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Development of statistical correlations between shear wave velocity and penetration resistance using MASW technique

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ABSTRACT

Prediction of ground shaking response at soil sites requires knowledge of the soil, expressed in terms of shear wave velocity (V_s). 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 values for different categories of soil in Surat city in the state of Gujarat, India, characterized by complex variation of soil condition. The extensive shear wave velocity measurement was carried out using Multichannel analysis of Surface Waves (MASW) technique at sites where SPT-N values are available. The correlations between shear wave velocity and SPT-N were developed for three categories of soil: all soils, sand and clay. The proposed correlations SPT-N were compared with regression equations proposed by various other investigators and found that the developed correlations exhibit good prediction performance. Proposed equation could be used to predict shear wave velocity at similar site condition sites which can use further for Seismic Microzonation and Ground response studies.

1 INTRODUCTION

The local soil plays a crucial role in the amplification of a seismic waves generating from the earthquakes. This fact has been demonstrated by many earthquakes during the past century (Guerrero earthquake (1985) in Mexico City, Spitak earthquake (1988) in Leninakan; Loma Prieta earthquake (1989) in San Francisco, Kobe earthquake (1995) in Japan, Koeaeli earthquake (1999) in Turkey.) Recently the Bhuj earthquake of January 26, 2001, in the state of Gujarat in India, had a magnitude (M_w) of 7.7. The city of Ahmedabad and Surat which are approx. 250 and 350km away from the epicentre, have received considerable damages along with other locations in the state. One of the major causes responsible for such high damages, is a strong possibility that the recently deposited sediments and loose soils could be a factor contributing to the damage pattern in these areas.

The ground motion parameters at the surface are generally obtain by conducting ground response analyses considering only the upward propagating shear waves. In these analyse, the shear wave velocity (V_s) is one of the most important input parameter to represent the stiffness of the soil layers. Surface wave techniques are the simple and efficient tool to measure shear wave velocity in the field as compare to other in situ methods. But it is not often economically feasible to carryout the shear wave velocity measurement in all cases particularly in urban areas due to space constraints. On the other hand Standard Penetration Test (SPT) is the most common in situ geotechnical test which is carried out in most geotechnical investigations. Hence reliable correlations between V_s and penetration resistance would be a

considerable advantage, reducing number of field verification required.

Several researchers have proposed a empirical relations between SPT-N and V_s (Shibata 1970, Ohba and Toriuma 1970, Ohta et al. 1972, Fujiwara, 1972, Ohasaki and Iwasaki, 1973, Imai and Yoshimura, 1975, Cambell and Duke, 1976, Imai, 1977, Ohta and Goto, 1978, Seed and Idriss, 1981, Imai Tonouchi, 1982, Barrow and Stokoe, 1983, Jinan, 1987, Okamoto et al. 1989, Lee 1990, Athanasopoulos, 1995, Kanai, 1966, Jafari et al. 1997, Pitilakis et al. 1999, Kiku et al. 2001, Tamura and Yamazaki, 2002, Hasancebi and Ulusay, 2007, Rao and Ramana, 2008, Dickman, 2009, Maheshwari et al. 2010). In addition some relations are given for specific ranges of shear wave velocities and based on the zones of an area (Rao and Neelima, 2006, Rao and Trivedi, 2011). These empirical relations need thorough process of validation before using them for coastal region of India (Maheshwari et al. 2010).

The present study deals with the development of the empirical correlations between SPT and V_s for the Surat region in the state of Gujarat, India. The shear wave velocity profiles (1D, 2D) are generated by carrying out MASW (Multi channel Analysis of Surface Wave) tests at around 63 locations in area of approx. 600 km². Around 600 Nos. geotechnical borehole data have been collected from the various Govt. / Private agencies. Also around 15 nos. of the confirmatory boreholes have been drilled in the area for verifications of the data. The statistical analyses have been carryout. A series of empirical correlations for prediction of shear wave velocity from SPT-N were developed taking in to account for the type of soil. The developed correlations are compared with the

number of other equations in the literature in order to evaluate prediction performance.

2 GEOLOGICAL AND GEOTECHNICAL CHARACTER OF THE STUDY AREA

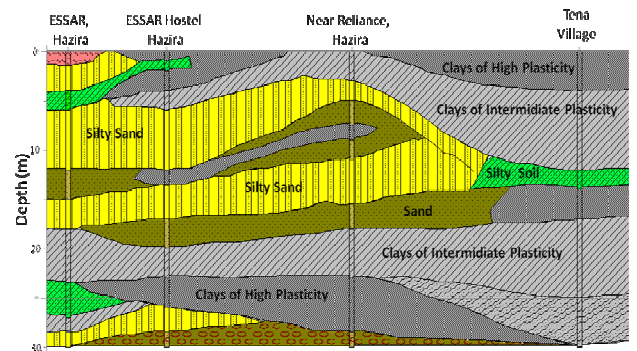
The geological diversity is reflected in the three major physiographic divisions; each is characterised by diverse structure, stratigraphy, and lithology. Each has its own evolutionary history. The geology of Gujarat comprises of a Precambrian basement over which younger rocks commencing with Jurassic, continuing through Cretaceous, Tertiary and Quaternary have given rise to varying sequences. A large part of Gujarat comprises of Deccan trap, with intervening Cretaceous and Tertiary rocks at many places. Stratigraphically the mainland Gujarat is represented by Precambrian crystalline, sedimentary rocks of Cretaceous, Tertiary and Quaternary periods and the Deccan Trap. The Saurashtra peninsula shows a sedimentary sequence as old as Upper Jurassic with extensive areas occupied by the basalts. A good development of both Mesozoic and Tertiary sequence is represented in Kutch.

Surat city is located on the intersection of Cambay and Narmada rift region. The cambay basin depicts a panplained landscape and is drained by the Luni, Banas, Sabarmati, Mahisagar, Narmada and Tapi river. The Luni and the Banas rivers debouch into the Rann of Kutch and the other rivers join the Gulf of Cambay. Babu (1977) carried out extensive geomorphological study of the Cambay basin. According to him, the basin is intracratonic, receiving the sediments from the Kutch, Katiawar plateau on one side and the Aravalli ranges on other. The Aravalli ranges contribute major part of the sedimentation in the Cambay basin. Their strikes swings from NNE-SSW to NE-SW direction (Biswas, 1999) and comprises mainly schists, phyllites and quartzites intruded by basic rocks granites and pegmatite. These crystalline rocks are exposed on the eastern margin of the Cambay basin and to the north of the Luni river. Recent sediments directly overlie these crystalline rocks may found at many places. Conglomerate, sand stone and shales of Himatnagar sandstone formation (Cretaceous) are exposed on the eastern margin. Basalts of Deccan are exposed around eastern margin.

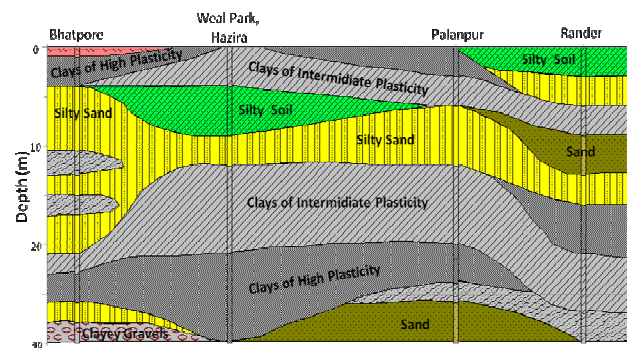
Surat region is bounded by Arabian Sea from the west, lies on the southern end of Cambay basin and Tapi river passes through all across the city and merges in the Sea at south-western side of the region. Most of the region is occupied by natural levees, black cotton soil, brown sandy river alluvium and swamps. As the region is in the flood plain of river Tapi, these deposits are flat and lie adjacent to streams, composed primarily of unconsolidated depositional material derived from sediment transported by the related streams. The Tapi river passes through the Deccan Trap from eastern side of the region. Also tidal currents from the Western side through the Sea also contribute significantly in the marine deposition characteristics of the region.

Geotechnical Investigation has been carried out in this area and total of 600 borehole data have been interpreted up to 30m depth. Various categories of soil deposits have been identified which may be due to sub areal weathering processes. Black cotton soil is a fine variety of argillaceous soil, calcareous, strongly adhesive when wetted found in an area which contains chalcedony/zeolite pieces and is derived from the decomposition of basalts. Brown to blackish yellow sands and sandy clays are derived from the decomposition of granites, schists and other rocks rich in ferromagnesian minerals which are exposed near by. The lateritic soils are derived from the laterites.

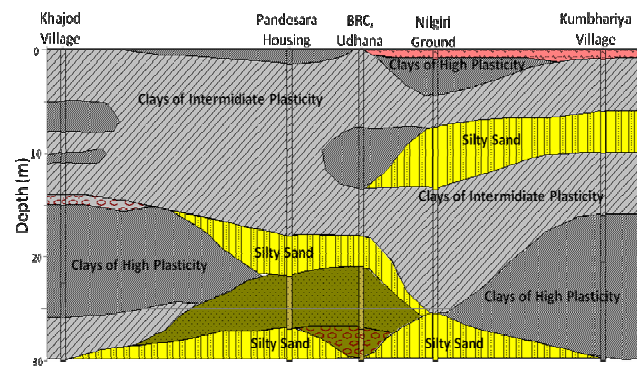
Typical Soil profiles of an area as shown in the Figure 1.



(a) South Western to North Western Section



(b) Western Central to North Section



(c) Southern to Eastern Section

Figure 1 Geotechnical Sections in the Various Part of Study Area (Surat City)

3 GEOPHYSICAL INVESTIGATIONS

A number of geophysical methods have been proposed for near-surface characterization. Bore hole logging is generally considered the standard for obtaining Vs data. In these methods, the determination of Vs is carried out in boreholes, using downhole and crosshole techniques. Such measurements are not cost effective because several boreholes need to be drilled, and this tends to cause difficulty in urban areas. This in part, has led to the development of numerous surface acquisition techniques to obtain shallow shear wave velocity.

In early stage of surface wave analysis, The SASW (Spectral Analysis of Surface Wave) method was widely used for shallow shear wave velocity characterization by Nazarian et al. (1983), Al-Hunaidi (1992), Stokoe et al. (1994), Tokimatsu (1995), and Ganji et al. (1997), in which only one pair of receiver was used for different spacing. The travel time between the receivers was calculated from phase differences (Nazarian and Stokoe, 1984). This method was widely used in geotechnical projects but it is very sensitive to noise and the coupling of receivers. During the dispersion curve estimation the unwrapping of the cross power spectrum phase is a critical step. The interference of different wave types may easily lead to misinterpretation of phase velocities. In addition, repeated measurements are needed in the field (Kanli et al., 2006). Most of these disadvantages are overcome by MASW (Multichannel Analysis of Surface Wave) method (Park et al., 1999). The field work is much easier and the measurement time is strongly reduced. Over all, MASW method is environment friendly, non-invasive, low cost, rapid and robust and moreover it consistently provides reliable shear wave velocity profiles within the first 30 m below the surface (Xia et al., 2002).

This paper presents the mapping of average shear wave velocity through the assessment of shear wave velocity profiles for 63 locations in Surat region in the state of Gujarat, India. These results will be further used for developing the statistical correlations between shear wave velocity and Standard penetration test values. These correlations can be further used for generating shear wave velocity profiles from SPT 'N' may serves as fundamental input for seismic hazard analysis and microzonation studies under taken for Surat city and surrounding region.

3.1 Field Testing Program

A detailed Site Characterization of Surat region is carried out by conducting the Multi Channel Analysis of Surface Wave (MASW) tests at 63 locations in a tentative grid of 3km x 3 km in an area of around 600km². The locations of MASW tests conducted is shown in Figure 2. The latitude and longitude of the test locations have been measured using GPS system. In this study, the 48 channel engineering seismograph McSEIS-SX 48 (Model-1126C) from OYO Corporation, Japan is used for acquiring wave form data. The MASW tests were carried out in region by spreading multiple geophones for estimating one and two dimensional shear wave velocity

profiles. It is very important to decide the source receiver configuration which include number of receivers, receiver spacing, source increment and total survey length. In this survey 24 geophones are used with a spacing of 3m between them. The offset distances i.e., distance between the source and the nearest geophone is fixed to 1.5m and the source is shifted with 3m intervals. These parameters are fixed after conducting several trial tests with four different configurations like 12 geophones with 3m spacing, 12 geophones with 6m spacing, 24 geophones with 3m spacing and 48 geophones with 3m spacing.

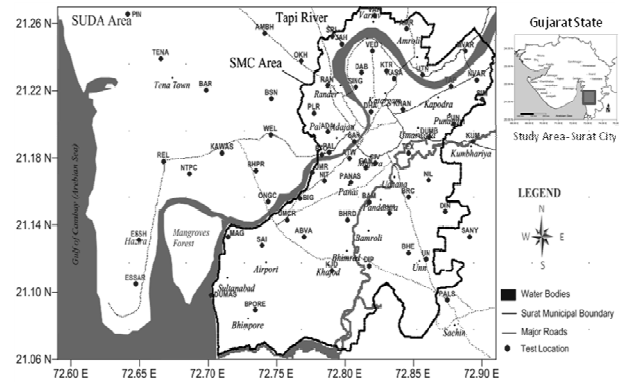


Figure 2 Study Area and Test Locations

The optimum acquisition parameters in the MASW technique are those that can produce the most accurate dispersion curve during the data processing. From only theoretical perspective of the dispersion curve analysis in the MASW method, it was concluded that a higher number of channels can always result in the higher resolution dispersion curve only if it is associated with the longer receiver spread length. There is no use in increasing the number of geophones without increasing the spread length. Another important parameter is the source increment which depends on the degree of horizontal variation in Vs along the entire survey line. A small increment would be necessary if a high degree of horizontal variation is expected. The entire procedure in MASW testing usually consists of three steps i.e., acquiring multichannel records (or shot gathers), extracting the fundamental mode dispersion curves and inverting these curves to obtain one-dimensional Vs profiles. Detailed testing procedure and analysis process of the test is explained in the following sections.

3.2 Data Acquisition

In this study, 24 geophones of 4.5 Hz natural frequency are laid out in a linear array with 3m spacing and are connected to seismograph. This made total survey length of 72m. Seismic energy is generated using a sledge hammer of 11kg weight, manually impacted on 165cm² aluminum plate at an offset distance of 1.5m (distance to nearest geophone). The source is shifted every time with 3m interval and total of 25 shots are made at each location. Also trigger geophone is used to initialize the recording. The generated rayleigh wave data are

recorded at all shot points. Data for each shot is digitally recorded and save in the equipment. Figure 3 shows the typical test program of field testing along with engineering seismograph and wiggle plot with 2D shear wave velocity profile. The acquired data from engineering seismograph is then transferred for the analysis using SeisImager-SW software. Table 1 gives the recording parameters for MASW testing during the acquisition

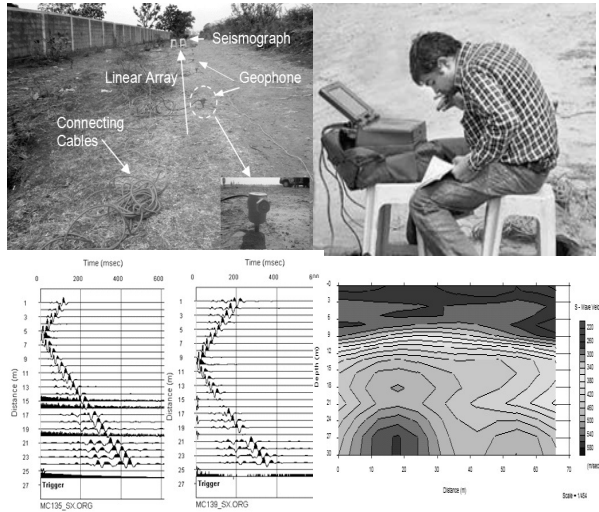


Figure 3 Typical Testing Program of MASW; (a) Typical Field Set up (b) Engineering Seismograph (c) Wiggle Plot (d) Typical 2D Shear Wave Velocity Profile

TABLE 1 Data Acquisition Parameters

Recording System:	McSEIS-SX 48
Sampling Interval:	500 ms
Memory:	4kb
Recording Format:	SEG-2
Pre Trigger:	ON
Stack Mode:	Average
Geophones:	24 Nos. of 4.5 Hz frequency
Geophones Array:	Linear with 3m spacing
Source:	11 kg sledge hammer
Source Array:	3m interval
Offset Distance:	1.5m

3.3 Data Analysis

Acquired surface wave seismic data has been transferred to the computer and processed using SeisImager SW software to obtain 1D and 2D shear wave velocity models. This software has three more software namely, PickWin95, WaveEq and Geoplot.

The first step in the analysis is making the file list in which all waveform files and source receiver

configuration are mentioned. The next step is to extract all pairs that have common mid point (CMP) from all traces and to calculate its cross relation CMP gathers. Cross relation CMP gather files are saved as pseudo shot gather files for each CMP locations. Then dispersion curves are generated by converting it into frequency domain for each cross correlation CMP gathers and then checked. Generation of a dispersion curve is one of the most critical steps for generating an accurate shear wave velocity profile. Dispersion curves are generally displayed as phase velocity versus frequency. This relation can be established by calculating the phase velocity from the linear slope of each component of the swept frequency record. The 1D shear wave velocity profiles are calculated using the dispersion curves obtained from waveform data by non linear least square method. Then, by placing each 1D Vs profile at a surface corresponding to the middle of the survey line, 2D Vs map is constructed in Geoplot software. That is, multiple Vs profiles obtained are then used for a 2D interpolation to create the final map.

4 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 shear wave velocity, V_s and Penetration resistance have been proposed for different soils and some of them are listed in Table 2. The majority of such relations are based on uncorrected SPT-N value. Hasancebi and Ulusay (2006), used energy-corrected SPT-N values in correlation estimation. However, their findings show a low correlation coefficient. Maheshwari et al. (2010) found that the uncorrected and energy corrected SPT-N relationships show a slight variation in the statistical analysis which indicates that both the uncorrected and energy corrected correlations can predict shear wave velocity with equal accuracy. Sykora and Stokoe (1983) suggested that the geological age and soil type are not important parameters in determining V_s , while the SPT-N value is of prime importance. Hence in the present study, the uncorrected SPT-N and actual shear wave velocity from the extensive field investigations have been used to propose relationships for three conditions (a) All soil (b) Sandy soil (c) Clayey soil.

In the present study, 602 data pairs (V_s and SPT-N) were used 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 and corresponding uncorrected SPT-N values for three categories of soil, i.e., for all soils, sand and clay. It has been noted that the nearest borehole to the MASW testing location has been used to develop the correlations. The engineering properties of the soil have been evaluated at selected locations. From the collected geotechnical data and evaluated soil properties soil classification have been carried out.

TABLE 2 Existing Correlations between Vs (m/s) and SPT-N

Author(s)	All Soils	Sand	Clays
Kanai (1966)	$V_s=19N^{0.6}$	----	----
Ohba and Toriumi (1970)	$V_s=84N^{0.31}$	----	----
Shibata (1970)	----	$V_s=32N^{0.5}$	----
Imai and Yoshimura (1970)	$V_s=76N^{0.33}$	----	----
Fujiwara (1972)	$V_s=92.1N^{0.337}$	----	----
Ohta et al. (1972)	----	$V_s=87N^{0.36}$	----
Ohsaki and Iwasaki (1973)	$V_s=82N^{0.39}$	----	----
Imai and Yoshimura (1975)	$V_s=92N^{0.329}$	----	----
Imai (1977)	$V_s=91N^{0.337}$	$V_s=80.6N^{0.331}$	$V_s=80.2N^{0.292}$
Ohta and Goto (1978)	$V_s=85.35N^{0.348}$	$V_s=88N^{0.34}$	----
JRA (1980)	----	$V_s=80N^{0.33}$	$V_s=100N^{0.33}$
Seed and Idriss (1981)	$V_s=61N^{0.5}$	----	----
Imai and Tonouchi (1982)	$V_s=97N^{0.314}$	----	----
Sykora and Stokoe (1983)	----	$V_s=100.5N^{0.29}$	----
Jinan (1987)	$V_s=116.1(N+0.3185)^{0.202}$	----	----
Okamoto et al. (1989)	----	$V_s=125N^{0.3}$	----
Lee (1990)	----	$V_s=57.4N^{0.49}$	$V_s=114.43N^{0.31}$
Sisman (1995)	$V_s=32.8N^{0.51}$	----	----
Athanasopoulos (1995)	$V_s=107.6N^{0.36}$	----	$V_s=76.55N^{0.445}$
Ilysan (1996)	$V_s=51.5N^{0.516}$	----	----
Jafari et al. (1997)	$V_s=22N^{0.85}$	----	----
Kiku et al. (2001)	$V_s=68.3N^{0.292}$	----	----
Jafari et al. (2002)	----	----	$V_s=27N^{0.73}$
Hasancebi and Ulusay (2007)	$V_s=90N^{0.308}$	$V_s=90.82N^{0.319}$	$V_s=97.89N^{0.269}$
Maheshwari et al. (2010)	$V_s=95.64N^{0.301}$	$V_s=100.53N^{0.265}$	$V_s=89.30N^{0.358}$

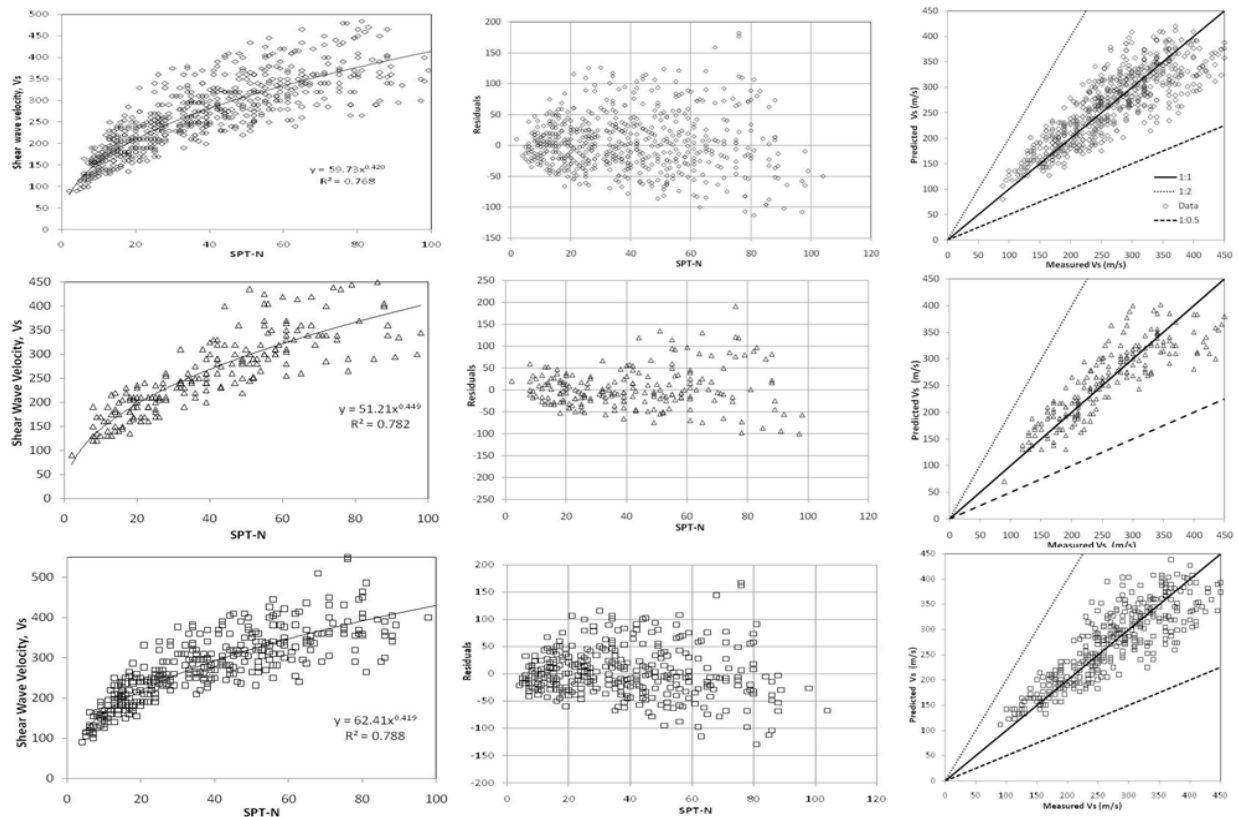


FIGURE 4 Correlations, Residual and Measured vs. Predicted Shear Wave Velocity Plot for (a) All Soils (b) Sandy Soil (c) Clayey Soil

The following relationships with their correlations coefficients (r) are proposed between V_s (m/s) and SPT-N values as shown in Figure 4.

$$\text{For all soils; } V_s = 59.72N^{0.42}, R^2 = 0.77 \quad (1)$$

$$\text{For sandy soil; } V_s = 51.21N^{0.45}, R^2 = 0.78 \quad (2)$$

$$\text{For clayey soil; } V_s = 62.41N^{0.42}, R^2 = 0.78 \quad (3)$$

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 4 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.

The Comparisons between the measured V_s and predicted V_s from Eqn. 1–3 are also presented in Figure 4. The plotted data are scattered between the lines with 1:0.5 and 1:2 slopes. The Majority of the values falling close to the line 1:1, confirming that the regression equations generally show a reasonable fit of the compiled data.

The correlations from the present study are plotted in Fig.5 to assess the effect of soil type. Figure 5 suggests that the correlations for different soil categories yield similar values of V_s indicating that soil type has little effect on these correlations. This is consistent with the findings of Iyisan (1996), Hasancebi and Ulusay (2007) and Maheshwari et al. (2010).

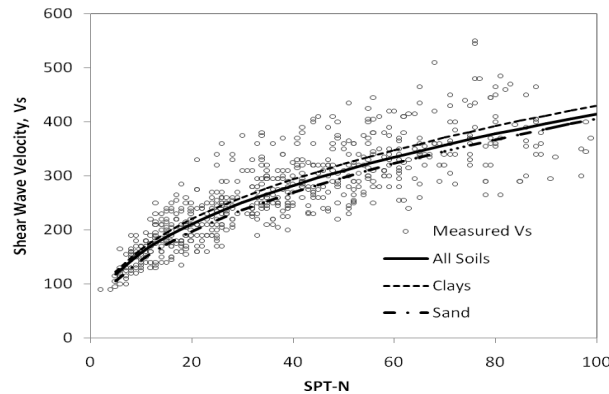


FIGURE 5 Effect of Soil Type on the Correlations

The normalized consistency ratio, C_d , is given as;

$$C_d = (V_{SM} - V_{SC}) / SPT-N \quad (4)$$

Where, V_{SM} is measured V_s from the MASW, V_{SC} is calculated from Eqn. 1-3 and SPT-N is uncorrected SPT blow counts corresponding to V_{SM} . Comparison between V_{SM} and V_{SC} to assess the predictive capability of the equations is shown in Figure 6. C_d value falls close to zero, which means that the proposed correlations have good performance in prediction of V_s except for small SPT-N values ($SPT-N < 15$). The depth of small SPT-N values (< 15) ranges from 1.5m to 22m. Therefore depth may not be considered as effective parameter on correlations, which is consistence with Dickman (2009).

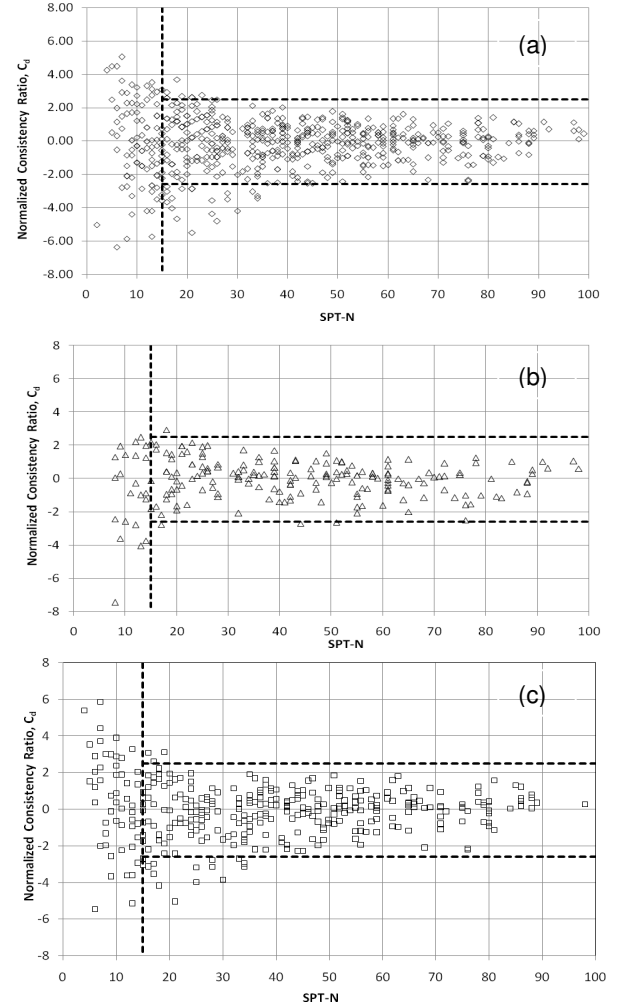


FIGURE 6 Normalized Consistency Ratio for (a) All Soils (b) Sandy Soils (c) Clayey Soils

4.1 Comparative Study with Correlations Published in the Literature

The developed correlations for all three categories of soils were compared with the earlier regression equations proposed by various investigators as shown in Figure 7. It is observed from Fig. 7 that the proposed equations for all soils yield similar V_s values with other regression equations except few. Fujiwara (1972), Ohsaki and Iwasaki (1973), Imai (1977), Seed and Idriss (1981), Ahanas-opoulos (1995), Iyisan (1996), Jafari (1997),

Hanumantha Rao and Ramana (2008) give high V_s values and these differences increases with increasing SPT-N value for all soils. Kanai (1966), Imai and Yoshimura (1970), Ohba and Toriumi (1970), Sisman (1995), Kiku et al. (2001), Dickman (2009) gives lower V_s values for all soils. All other correlations given in the Table 2 have minor differences and give similar values for all soils.

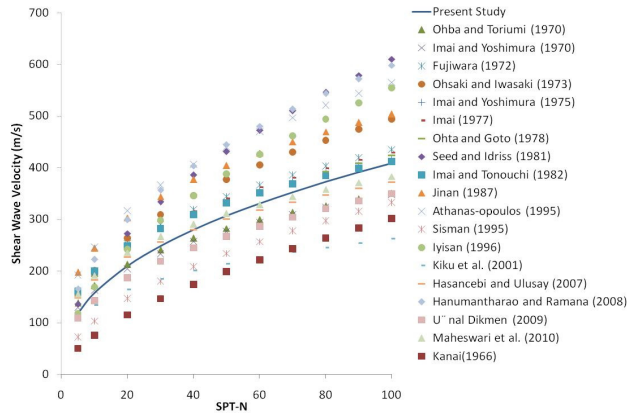


FIGURE 7 Comparisons between Proposed and Previous V_s and SPT-N Correlations for All Soils

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.

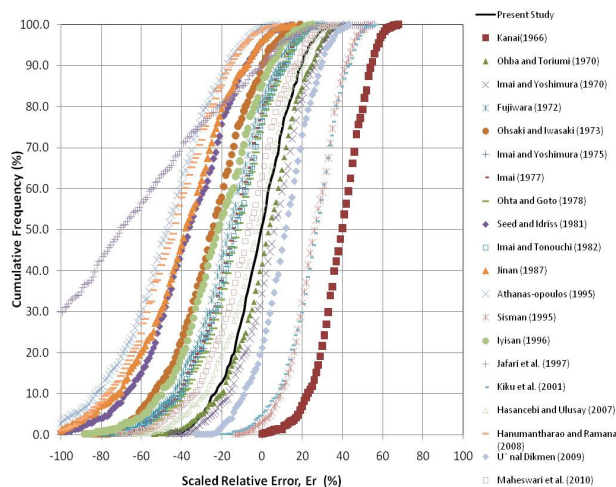


FIGURE 8(a) Relative Error of V_s Predicted for All Soils

4.2 Scaled Percent Error vs. Cumulative Frequency

In addition to the comparison shown in Fig. 7, In order to gain an insight into the capabilities of the proposed correlations, graph between the scaled percent error

given in Eq-4 and cumulative frequency was drawn considering the data employed in this study.

$$\text{Scaled percentage error} = 100 (V_{SC} - V_{SM}) / V_{SM} \quad (5)$$

where V_{SC} and V_{SM} are the predicted and measured, shear wave velocities, respectively. As depicted in Fig. 8 (a) using relationship (1) for all soils, about 80% of the V_s values were predicted within $\pm 20\%$ error margin. Using Eqn. (2), 82% of the V_s values were predicted within $\pm 20\%$ error found for sandy soils (Fig. 8b). For Clayey soils, 85% of the V_s values were predicted within $\pm 20\%$ error (Fig. 8c). These results show that the proposed relationships for all soils, sand and clayey type soils give better estimation than those predicted from previous existing correlations.

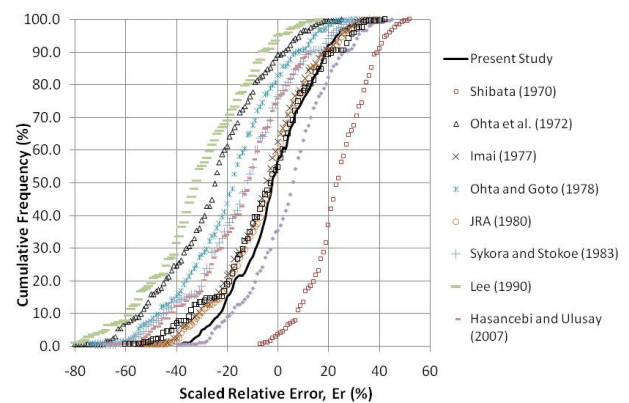


FIGURE 8(b) Relative Error of V_s Predicted for Sandy Soils

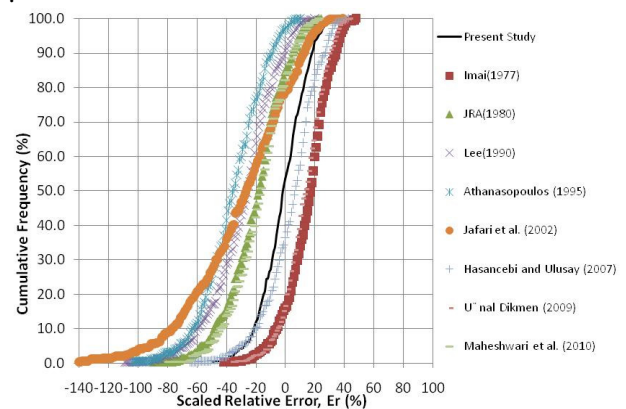


FIGURE 8(c) Relative Error of V_s Predicted for Clayey Soils

5 SUMMARY AND CONCLUSIONS

The extensive field testing work has been carried out by conducting MASW tests at 63 locations in Surat city in the state of Gujarat, India. In a highly populated urban area like Surat, it is not possible to conduct tests at all locations due to space congestion. Hence Geotechnical data have been collected from various Govt. and Private

Agencies. All the data have been put to the common platform and around 25 boreholes up to 30m depth have been excavated and geotechnical properties have been found out compared with the collected data. After critical reviews of the data some of the boreholes nearer to the MASW test locations have been selected to develop correlations between SPT-N and Vs.

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.

The proposed correlations were compared with the regression equations proposed by various other investigators. About 80 to 85% of the Vs 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.

Investigation of previous correlations between SPT-N and Vs showed that previous researchers used soils with different physical properties, for example fine content, water content, pore ratio, unit weight, etc; therefore, different relationships can be expected between existing correlations and those proposed in this study. All the results obtained from this study and previous research reveals that empirical correlations derived from a local dataset should not be used to approximate Vs directly from SPT-N values for different sites. Therefore, these proposed relationships should be used with caution in geotechnical engineering and should be checked against measured Vs.

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