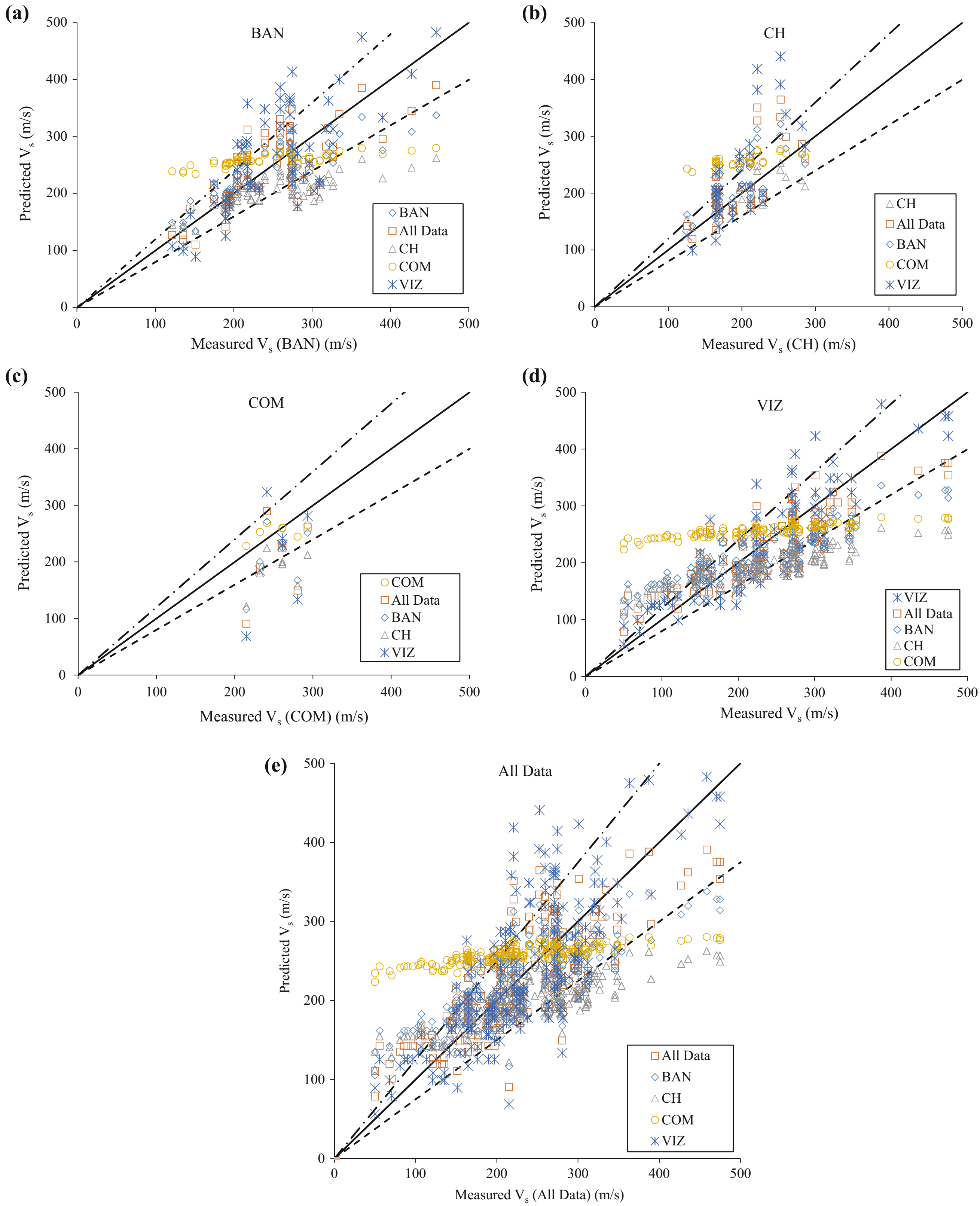


Fig. 7 Comparison between measured and predicted V_s values for each city using different models given in Figs. 4 and 5 for four cities excluding SPT N value 100 **a** Bangalore (BAN), **b** Chennai (CH), **c** Coimbatore (COM), **d** Vizag (VIZ) and **e** all data

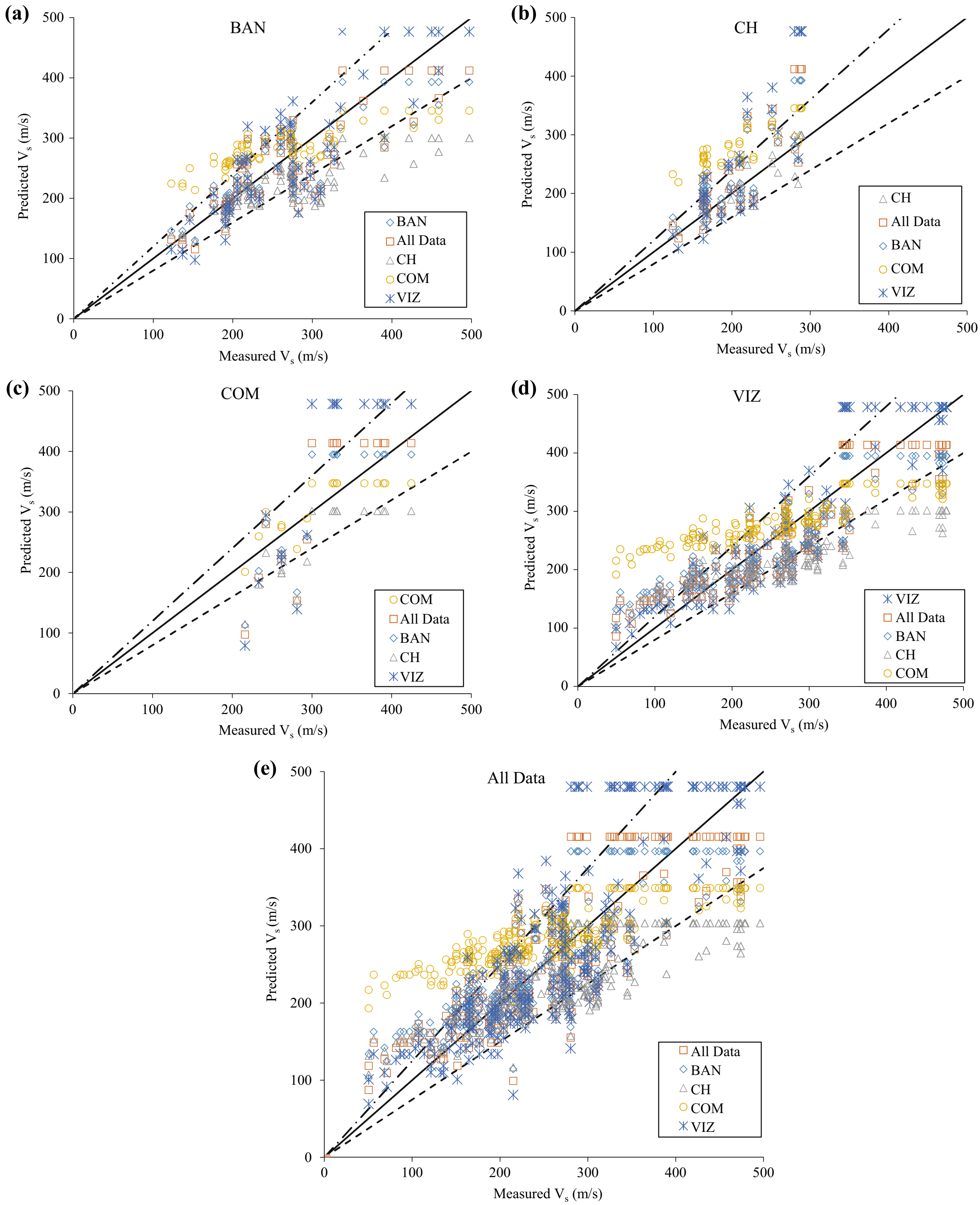
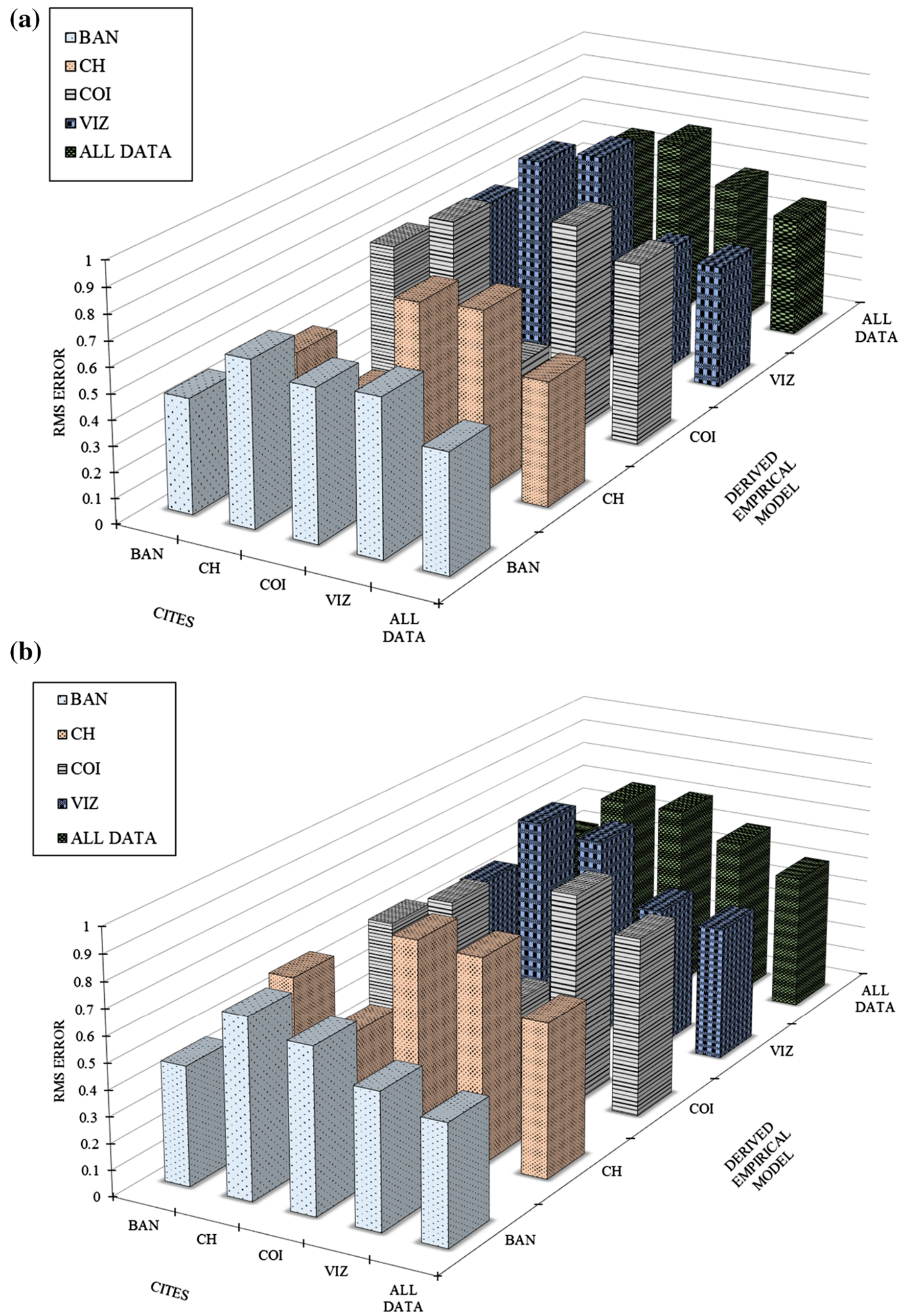


Fig. 8 Comparison between measured and predicted V_s values for each city using different models given in Figs. 4 and 5 for four cities including SPT N value 100 **a** Bangalore (BAN), **b** Chennai (CH), **c** Coimbatore (COM), **d** Vizag (VIZ) and **e** all data

Fig. 9 **a** and **b** Comparison of RMS error between measured and derived V_s values for different cities and combined database **a** excluding SPT N value 100 and **b** including SPT N value 100



for SPT rebound at lower depth, capping on N-value to either 50 or 100 significantly improves the correlation, which was seen in case of Coimbatore. The difference in V_s prediction may be due to the difference in the geotechnical condition, soil characteristics and stress condition. This study shows that even though the four cities are in the same region i.e. South India with similar geological setting, correlation developed for a particular city is not effectively predicting V_s values for other cities. One has to be careful in selecting V_s correlation based on soil and geology for estimating V_s values at different study areas or sites. Correlation developed considering all data is capable of effectively predicting V_s values for Bangalore and Vizag, where the number of data points from these cities is considerably more than other two cities data.

Comparison of V_s and N Empirical Relationship with Previous Studies

In the present study, empirical relationship between V_s and N values has been derived for four cities viz. Bangalore, Coimbatore, Chennai and Vizag by excluding and

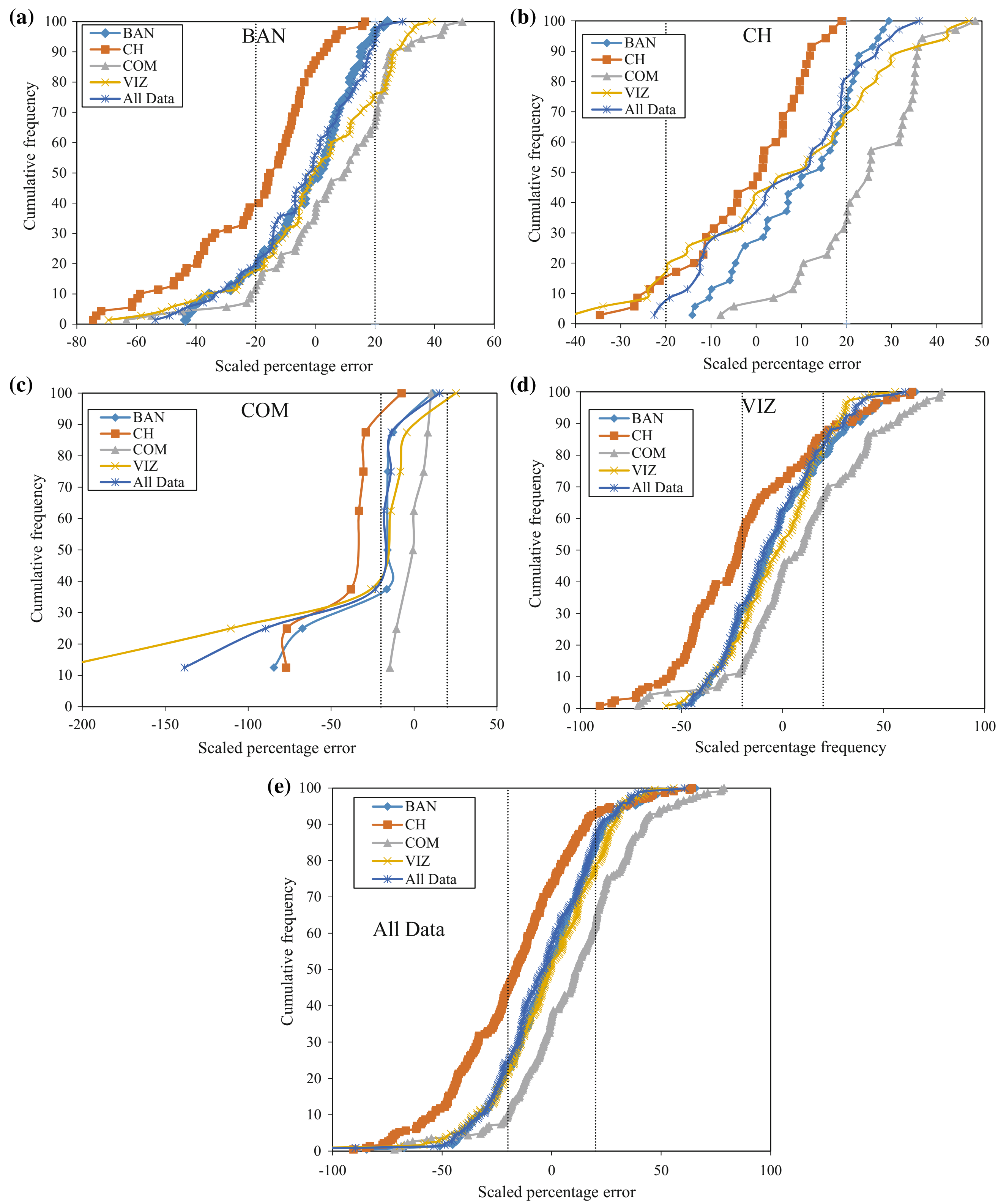


Fig. 10 Scaled percent error for five correlations proposed for respective city and combined data. **a** Bangalore (BAN), **b** Chennai (CH), **c** Coimbatore (COM), **d** Vizag (VIZ) and **e** all data excluding SPT N 100

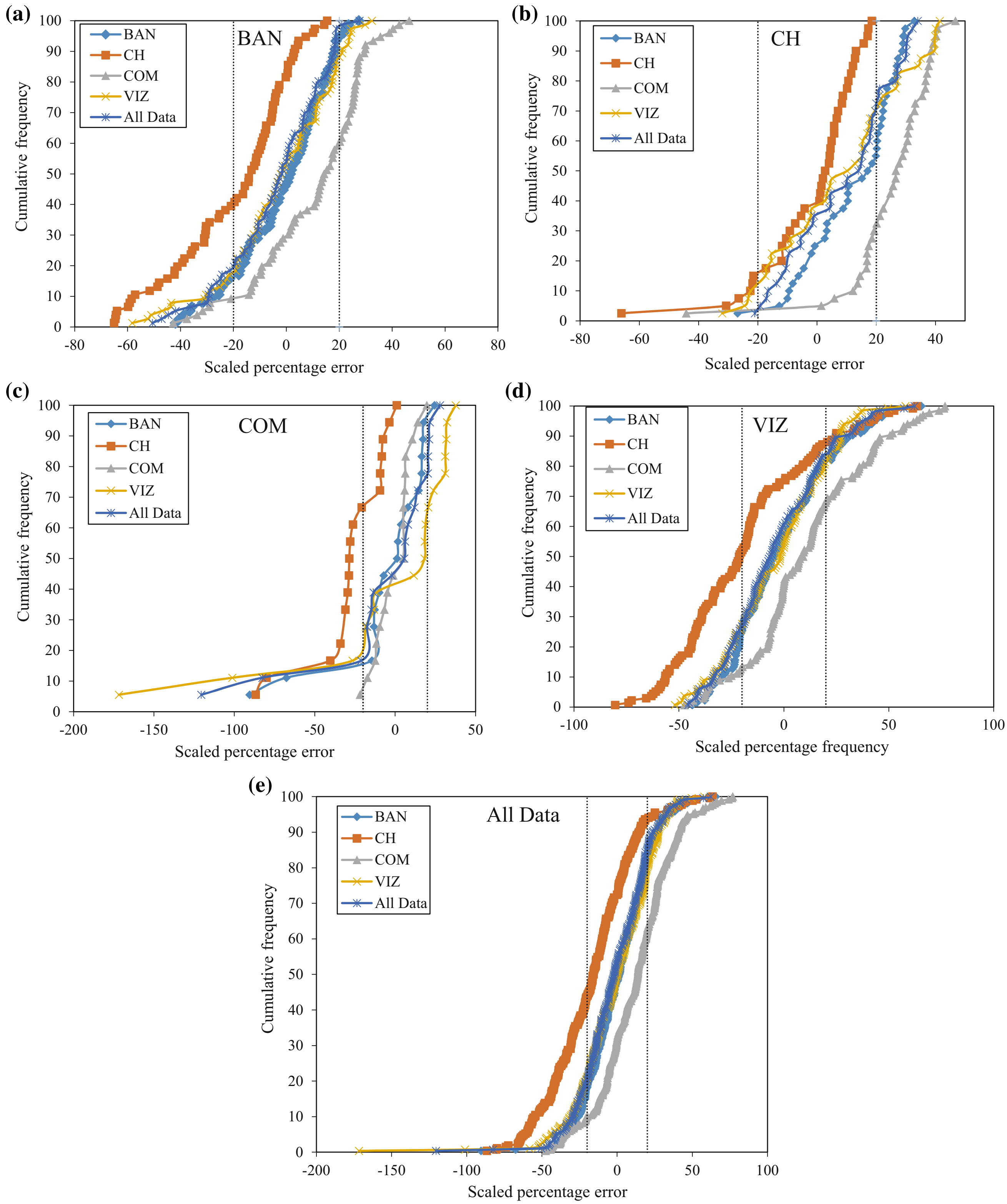


Fig. 11 Scaled percent error for five correlations proposed for respective city and combined data. **a** Bangalore (BAN), **b** Chennai (CH), **c** Coimbatore (COM), **d** Vizag (VIZ) and **e** all data including SPT N 100

including SPT N value of 100 for rebound layer. However, various comparative studies are available for shear wave velocity correlations in the existing literatures. Most of these studies highlight that the correlation developed for a particular site is better than previous correlations. Moreover, very limited attempts are available to compare different sites data within the same region i.e. southern part of India. In the previous section and Figs. 7, 8, 9, 10, 11, it has been shown that, even though for similar geological formation, the correlation derived for one site is computing V_s value for other site in the same region having large error as compared to the measured value. However, in most of the sites it would not be possible to perform either SPT or any seismic test, in that case it is very difficult to produce site specific V_s and N correlation. In order to identify best suitable correlation applicable to particular city, quantitative selection of existing empirical relations between V_s and N for a particular are presented in this section.

There are various empirical relationship between corrected and uncorrected N and V_s developed by various researchers (Ohba and Toriuma [12]; Fujiwara [13]; Ohsaki and Iwasaki [14]; Imai and Yoshimura [15]; Imai et al. [16]; Imai [17]; Ohta and Goto [18]; Seed et al. [19]; Imai and Tonouchi [20]; Athanasopoulos [21]; Sisman [22]; Jafari et al. [23]; Kiku et al. [24]; Hasancebi and Ulusay [25]; Hanumanth Rao and Ramana [2]; Anbazhagan and Sitharam [3]; Maheshwari et al. [4]; Anbazhagan et al. [5]; Mhaske and Choudhury [31]; Rao and Thaker [32]). Some researchers have proposed correlations between N and V_s for different soils, such as sand, silt and clay. Others have developed correlation equations which included stress. Most of relationship between V_s and N values were developed using N values measured in the field, except Anbazhagan and Sitharam [3], which was developed using corrected N values. The correlation between the measured and corrected N values can be found in Anbazhagan and Sitharam [26]. Anbazhagan and Sitharam [26] showed that measured and corrected N-SPT values gave similar RMS values for residual soil. Worldwide several researchers have developed similar correlations for their sites. These correlations are also used in the sites or study areas where geotechnical materials are similar. A summary of these N versus V_s correlations are given in Table 2. Available correlations between the N and V_s values from worldwide data (Sr. No 1- 15) and correlations developed in India (Sr. No 16–23) have been given in Table 2. For comparing these models Euclidean Distance (ED) concept has been used. ED is defined as the square root of a sum of square of differences between N data pairs ($x_i y_i$). Let x_i be the observed V_s values and y_i be the calculated V_s values, hence ED is defined theoretically as $ED^2 = \sum_{i=1}^{N}(x_i - y_i)^2$. However, log-ED seems to be much simpler in the present case as the distance between the two vectors or tensor is a straight line in logarithm and secondly, the variation in measured and calculated is very large, hence logarithm ED has been used. Log-ED can be defined by taking the log of the ED and can be given as $logED = \|logx_i - logy_i\|$, where, $\|\cdot\|$ is Euclidian norm in vector space. Using this relationship, a significant trend between the V_{SM} and V_{SC} can be interpreted as the biased representation of observed data by the predicted ones, calculated using different empirical relationships. The lower the $logED$ value between the measured and calculated V_s, better is the empirical relationship.

In this study, $logED$ value corresponds to V_s calculated from each predictive equation (See Table 2) and measured for respective city is given as Table 2. It can be seen from Table 2 that, the first four best empirical relations for Bangalore city excluding N value 100 (apart from correlation developed using Bangalore database) are the relationships developed using all data in the present study [No. 23], Rao and Thaker [32] [No. 22], Ohba and Toriuma [12] [No. 1], Hasancebi and Ulusay [25] [No. 15], Imai and Yoshimura [15] [No. 4], last four equation are developed for Osaka plains, Gujarat, Yenisehir town (Turkey) and Japan respectively. However, including N value 100 both equations (excluding and including) of present study for Bangalore data and combined data is suitable, additionally. Similarly for Chennai (EXC), Imai and Yoshimura [15] [No. 4], Ohba and Toriuma [12] [No. 1], Kiku et al. [24] [No. 14] and using all data (EXC) and Bangalore data (EXC) [No. 23] in the present study found to be suitable for Chennai. However, including N value 100, additionally, Imai and Tonouchi [20] [No. 9], Ohta and Goto [18] [No. 7] are satisfactory. For Coimbatore city (excluding N 100), the empirical relations derived by Imai and Tonouchi [20] [No. 9], Maheshwari et al. [4] [No. 18], Fujiwara [13] [No. 2] and Imai [17] [No. 6] are surfaces. Whereas, including N 100, additionally, equation derived in the present study Bangalore (EXC and IND) and Chennai (EXC) is fitting better as per the analysis. As far as Vizag city (including and excluding N 100) is concerned relationships developed using all data (EXC and IND) [No. 27] and Bangalore city (EXC and IND) [No. 23] in the present study, Rao and Thaker [32] [No. 22], Imai and Yoshimura [15] [No. 4], Iyisan [30] [No. 12] and Ohba and Toriuma [12] [No. 1] are the six best relationships. Whereas, combining whole data (excluding N 100), other than relationships developed using Bangalore city (EXC) [No. 22] and Vizag city (EXC) [No. 26], the best five are Rao and Thaker [32] [No. 22], Imai and Yoshimura [15] [No. 4], Ohba and Toriuma [12] [No. 1], Hasancebi and Ulusay [25] [No. 15] and Maheshwari et al. [4] [No. 18]. However, including N value 100, additionally, the best suitable equations are Bangalore (EXC and IND) [No. 23], Vizag (EXC and IND) [No. 26] equation developed in present study. From Table 2, it can also be

Table 2 Correlation between SPT-N value and V_S used for comparison along with *logED* values based on the measured and calculated V_S values excluding (EXC) and including (IND) SPT N value of 100 rebound layer

Sl. No	Authors		Existing correlation for all types of soil	ED-value									
				Bangalore		Coimbatore		Chennai		Vizag		All data	
				EXC	IND	EXC	IND	EXC	IND	EXC	IND	EXC	IND
1	Ohba and Toriuma [12]		$V_s = 84N^{0.31}$	0.378	0.436	0.233	0.129	0.108	0.288	2.235	2.362	2.952	3.214
2	Fujiwara [13]		$V_s = 92.1N^{0.337}$	0.737	0.757	0.754	0.163	0.063	0.889	2.984	3.054	4.541	4.862
3	Ohsaki and Iwasaki [14]		$V_s = 81.4N^{0.39}$	1.005	1.049	0.953	0.306	0.086	1.171	3.144	3.310	5.190	5.836
4	Imai and Yoshimura [15]		$V_s = 76N^{0.33}$	0.398	0.460	0.180	0.163	0.141	0.233	2.106	2.243	2.826	3.099
5	Imai et al. [16]		$V_s = 89.9N^{0.341}$	0.690	0.709	0.708	0.161	0.066	0.839	2.861	2.928	4.326	4.637
6	Imai [17]		$V_s = 91N^{0.337}$	0.686	0.705	0.706	0.155	0.064	0.834	2.879	2.944	4.337	4.637
7	Ohta and Goto [18]		$V_s = 85.35N^{0.348}$	0.581	0.599	0.597	0.154	0.073	0.718	2.589	2.650	3.842	4.122
8	Seed et al. [19]		$V_s = 61.4N^{0.50}$	1.650	1.827	1.328	0.743	0.153	1.773	3.513	4.109	6.645	8.452
9	Imai and Tonouchi [20]		$V_s = 97N^{0.314}$	0.644	0.663	0.671	0.119	0.056	0.777	2.933	2.996	4.311	4.555
10	Athanasopoulos [21]		$V_s = 107.6N^{0.36}$	2.471	2.585	2.029	0.565	0.135	2.378	6.054	6.452	10.69	11.981
11	Sisman [22]		$V_s = 32.8N^{0.51}$	1.556	1.623	0.453	0.617	0.594	0.505	3.232	3.381	5.836	6.125
12	Iyisan [30]		$V_s = 51.5N^{0.516}$	0.883	0.986	0.764	0.564	0.166	1.094	2.115	2.475	3.930	5.119
13	Jafari et al. [23]		$V_s = 22N^{0.85}$	3.837	4.898	2.225	2.922	0.472	3.710	4.654	7.889	11.18	19.418
14	Kiku et al. [24]		$V_s = 68.3N^{0.292}$	1.426	1.702	0.222	0.547	0.354	0.309	3.546	4.226	5.549	6.783
15	Hasancebi and Ulusay [25]		$V_s = 90N^{0.309}$	0.411	0.446	0.378	0.102	0.076	0.447	2.414	2.494	3.280	3.490
16	Hanumanth Rao and Ramana [2]		$V_s = 82.6N^{0.43}$	2.164	2.320	1.745	0.677	0.139	2.160	4.965	5.456	8.976	10.613
17	Anbazhagan and Sitharam [3]		$V_s = 78\,N_{60}^{0.40}$	0.954	0.999	0.905	0.315	0.091	1.125	2.979	3.150	4.930	5.589
18	Maheshwari et al. [4]		$V_s = 95.641N^{0.3013}$	0.479	0.508	0.483	0.932	0.061	0.560	2.605	2.708	3.664	3.869
19	Chatterjee and Choudhury [6]		$V_s = 78.21N^{0.3767}$	0.625	0.613	0.422	0.422	0.855	0.855	3.579	3.579	3.567	2.126
20	Anbazhagan et al. [5]		$V_s = 68.96N^{0.51}$	3.153	3.497	2.278	1.193	0.217	2.946	5.968	7.075	11.61	14.710
21	Mhaske and Choudhury [31]		$V_s = 72N^{0.4}$	0.593	0.617	0.589	0.751	0.100	0.237	2.290	2.386	2.815	3.992
22	Rao and Thaker [32]		$V_s = 59.7N^{0.42}$	0.376	0.394	0.275	0.383	0.166	0.231	1.703	1.759	2.521	2.768
23	This study (Bangalore)	EXC	$V_s = 70.71N^{0.36}$	0.366	0.396	0.218	0.263	0.142	0.147	1.830	1.951	2.607	2.682
		IND	$V_s = 65.67N^{0.39}$	0.405	0.389	0.285	0.191	0.190	0.167	2.035	1.887	2.894	2.820
24	This Study (Chennai)	EXC	$V_s = 84.87N^{0.26}$	0.672	0.789	0.112	0.113	0.199	0.205	2.517	2.833	3.509	3.934
		IND	$V_s = 75.91N^{0.30}$	0.994	0.817	0.175	0.164	0.322	0.274	3.331	2.858	4.823	4.114
25	This study (Coimbatore)	EXC	$V_s = 206.9N^{0.07}$	0.815	0.851	0.736	0.881	0.009	0.018	4.344	4.793	6.094	6.347
		IND	$V_s = 159.1N^{0.17}$	1.005	0.911	0.796	0.769	0.118	0.040	5.253	4.479	7.417	6.364
26	This study (Vizag)	EXC	$V_s = 27.37N^{0.66}$	0.513	0.717	0.321	0.468	0.307	0.384	1.231	1.310	2.456	2.810
		IND	$V_s = 36.68N^{0.56}$	0.842	0.553	0.845	0.527	0.844	0.510	1.664	1.460	4.169	3.049
27	This study (All Data)	EXC	$V_s = 45.69N^{0.49}$	0.399	0.429	0.234	0.273	0.214	0.248	1.441	1.576	2.386	2.432
		IND	$V_s = 52.21N^{0.45}$	0.450	0.417	0.421	0.343	0.361	0.281	1.633	1.521	2.753	2.675

concluded that, equation developed excluding N value 100 would be applicable or best for the region having data including N value 100, even though the rest of the data could be same. For Coimbatore and Chennai, equation developed excluding N value 100 do not seem to be best or much applicable statistically for the database including N value 100 (data is same for less than N 100), however vice-a-versa might be true. Mismatch of correlations might be due to the depth of N-SPT measured and soil variation in the region. Here it can be noted that within the city also there maybe variation in the V_s values, which need to be studied. Based on the study, it can be concluded that the empirical correlations should be site specific or a quantitative if site specific data is not available instead of qualitative analysis.

Conclusions

This study presented the geotechnical and geophysical investigation of four major cities of Bangalore, Chennai, Coimbatore and Vizag in South India. Most of the sites investigated are on shallow bedrock i.e. engineering rock within 25 m and soil thickness varying from 1 to 20 m. Soil found in these shallow bedrock sites are mainly sandy silt or silty sand with a little clay. Available N and V_s values for each city have been used to derive V_s correlations for each city and a combined one. Further the effect of including SPT N value of 100 for rebound layer is investigated. V_s correlation developed using uniform distributed data for entire range of N values is not affected by including or excluding SPT of 100 for rebound layer irrespective of number of data. Missing of data in particular range of N values show large difference between correlation including and excluding N value of 100. In general, including of SPT N 100 in the V_s correlation results in higher correlation coefficient, prediction capability and better correlation for the region. These cities are having a similar geology and soil type, so in this study, the applicability of a correlation developed elsewhere to a particular city was checked. This study shows that in general, city specific correlation is showing better prediction values when compared to another city correlation and combined data correlation. More caution is required for the selection of V_s correlation for other cities to estimate site specific dynamic properties. Additionally, the developed empirical correlations have been compared with the existing worldwide correlations using logarithmic Euclidian distance (*logED*). The *logED* value corresponds to V_s calculated from each predictive equation and measured for respective city has been calculated. The lower the *logED* value between the measured and calculated V_s, better is the empirical relationship. Statistically, it is seen that, even though database for the relationship developed excluding and including N value 100 for less than N 100 is same, but the relationship is not suitable for same region, hence, maximum N value has a lot of significance in these relationships.

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