

Use of Surface Waves in Statistical Correlations of Shear Wave Velocity and Penetration Resistance of Chennai Soils

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Abstract Shear wave velocity (V_s) is one of the most important input parameter to represent the stiffness of the soil layers. It is preferable to measure V_s by in situ wave propagation tests, however it is often not economically feasible to perform the tests at all locations. Hence, a reliable correlation between V_s and standard penetration test blow counts (SPT-N) would be a considerable advantage. This paper presents the development of empirical correlations between V_s and SPT-N value for different categories of soil in Chennai city characterized by complex variation of soil conditions. The extensive shear wave velocity measurement was carried out using Multichannel Analysis of Surface Waves (MASW) technique at the sites where the SPT-N values are available. The bender element test is performed to compare the field MASW test results for clayey soils. The correlations between shear wave velocity and SPT-N with and without energy corrections were developed for three categories of soil: all soils, sand and clay. The proposed correlations between uncorrected and energy corrected SPT-N were compared with regression equations proposed by various other investigators and found that the developed correlations exhibit good prediction performance. The

proposed uncorrected and energy corrected SPT-N relationships show a slight variation in the statistical analysis indicating that both the uncorrected and energy corrected correlations can predict shear wave velocity with equal accuracy. It is also found that the soil type has a little effect on these correlations below SPT-N value of about 10.

Keywords In situ wave propagation test · Shear wave velocity · Standard penetration test blow counts · Multichannel analysis of surface waves (MASW) test · Bender element test

1 Introduction

The propagation of seismic waves near the surface is strongly influenced by the presence of unconsolidated loose sediments overlying the bedrock resulting in modifications of the ground motion characteristics at the surface. The ground motion parameters at the surface are generally obtained by conducting one dimensional ground response analysis considering only the upward propagating shear waves. In these analyses, the shear wave velocity (V_s) is one of the most important input parameter to represent the stiffness of the soil layers. Hence, it is important to determine the shear wave velocity for the estimation of ground motion parameters at the surface. Field

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measurements of shear wave velocity include cross-hole tests, downhole tests, suspension logging, seismic reflection, seismic refraction and surface waves tests (Kramer 1996). Surface waves test is a simple and an efficient technique compared to other in situ tests to measure the shear wave velocity in the field. But, it is not often economically feasible to carry out the shear wave velocity measurements in all cases particularly in urban areas for microzonation studies. The penetration tests have been widely accepted in India as routine tests in geotechnical site investigation and abundant SPT data is available. Though the SPT tests are not meant for clayey soils, correlations are also available between the unconfined compressive strength and SPT-N value in the literature (Terzaghi and Peck 1967). The current application of SPT results for the derivation of maximum shear modulus for International geotechnical design is also mentioned in ENV 1997-3 (1999).

Several researchers have proposed empirical correlations based on standard penetration test to evaluate the dynamic soil properties of the soils (Ohba and Toriumi 1970; Imai and Yoshimura 1970; Fujiwara 1972; Imai 1977; Ohta and Goto 1978; Seed and Idriss 1981; Imai and Tonouchi 1982; Sykora and Stokoe 1983; Jinan 1987; Lee 1990; Mayne and Rix 1995; Sisman 1995; Iyisan 1996; Jafari et al. 1997, 2002; Kiku et al. 2001; Hasancebi and Ulusay 2007). These empirical relationships seem to be site specific and require thorough process of validation before using them for coastal regions of India.

This paper presents the development of empirical correlations between V_s and SPT-N value for different categories of soil in Chennai city, located on the southeastern coast of India characterized by complex variation of soil conditions. The measurement of shear wave velocity was carried out extensively using Multichannel Analysis of Surface Waves (MASW) technique at the sites where the SPT-N values are available. The bender element test is performed to compare the results obtained in the field MASW test with the laboratory test results for clayey soils so as to develop a greater level of confidence in the in situ MASW test results at small strain. Earlier researchers have compared the shear wave velocity obtained from MASW tests with laboratory tests such as resonant column and bender element tests (Schneider et al. 1999; Long and Menkiti 2007). However, the

shear wave velocity values obtained from MASW test for typical Indian marine clays are not reported in literature. Hence, in the present study the bender element test was carried out on undisturbed clay samples to confirm the V_s obtained from the MASW test. Based on statistical assessments and taking into account the type of soil, a series of empirical correlations for the prediction of shear wave velocity were developed based on uncorrected and energy corrected SPT-N for different categories of soil. The developed correlations were compared with the number of other available equations in order to evaluate the prediction capability of the equations and found that developed correlations exhibit good prediction performance.

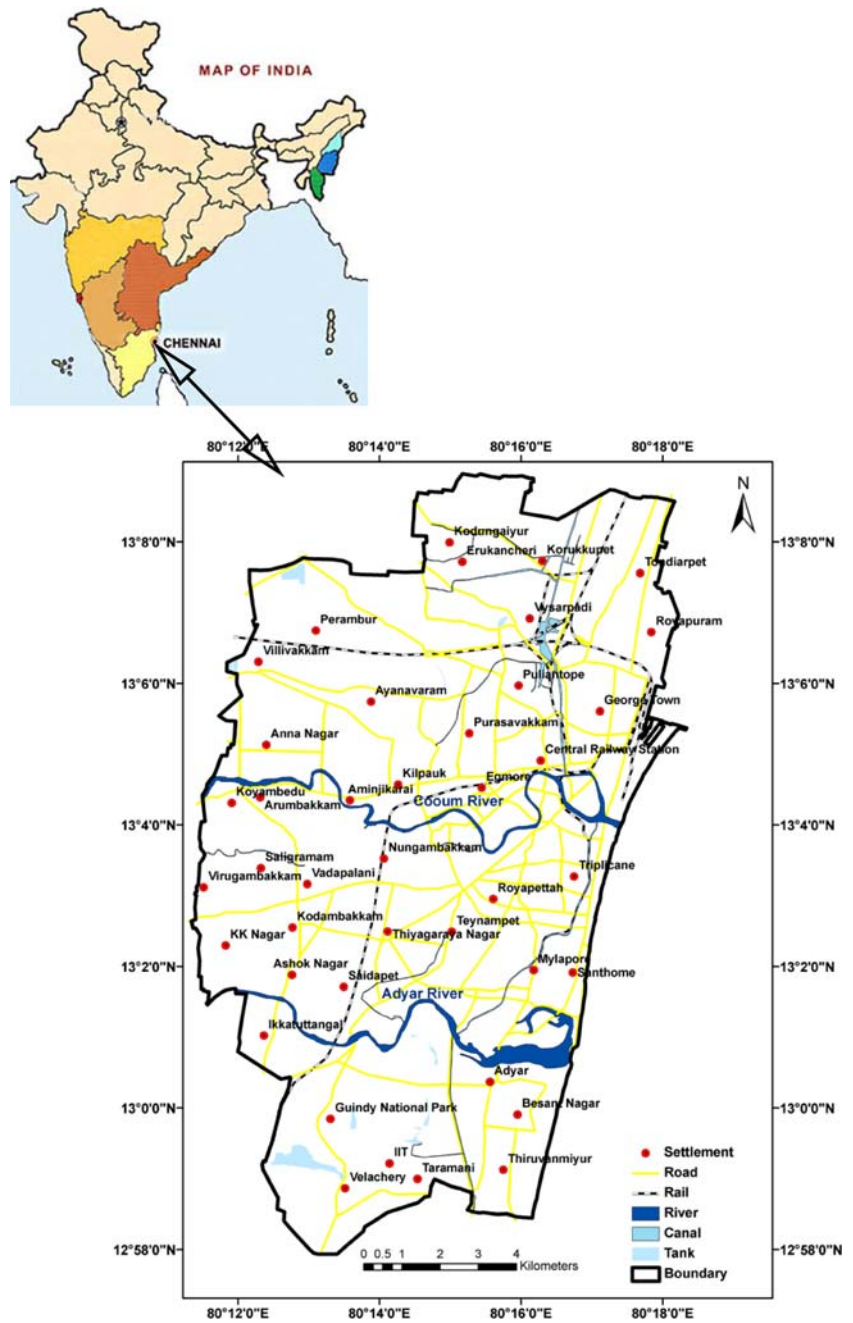
2 Geology of the Study Area

Chennai, India's fourth largest metropolitan city, is located between 12.75°–13.25°N and 80.0°–80.5°E on the southeastern coast of India (Fig. 1). The city spreads over 19 km in length along the Coromandel coast and extends inland about 9 km and covers an area of about 172 km². The general geology of the city comprises mostly of sand, clay, shale and sandstone as shown in Fig. 2 (GSI 1999). The surface geology of the study area and its surroundings are reported in Ballukraya and Ravi (1994), Seismotectonic Atlas of India (2000) and Subramanian and Selvan (2001). The study area has two distinct geological formations: the shallow bedrock (crystalline) on the east and south, and the Gondwanas (conglomerate, shale and sandstone) below the alluvium to the north and west.

3 Geotechnical Investigations

It is well known that the average shear wave velocity in the upper 30 m of the ground surface is an important factor for seismic site characterization (Borcherdt 1994; Dobry et al. 2000). Therefore, in the present study, the borehole details were collected to a depth of about 30 m or up to the bedrock. The SPTs were conducted as per Indian Standard IS 2131 (1981) which is similar to ASTM D 1586 (2008). Nearly thirty spatially distributed

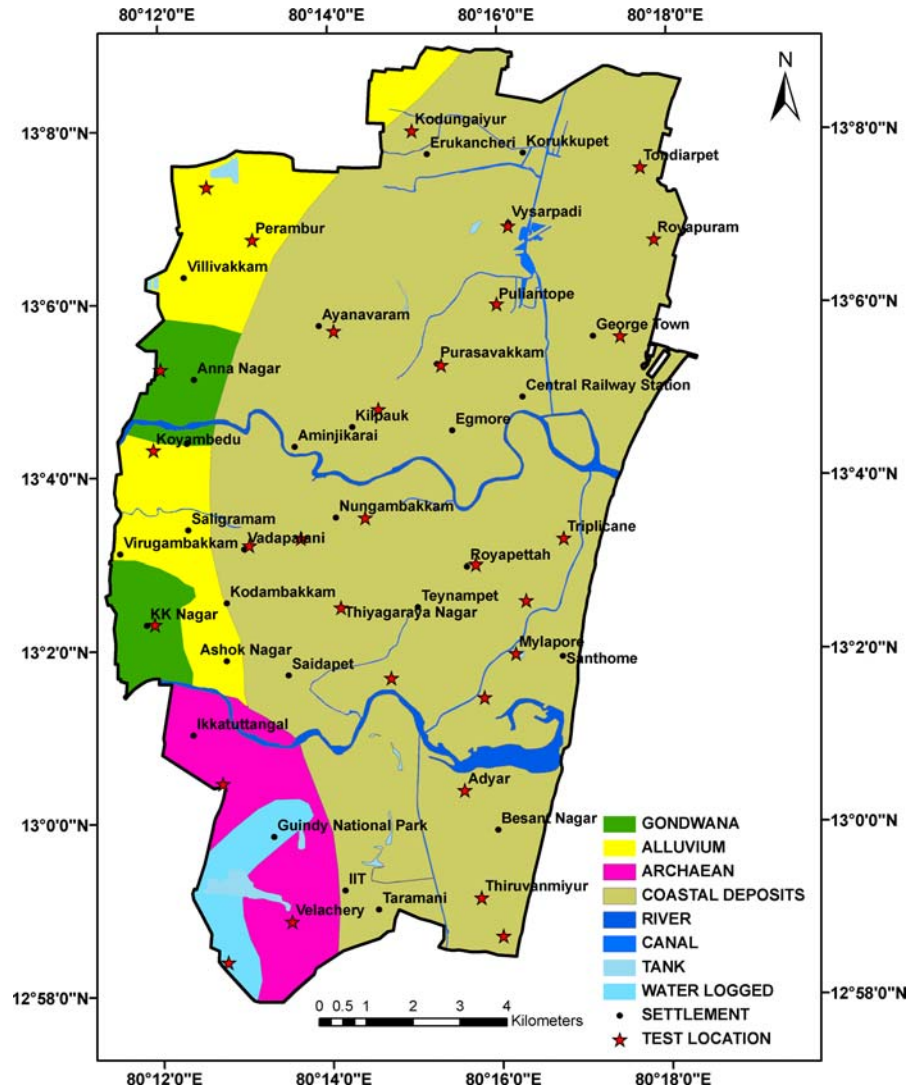
Fig. 1 Location map of Chennai



sites were considered in Chennai for geotechnical and geophysical investigations as depicted in Fig. 2. The typical borelog with SPT-N profile at southern, eastern and western regions of Chennai is shown in Fig. 3. The soil profile in southern region consists of shallow deposit of sandy clay layer underlain by weathered rock/rock. In some places in southern

suburbs, rock outcrop is also identified. The east coastal region of the city is fully covered by marine sediments. It mainly consists of loose to dense sand with silty/sandy clay intrusion at some depths. The thickness of soil deposit varies from 30 to 40 m. In the western suburbs, the soil profile predominantly consists of clayey deposits. The consistency of the

Fig. 2 Geological map of the study area and locations of geotechnical and geophysical investigations



clay varies widely from soft to hard. The thickness of soil deposit in the western suburbs varies from 25 to 30 m.

4 Surface Wave Method

Surface wave geophysical methods provide a rapid, cost-effective, noninvasive approach for solving a variety of geotechnical engineering problems. Surface based techniques employ surface receivers to measure the travel time of seismic waves with distance along the surface. The surface wave methods offer advantages over other surface based in situ seismic techniques including the ability to measure

both shear wave velocity and material damping profiles with depth and the ability to detect low velocity features underneath higher velocity layer of deposit, allowing for more accurate site characterization.

4.1 Multichannel Analysis of Surface Waves

Nazarian et al. (1983) introduced a surface wave method called spectral analysis of surface waves (SASW) to produce near surface shear wave velocity profiles. The main drawback of SASW test is the time consumption for field survey as it involves only a single pair of receivers. Later on, a four-phase research project team from Kansas Geological Survey

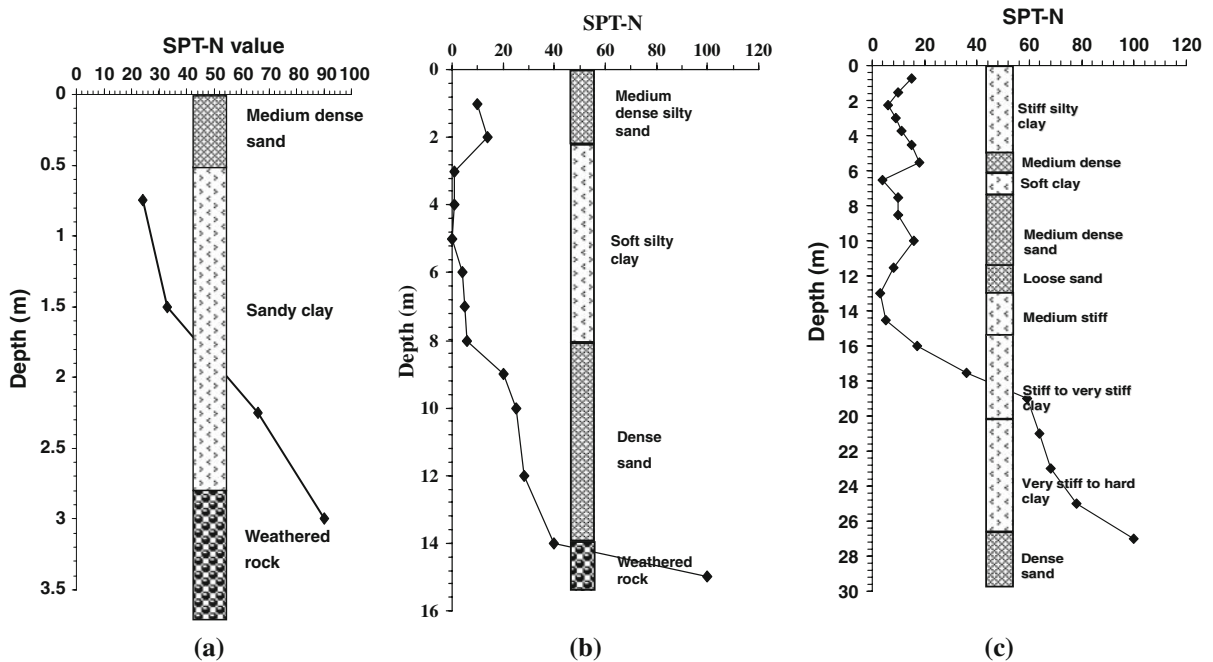


Fig. 3 Typical borelogs at **a** south; **b** east; **c** western region of Chennai

developed an efficient and accurate method to estimate near surface shear wave velocity from ground roll using multichannel seismic data from Multichannel Analysis of Surface Waves (MASW) technique. The shear wave velocity profile obtained from surface wave method involves three steps: acquisition of ground roll, construction of dispersion curve (phase velocity vs. frequency) and back calculation (inversion) of the V_s profile from the calculated dispersion curve (Park et al. 1999).

4.2 Field Test Set-up and Procedure

In the present study the MASW tests are carried out using Geometrics make 24 channels Geode seismic recorder with single geode operating software (SGOS). The vertical geophones of natural frequency 4.5 Hz (24 nos.) are used to receive the wave fields generated by the active source of 8 kg sledgehammer. Twenty-four geophones were deployed in a linear pattern with equal receiver spacing in the range of 0.5 to 1 m interval with the nearest source to geophone offset in the range of 5 to 15 m to meet the requirement of different types of soil as suggested by Xu et al. (2006). The source and each receiver are connected to an individual recording channel as

shown in Fig. 4. The acquired wave data were processed using the SurfSeis software to develop experimental dispersion curve as shown in Fig. 5. The experimental dispersion curve shows the variation of phase velocity with frequency in the fundamental mode. The signal to noise (S/N) ratio as depicted in Fig. 5 helps to identify the optimum field configuration. Effectiveness in signal analysis is further enhanced by the data processing step. The experimental dispersion curve was subjected to inversion analysis to develop one- and two-dimensional (1D and 2D) shear wave velocity profiles. The variations of shear wave velocity with depth for three suburbs in the city namely Kottivakkam (east), Koyembedu (west) and Velachery (south) are shown in Fig. 6. The SPT-N profile is also depicted in Fig. 6. It is evident from the figure that the variation of shear wave velocity practically matches with the SPT-N profile. Figure 7 shows the 2D shear wave velocity profile for the Egmore site and the corresponding soil stratum is shown in Fig. 3b. The soil stratum indicates the occurrence of soft clay layer at a depth of 3 m sandwiched between medium dense sand layers. The 2D shear wave velocity profile also indicates the intrusion of soft clay layer with V_s of 100 m/s at a depth of 3 m and is sandwiched between

Fig. 4 Field configuration of MASW test

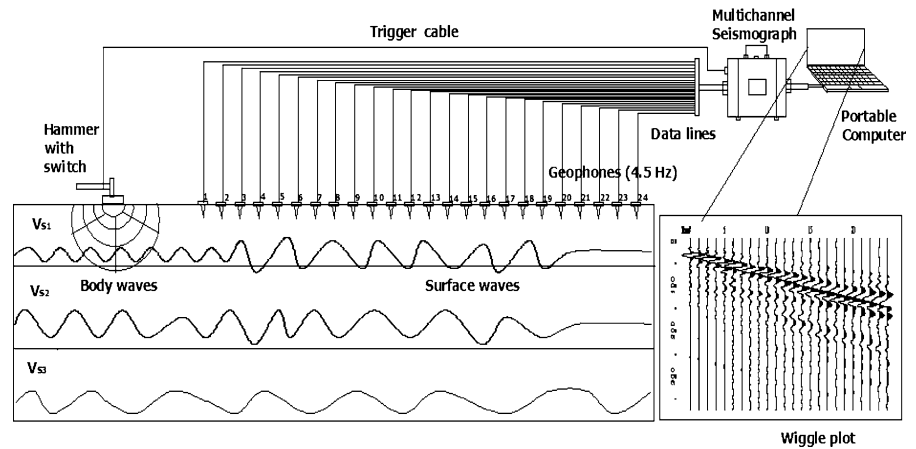
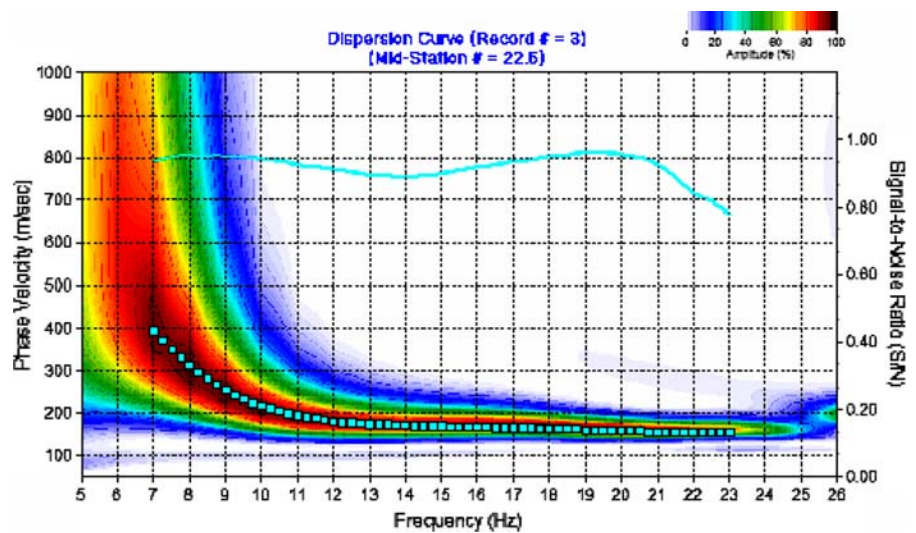


Fig. 5 Typical dispersion curve with signal to noise (S/N) ratio



relatively dense sand layers having V_s of 150 m/s. It is evident from the above inferences that the MASW test is capable of detecting the soft clay pockets with low shear wave velocity underneath stiff and/or dense soil.

5 Field vs. Laboratory Tests Measurements

5.1 Bender Element Test

The measurement of shear wave velocity in soil samples in the laboratory is commonly carried out using resonant column apparatus. Nowadays, a bender element test originally proposed by Shirley and Hampton (1977) is also used to measure the shear

wave velocity in the laboratory. Dyvik and Madhus (1985) showed the agreement between maximum shear modulus (G_{max}) with bender element and resonant column tests. The piezoelectric bender element test is relatively simple non-destructive test for the measurement of shear wave velocity and subsequent determination of maximum shear modulus.

5.2 Test Set-up and Procedure

The bender element test setup of Wykeham Farrance, UK make was used in the present study. The bender elements are fixed in a servo controlled cyclic triaxial system. The function generator generates a signal with specified amplitude and frequency as input signal and PC based oscilloscope records data from

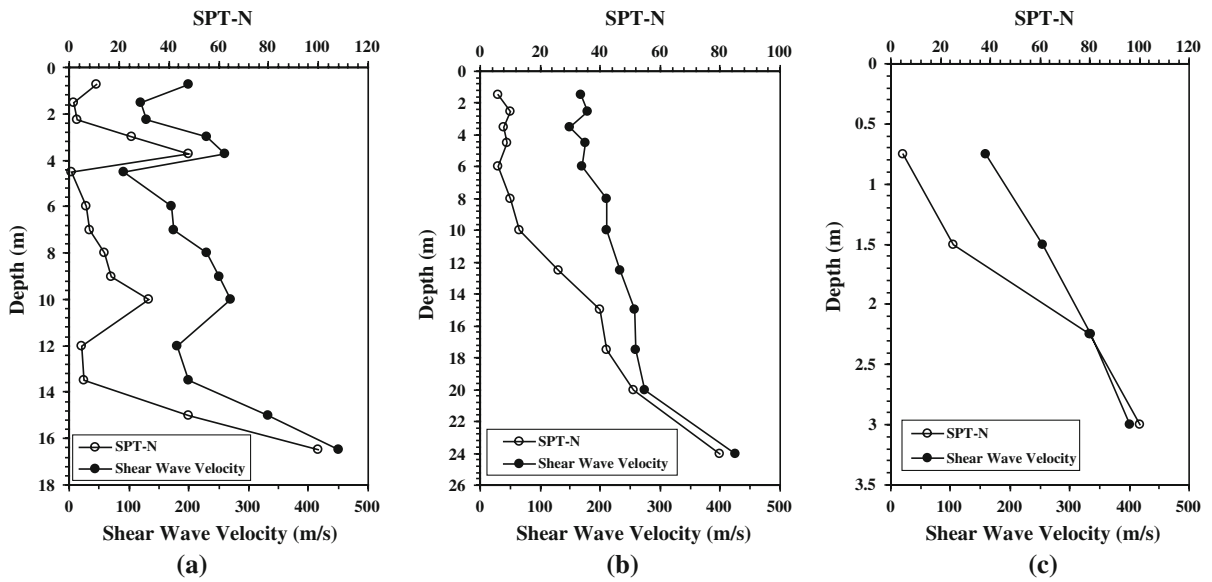
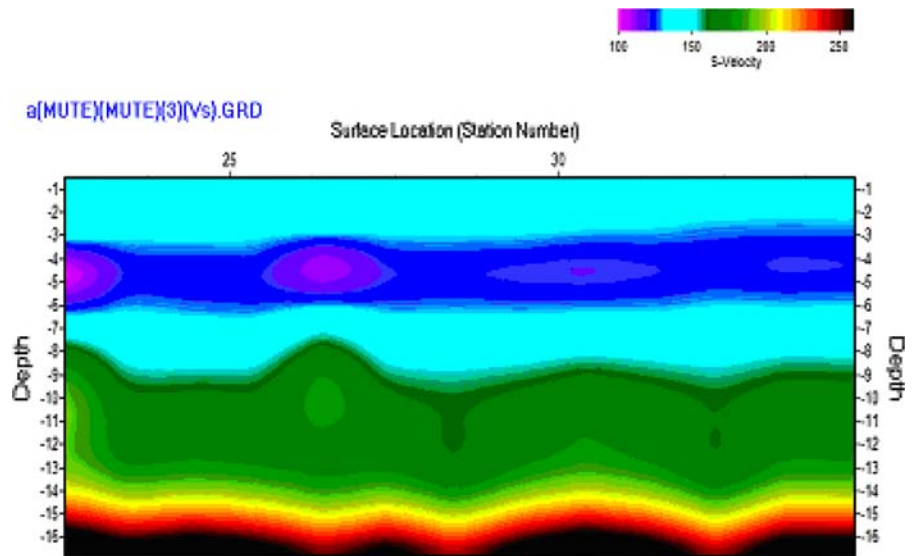


Fig. 6 Variation of v_s and SPT-N with depth at **a** Kottivakkam; **b** Koyembedu; **c** Velachery

Fig. 7 Typical 2D shear wave velocity profile (Egmore)



the transmitter and receiver bender elements. The PC based oscilloscope is controlled through software that allows the user to quickly and easily calculate the shear wave velocity. The typical test configuration of the bender element test is shown in Fig. 8.

The bender element tests are carried out on the undisturbed clay samples collected from the two sites, where the MASW test was carried out. The index properties of the collected undisturbed clay

specimens used in the present study are summarized in Table 1. The undisturbed specimens are trimmed to the required size of $50 \times 100 \text{ mm}^2$ with minimum sample disturbance to maintain the density and initial water content. The specimen is mounted using the membrane stretcher. After assembling and filling the triaxial chamber with water, back pressure is applied in the specimen in steps and the degree of saturation is evaluated at appropriate intervals by measuring

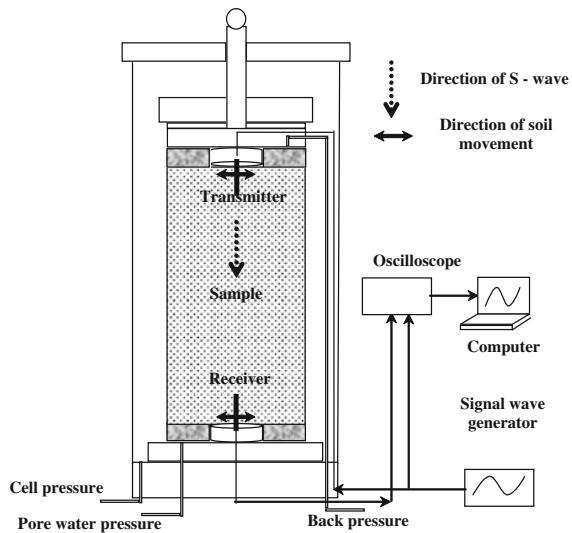


Fig. 8 Bender element test configuration

Skempton's porewater pressure parameter (B) and a value of more than 0.95 is ensured. Then the saturated soil sample was isotropically consolidated to the required in situ effective confining stress. The soft and stiff clay specimens collected from Tondiarpet and Siruseri sites at a depth of 10 and 2.25 m were consolidated under an effective consolidation stress of 120 and 34 kPa, respectively which correspond to in situ stress. The consolidated height and volume of the sample were noted by using the data acquisition system incorporated within the cyclic triaxial apparatus.

After consolidation, wave signal was generated using signal wave generator in the transmitter bender element. The simplest way to obtain a bender element trace that may be interpreted objectively is to use a sinusoidal wave rather than a more usual square wave. For better interpretation of arrival time a sine wave pulse was adopted in this study as proposed by Viggiani and Atkinson (1995). Brignoli et al. (1996) suggested a frequency range of 3 to 10 kHz for shear wave measurements on clay specimen for most

interpretable wave forms. In this study, a sine wave form with 4 kHz frequency and input voltage amplitude of $20 V_{pp}$ (peak to peak voltage) was used. The quality of the receiver signal is improved by applying the following performance criteria: the signal to noise ratio of the receiver signal is at least 4 db and the wave path length to wavelength ratio (L_{tt}/λ) is at least 3.33.

5.3 Comparison of V_s from MASW and Bender Element Tests

The arrival of first shear wave was identified based on the period between the initial/peak/trough point of the input sine wave and the corresponding output wave as shown in Fig. 9. The typical shear wave velocity profiles obtained from the MASW tests conducted at the same sites are shown in Fig. 10. The measured shear wave velocity obtained from the bender element and MASW tests are presented in Table 2. It is noted that the shear wave velocity obtained from the bender element test is 20 and 14% lower than that obtained from the MASW test for the soft and stiff clays respectively. The lower value of shear wave velocity from bender element tests is attributed to the disturbance in the sampling process and boundary conditions involved in the bender element testing procedure (Marcuson and Curro 1981).

6 Development of Empirical Correlations for V_s -SPT (N)

It is preferable to determine shear wave velocity directly from field tests, but it is often not economically feasible to make V_s measurements at all locations. Many correlations between V_s and penetration resistance have been proposed for different soils and it is listed in Table 3. But, the majority is based on uncorrected SPT-N value. Sykora and Stokoe (1983) suggested that the geological age and

Table 1 The index properties of test materials

Location	Depth (m)	Soil description (soil classification)	G_s	Unit weight (kN/m^3)	NMC (%)	Atterberg limits (%)		
						LL	PL	PI
Tondiarpet	10.00	Soft clay (CH)	2.7	20	60	77	28	49
Siruseri	2.25	Stiff clay (CH)	2.7	21	34	85	26	59

Fig. 9 Typical receiver signals obtained from bender element test

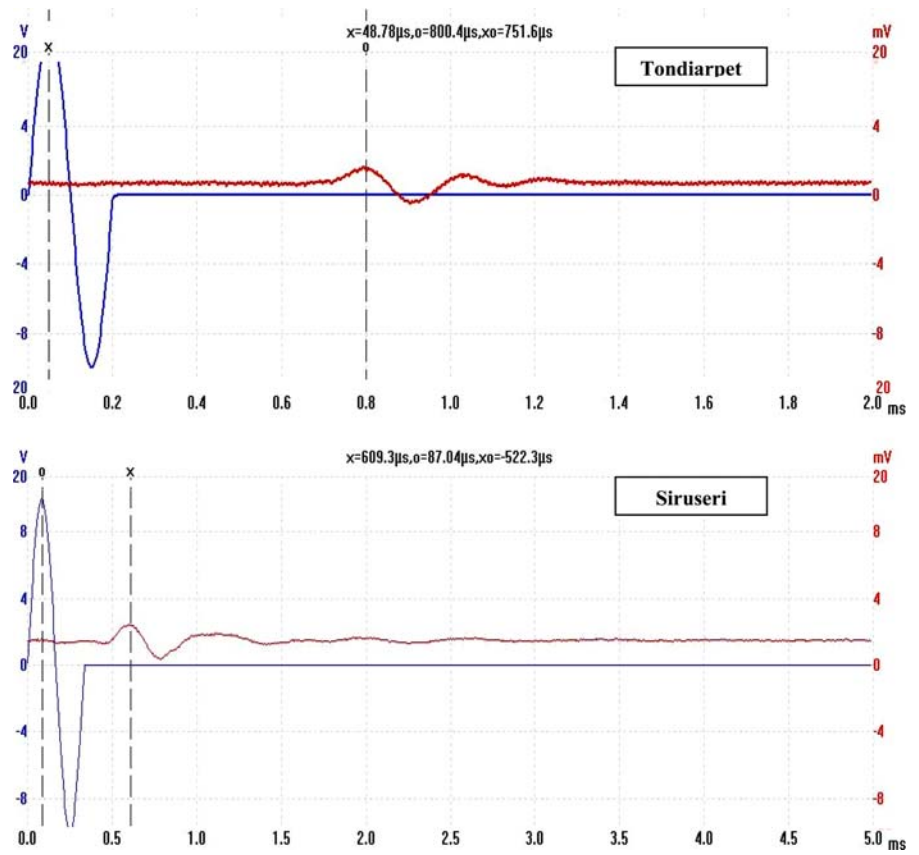


Fig. 10 Typical shear wave velocity profile obtained from MASW tests

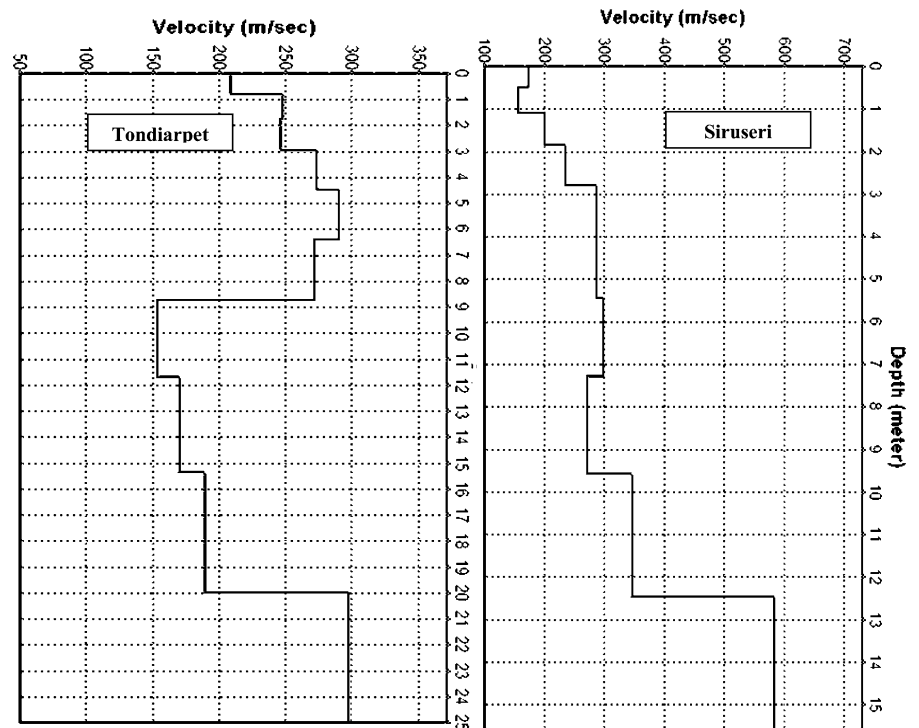


Table 2 Shear wave velocity from MASW and bender element tests

Test location	Soil description	V_s (m/s)	
		MASW	Bender element
Tondiarpet	Soft clay (CH)	150	120
Siruseri	Stiff clay (CH)	220	190

soil type are not important parameters in determining V_s , while the SPT-N value is of prime importance.

6.1 Proposed Empirical Correlations Between V_s and SPT-N

In this study, 200 data pairs (V_s and SPT-N) were employed in the development of correlations between V_s and SPT-N. The correlations were developed using a simple regression analysis for the existing database.

In this analysis, new relationships were proposed between V_s (m/s) and corresponding uncorrected SPT-N values for three categories of soil, i.e. for all soils, sand and clay (Fig. 11). The following relationships with their correlation coefficients (r) are proposed between V_s (m/s) and SPT-N values for the three different soil categories.

$$\text{For All Soils : } V_s = 95.64N^{0.301}; (r^2 = 0.84) \quad (1)$$

$$\text{For Sand : } V_s = 100.53N^{0.265}; (r^2 = 0.84) \quad (2)$$

$$\text{For Clay : } V_s = 89.31N^{0.358}; (r^2 = 0.93) \quad (3)$$

Comparisons between the measured V_s and predicted V_s from Eqs. 1–3 are presented in Fig. 12. The plotted data are scattered between the lines with 1:0.5 and 1:2 slopes with $V_s < 250$ m/s falling close to the line 1:1 confirming that the regression equations generally show a reasonable fit of the compiled data for the investigated soils. The correlations from the

Table 3 Some existing correlations between V_s and SPT-N

Author (s)	V_s (m/s)		
	All soils	Sand	Clay
Kanai (1966)	$19N^{0.6}$	–	–
Ohba and Toriumi (1970)	$84N^{0.31}$	–	–
Shibata (1970)	–	$32N^{0.5}$	–
Imai and Yoshimura (1970)	$76N^{0.33}$	–	–
Fujiwara (1972)	$92.1N^{0.337}$	–	–
Ohta et al. (1972)	–	$87N^{0.36}$	–
Ohsaki and Iwasaki (1973)	$82N^{0.39}$	–	–
Imai and Yoshimura (1975)	$92N^{0.329}$	–	–
Imai (1977)	$91N^{0.337}$	$80.6N^{0.331}$	$80.2N^{0.292}$
Ohta and Goto (1978)	$85.35N^{0.348}$	$88N^{0.34}$	–
JRA (1980)	–	$80N^{0.33}$	$100N^{0.33}$
Seed and Idriss (1981)	$61N^{0.5}$	–	–
Imai and Tonouchi (1982)	$97N^{0.314}$	–	–
Sykora and Stokoe (1983)	–	$100.5N^{0.29}$	–
Jinan (1987)	$116.1(N + 0.3185)^{0.202}$	–	–
Lee (1990)	–	$57.4N^{0.49}$	$114.43N^{0.31}$
Sisman (1995)	$32.8N^{0.51}$	–	–
Iyisan (1996)	$51.5N^{0.516}$	–	–
Jafari et al. (1997)	$22N^{0.85}$	–	–
Pitilakis et al. (1999)	–	$145N_{60}^{0.178}$	$132N_{60}^{0.271}$
Kiku et al. (2001)	$68.3N^{0.292}$	–	–
Jafari et al. (2002)	–	–	$27N^{0.73}$
Hasancebi and Ulusay (2007)	$90N^{0.308}$	$90.82N^{0.319}$	$97.89N^{0.269}$
Hasancebi and Ulusay (2007)	$104.79N_{60}^{0.26}$	$131N_{60}^{0.205}$	$107.63N_{60}^{0.237}$

N uncorrected SPT-N, N_{60} energy corrected SPT-N

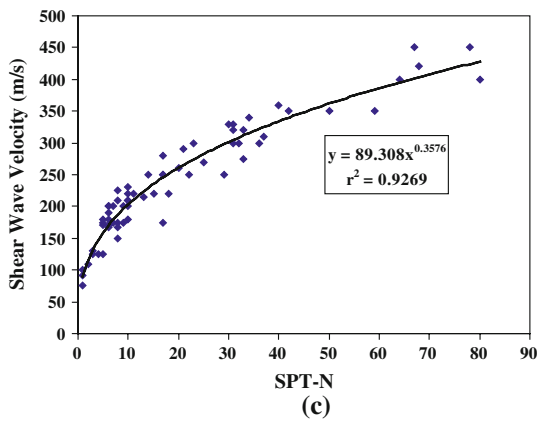
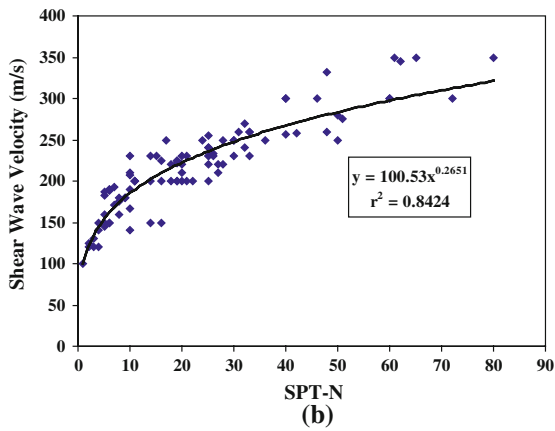
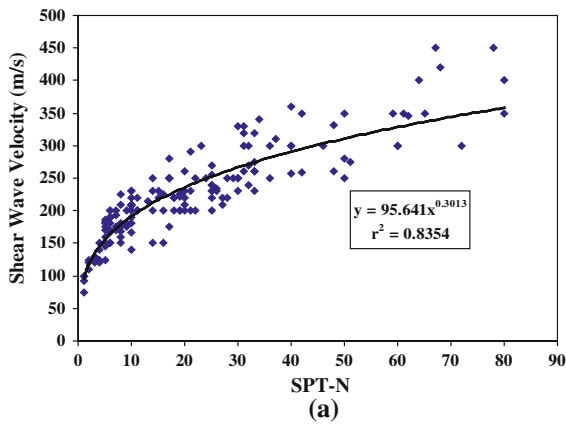


Fig. 11 Correlations between V_s and SPT-N for **a** all soils; **b** sand; **c** clay

present study are plotted in Fig. 13 to assess the effect of soil type. Figure 13 indicates that the soil type has a little effect on these correlations below SPT-N value of about 10.

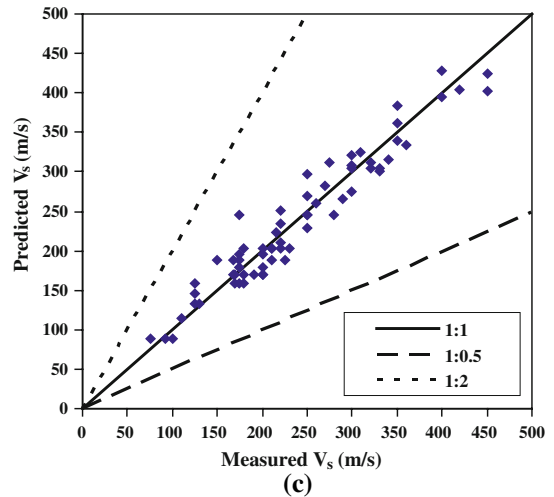
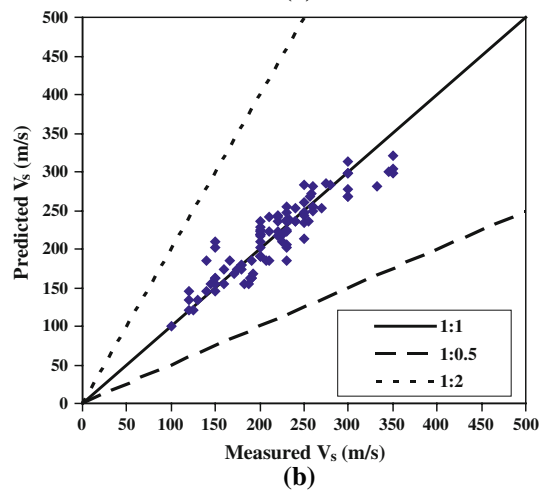
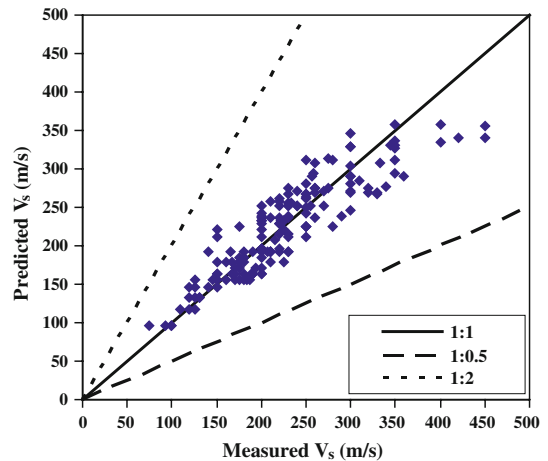


Fig. 12 Measured versus predicted shear wave velocities (uncorrected) for **a** all soils; **b** sand; **c** clay

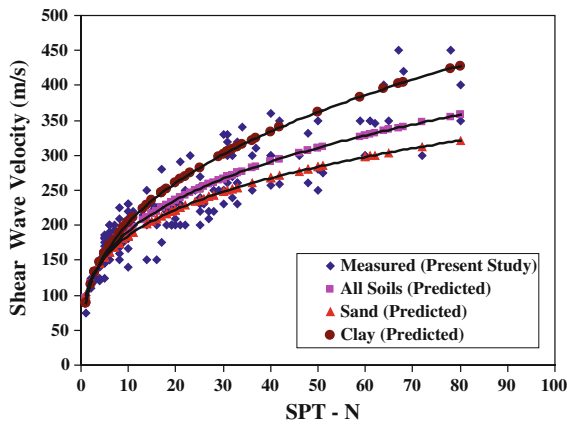


Fig. 13 Effect of soil type on V_s -SPT (N) relationship

6.2 Validation of Model by Graphical Residual Analysis

There are many statistical tools for model validation, but the primary tool for most process modeling applications is graphical residual analysis. Different types of plots of the residuals from a fitted model provide information on the adequacy of different aspects of the model. Numerical methods for model validation, such as the R^2 statistics are also useful, but usually to a lesser degree than graphical methods. Graphical methods readily illustrate a broad range of complex aspects of the relationship between the model and the data. Hence, the adequacy of the regression model is further analyzed by conducting residual analysis. Figure 14 shows the graphical residual plots for all soils, sand and clay. The figure indicates that the residuals are horizontal, uniformly scattered with equal variance from the horizontal axis and random showing good regression model fit to data. Figure 15 shows the probability residual plots for all soils, sand and clay. The figure indicates that the data points lie on the straight line showing the good regression fit of the model.

6.3 Comparative Study with the Published Correlations

The developed correlations for all three categories of soil: all soils, sand and clay were compared based on 90% confidence interval with the earlier regression equations proposed by various investigators as shown

in Fig. 16a–c, respectively. It can be observed from Fig. 16a that the proposed equations for all soils yield similar V_s values with other regression equations except few. Ohsaki and Iwasaki (1973), Seed and Idriss (1981), Iyisan (1996) and Jafari et al. (1997) give high V_s values and these differences increase with increasing SPT-N value for all soils (Fig. 16a). Kanai (1966), Sisman (1995) and Kiku et al. (2001) give lower V_s values for all soils. All the other correlations given in Table 3 show minor differences and give similar V_s values for all soils. Similar comparisons are made for sand type of soils and depicted in Fig. 16b. The relationships presented by Ohta et al. (1972), Ohta and Goto (1978) and Lee (1990) predict significantly higher V_s values but Shibata (1970) predicts much lower V_s values. Based on the distribution of the plotted data, the equation of Lee (1990) generally under predicts V_s for $SPT-N \leq 15$ and over predicts V_s for $SPT-N > 15$. The comparisons made for clay type of soils as shown in Fig. 16c indicate that Imai (1977) and Hasancebi and Ulusay (2007) give lower V_s values. Jafari et al. (2002) yields lower V_s values for $SPT-N \leq 25$ but over predicts V_s values for $SPT-N > 25$. In general, it is noted that the specific geotechnical conditions of the studied areas, considered by the previous investigators, are probably the main cause of this variation, while the quantity of the processed data, the SPT procedure and the different methods of shear wave velocity measurements employed in previous studies may be the other causes for variations in the V_s values.

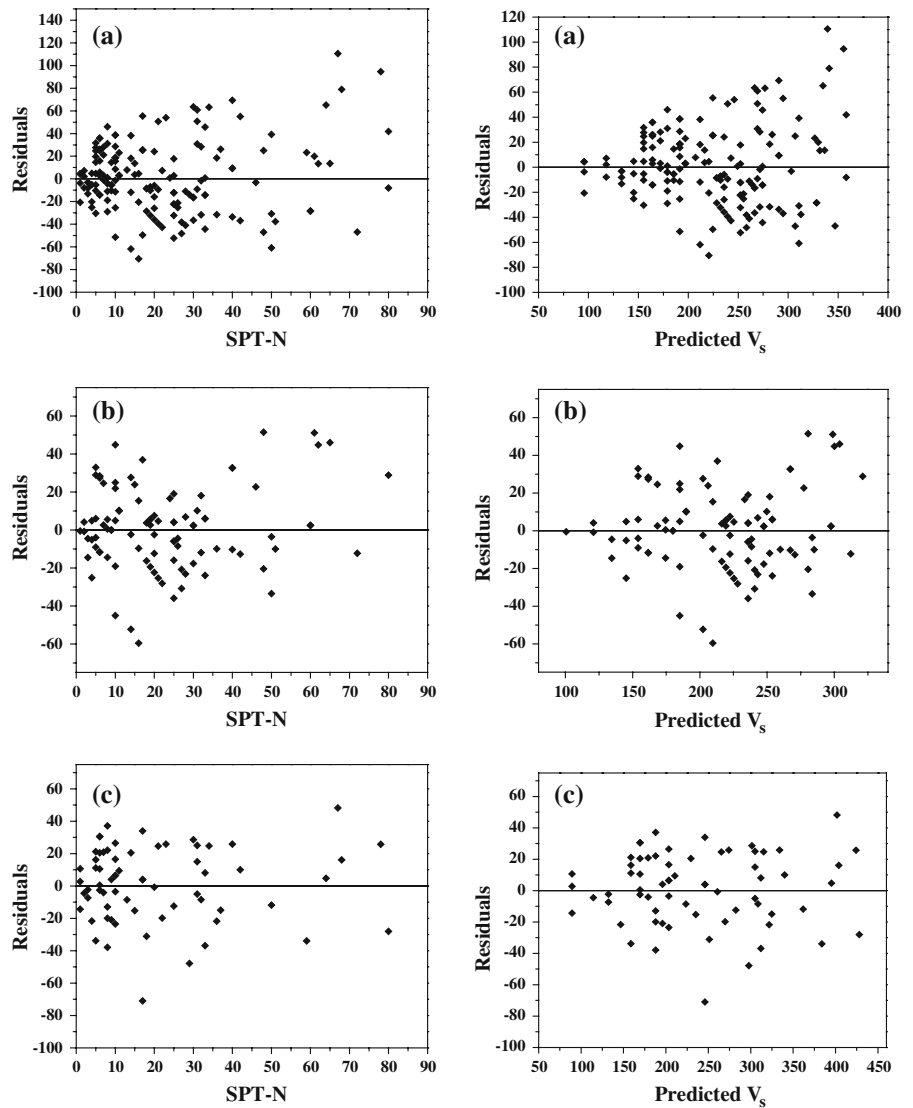
6.4 Scaled Percent Error vs. Cumulative Frequency

In addition to comparison shown in Fig. 16 a–c, in order to compare the performance of the relationships, a graph between the scaled percent error given in Eq-4 and cumulative frequency was drawn (Fig. 17) considering the data employed in this study.

$$\text{Scaled percent error} = \frac{V_{sc} - V_{sm}}{V_{sm}} \times 100 \quad (4)$$

where V_{sc} and V_{sm} are the predicted and measured shear wave velocities, respectively. As depicted in Fig 17a, using relationship (1) for all soils, about 95% of the V_s values were predicted within a $\pm 20\%$ error margin. Using equation (2), 90% of the V_s

Fig. 14 Residual plots for **a** all soils; **b** sand; **c** clay



values were predicted within $\pm 20\%$ error found for sand soil (Fig. 17b). For clay type soils, 90% of the V_s values were predicted within $\pm 20\%$ error (Fig. 17c). These results show that the proposed relationships for all soils, sand and clay type soils give better estimation than those from previous existing correlations.

7 Development of Empirical Correlations for V_s - N_{60}

The relationship between V_s and energy corrected SPT-N (N_{60}) was also investigated and equations for

all soils, sand and clay were established. The SPT blow counts were corrected for striking energy during the test employed in this study (donut-type hammer raised and dropped by two turns of rope). The developed relationships for different soils are given in Fig. 18a–c, respectively. The following relationships with their correlation coefficients (r) are proposed between V_s (m/s) and N_{60} values for the three different soil categories.

For All Soils: $V_s = 90.75N_{60}^{0.304}; (r^2 = 0.83)$ (5)

For Sand : $V_s = 96.29N_{60}^{0.266}; (r^2 = 0.83)$ (6)

For Clay : $V_s = 83.27N_{60}^{0.365}; (r^2 = 0.92)$ (7)

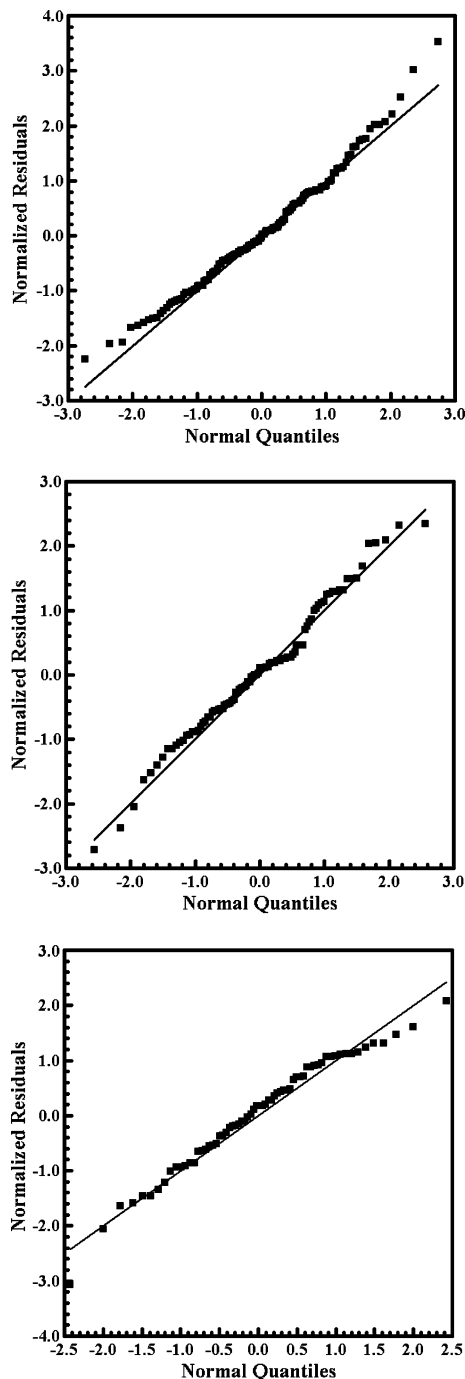


Fig. 15 Probability plots for **a** all soils; **b** sand; **c** clay

The measured versus predicted shear wave velocity is shown in Fig. 19. A graphical comparison between the proposed equations based on N_{60} data and the regression equations of Pitolakis et al. (1999)

and Hasancebi and Ulusay (2007) for clay and sand is given in Fig. 20 a, b respectively. It is seen that the proposed equations based on N_{60} data compare well with the regression equation of Pitolakis et al. (1999) for clay and Hasancebi and Ulusay (2007) for sand. However, the equation of Hasancebi and Ulusay (2007) yields higher V_s for clay whereas Pitolakis et al. (1999) yields lower V_s for sand when compared to those from the equation developed in the present study based on 90% confidence interval.

In addition to the above, the developed correlations are validated by comparing the statistical parameters of the uncorrected and energy corrected SPT-N are tabulated in Table 4. The statistical assessment results show minor variations in the correlation coefficient and standard error obtained for the uncorrected and energy corrected SPT-N relationships, which indicates that both the uncorrected and energy corrected correlations can predict shear wave velocity with equal accuracy.

8 Conclusions

Extensive measurement of shear wave velocity employing sophisticated MASW technique was carried out for Chennai city. Laboratory based bender element test is also utilized to obtain the shear wave velocity for typical clay soils of the study area.

It is found that the shear wave velocity from the bender element test is 20 and 14% lower than that obtained from the MASW test for soft and stiff clays respectively.

The correlations between shear wave velocity and standard penetration test blow counts with and without energy corrections were developed for three categories of soil: all soils, sand and clay. It is found that the soil type has a little effect on these correlations below SPT-N value of about 10. The proposed correlations were compared with the regression equations proposed by various other investigators. About 90 to 95% of the V_s values predicted from the developed uncorrected SPT-N correlations for all soils, sand and clay are within $\pm 20\%$ of the scaled percent error, indicating a better estimate than those from the existing equations.

In case of energy corrected SPT-N correlations using N_{60} data compare well with the regression equation of Pitolakis et al. (1999) for clay and

Fig. 16 Comparisons between proposed and previous V_s and SPT-N correlations for **a** all soils; **b** sand; **c** clay

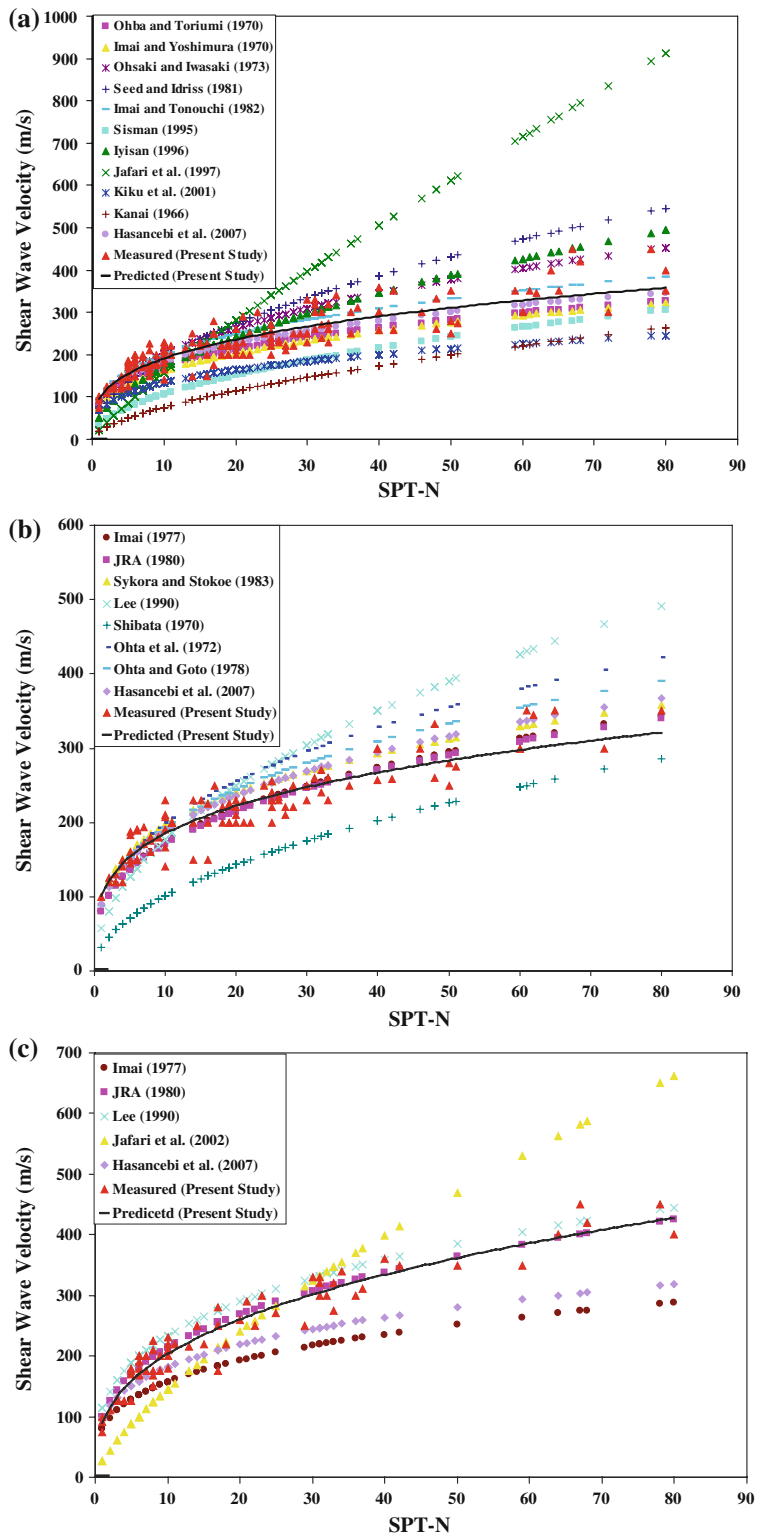
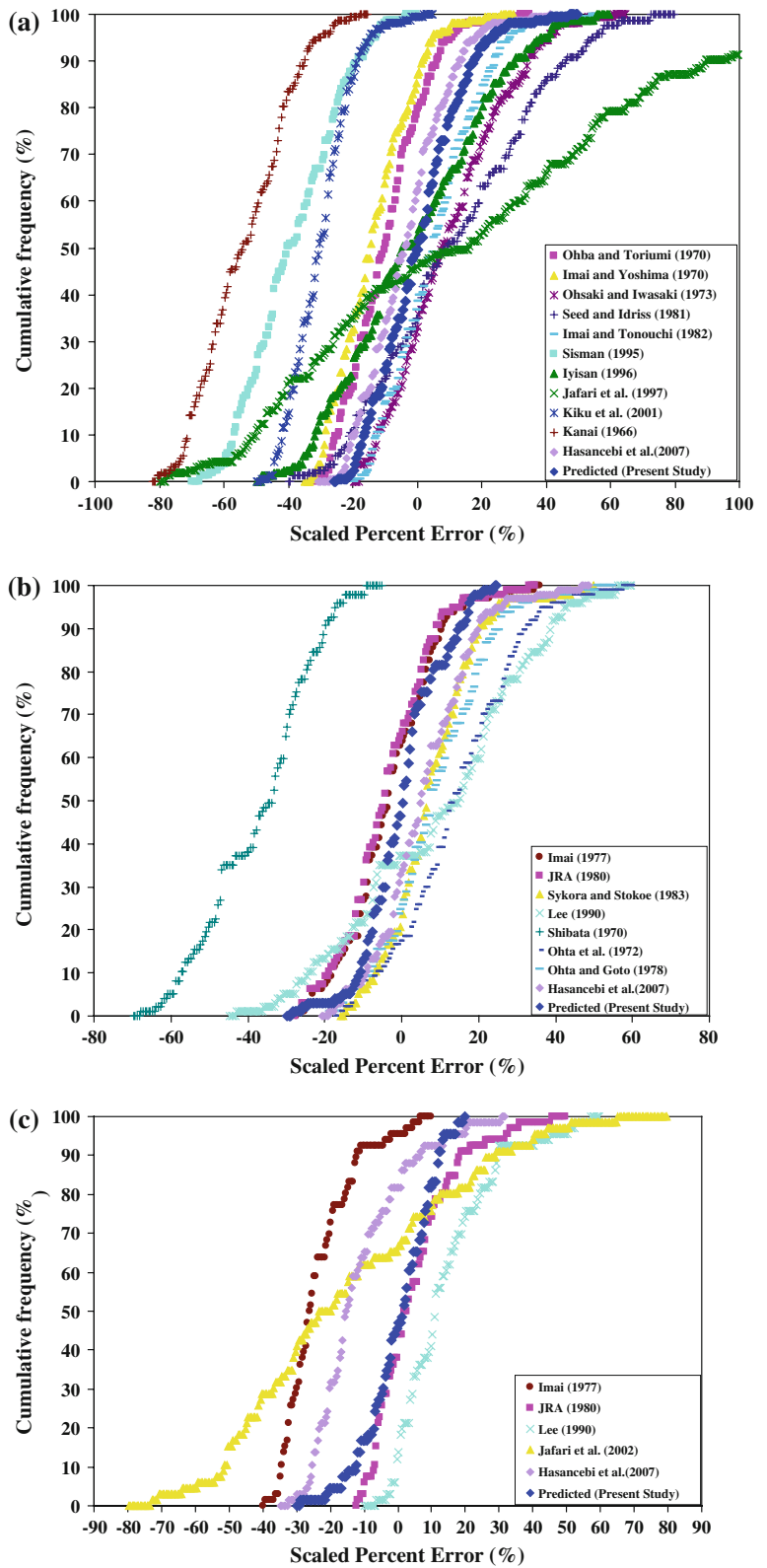
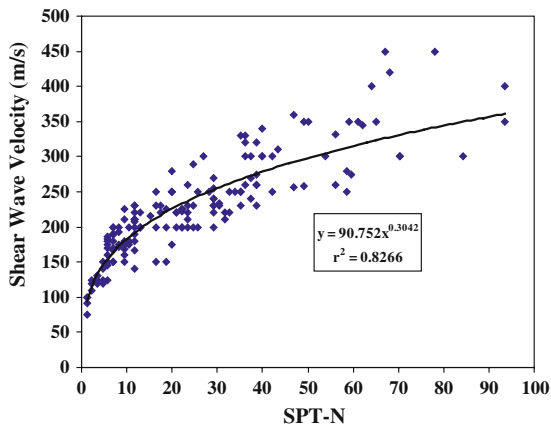
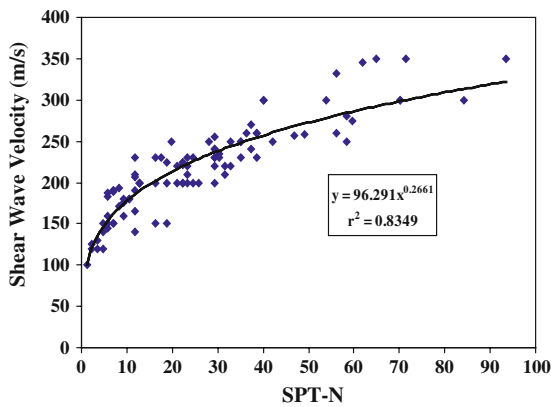


Fig. 17 Scaled percent error of V_s predicted for **a** all soils; **b** sand; **c** clay

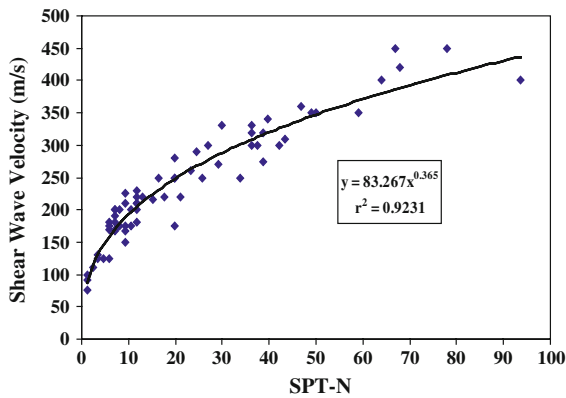




(a)



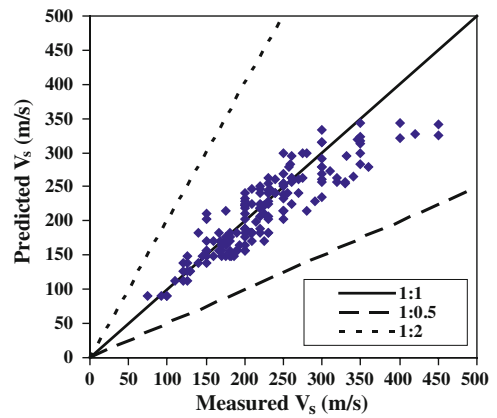
(b)



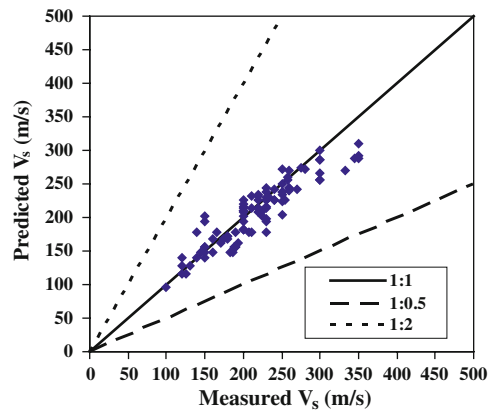
(c)

Fig. 18 V_s — N_{60} relationships for **a** all soils; **b** sand; **c** clay

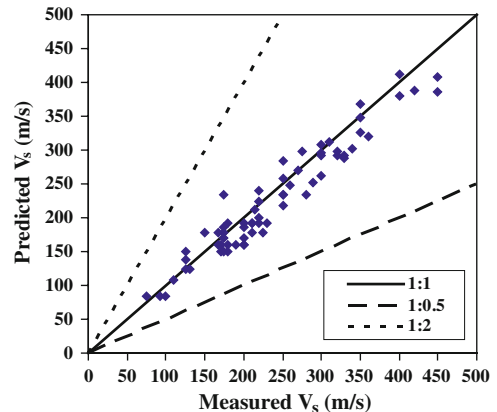
Hasancebi and Ulusay (2007) for sand. It is found that the proposed uncorrected and energy corrected SPT-N relationships show a slight variation in the statistical analysis which indicates that both the



(a)



(b)



(c)

Fig. 19 Measured versus predicted shear wave velocities (energy corrected) for **a** all soils; **b** sand; **c** clay

uncorrected and energy corrected correlations can predict shear wave velocity with equal accuracy.

It is noted that the regression equations developed provide a viable way of estimating V_s from

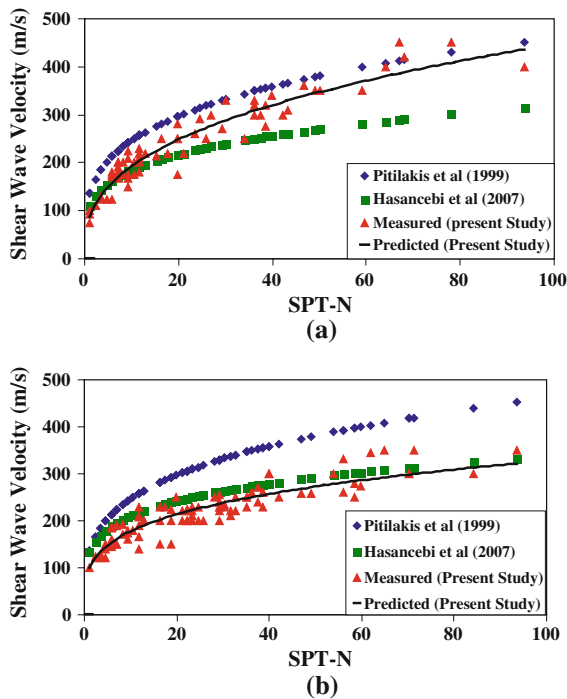


Fig. 20 Comparison between proposed and previous V_s and N_{60} correlations for **a** clay; **b** sand

Table 4 Comparison of statistical parameters for the developed correlations

	Uncorrected SPT-N			Energy corrected SPT-N		
	All soils	Sand	Clay	All soils	Sand	Clay
Regression coefficient	0.84	0.84	0.93	0.83	0.83	0.92
Standard error	31.20	21.86	23.15	32.73	22.81	24.72
Variance	80.55	84.13	93.16	78.58	82.72	92.20

SPT blow counts for preliminary regional ground shaking hazard mapping and site specific ground response analysis. These empirical equations can also be used for the sites where a similar ground conditions exist and if possible they should be checked against measured V_s values. The developed correlations for different types of soil such as all soils, sand and clay can effectively be utilized for the seismic microzonation studies for the east coastal regions of India.

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