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DEVELOPMENT OF CORRELATIONS BETWEEN SHEAR WAVE VELOCITY AND SPT-N FOR VADODARA REGION, GUJARAT, INDIA

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ABSTRACT

Shear wave velocity (V_s) and standard penetration test number (SPT-N) are important parameters for seismic site characterization. Shear wave velocity profiles have been evaluated in a grid size of 2 km × 2 km using Multichannel Analysis of Surface Waves (MASW) at 67 locations of Vadodara city. Shear wave velocity profiles for study region are developed at different depths to study the local site conditions. SPT-N values have been extracted from geotechnical details through 430 bore hole data which spread over entire region. SPT-N value maps are also generated at 5 m, 10 m, 15 m, and 20 m depths to understand the variation of soil properties with varying depth. The correlations between V_s and SPT-N values (uncorrected and energy corrected) have been developed for different categories of soil (all soil, clay, sand). Various statistical tools such as scaled relative error and cumulative frequency plot have been used to assess the accuracy of obtained correlations. Further, the comparison has also been made for proposed correlations with the existing correlations developed by other researchers. The study reveals that 90% of predicted velocities from uncorrected SPT-N values with proposed relations fall within ±20% error for all soil, clay and sand. It is observed that V_s and uncorrected SPT-N relationships give more accuracy as compare to V_s and energy corrected SPT-N relationships. The correlations will be further useful to develop shear wave velocity profiles for other regions having similar site conditions.

Key words: Shear wave velocity, standard penetration test number, multichannel analysis of surface waves, correlations, subsoil lithology.

1. INTRODUCTION

Local geology plays a significant role in amplification of ground motion which causes higher damages during earthquake. This has been witnessed by many past earthquakes like 1985 Mexico earthquake, 1989 San Francisco earthquake, 1995 Kobe earthquake and 2001 Bhuj earthquake. Shear wave velocity (V_s) of near-surface material is an important parameter for the ground motion amplification. The site conditions can be characterized by estimating shear wave velocity profiles of soil deposits. Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW) are two most prevalently used techniques for determining site characteristics. SASW technique has its own limitation. In SASW technique, dispersion curve is obtained by using two-receiver test configuration. But MASW multi station recoding permits multiple measurements in synchronized and controlled manner so that complicated interplay of seismic waves can be accurately identified and therefore signal-extraction process can become most robust (Penumadu and Park 2005). MASW technique overcomes drawbacks associated with SASW technique. However, it is difficult to conduct this test at locations having space constraints. On the other hand, Standard Penetration Test (SPT) is the most common in situ geotechnical test which is used to investigate various aspects of design parameters for soils. Hence, a reliable correlation between V_s and SPT-N would be advantageous for those locations where tests would not be possible. The correlation will be further useful for detailed seismic site characterization.

Development of empirical relationships between V_s and SPT-N has started way back worldwide for different soil deposits (Kanai 1966; Shibata 1970; Ohba and Toriuma 1970; Ohta *et al.* 1972; Fujiwara 1972; Ohasaki and Iwasaki 1973; Imai and Yoshimura 1975; Imai 1977; Seed and Idriss 1981; Imai and Tonouchi 1982; Jafari *et al.* 1997). Ohta and Goto (1978) have developed fifteen sets of empirical equations for alluvial plains of Japan considering four indexes, *i.e., N*-value, depth, geological age and soil type. Zheng (1987) has generated correlation between V_s and SPT-N for soft soil of Shanghai to investigate the dynamic analysis of foundations. Regression equations were developed for Taipei basin, Taiwan by Lee (1990) and observed that soil type and geological effects were not the best parameters with the SPT-N values. Athanasopoulos (1995) has evaluated the empirical correlations between V_s and SPT-N for Greece soils and found that empirical values of V_s have deviated by − 20% to +30% with the measured values. Dikmen (2009) has generated the empirical relation between V_s and SPT-N for the western central Anatolia region of Turkey. It has been observed that the plasticity contents of cohesive soils and the graded contents of non-cohesive soils except for gravels have no major effects in estimation of V_s (Dikmen 2009). The efforts have been made to develop the correlations between V_s and SPT-N for different categories of soils in India for the cities of Delhi (Hanumantharao and Ramana 2008), Chennai (Maheshwari *et al.* 2010), Surat (Thaker 2012), Lucknow (Anbazhagan *et al.* 2013), Roorkee (Kirar *et al.* 2015), Dholera-Gujarat (Thokchom *et al.* 2017). Many researchers have developed the

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correlation between SPT-N and V_s considering overburden stress (Brandenberg *et al.* 2010; Kwak *et al.* 2015; Kishida and Tsai 2017; Tsai *et al.* 2019). Brandenberg *et al.* (2010) developed the correlations between SPT-N, V_s and overburden stress σ_v' using a dataset of various California bridge sites for sand, silt and clay soil types. The developed correlations between V_s and N_{60} depend on overburden stress σ_v' as V_s and N_{60} normalize differently with overburden stress (Brandenberg *et al.* 2010). Kwak *et al.* (2015) suggested correlations between SPT-N, V_s and vertical effective stress using a dataset from Japan. Kwak *et al.* (2015) recommended that V_s to be more sensitive to overburden pressure than to N for coarse grained soils, whereas V_s is more sensitive to N for fine grained soils. Kishida and Tsai (2017) developed prediction model of SPT-N and V_s based on conditional probability framework. Kishida and Tsai (2016) suggested prediction model of shear wave velocity using SPT blow counts based on conditional probability framework. Tsai *et al.* (2019) developed the unified correlations between SPT-N and V_s and influence of various soil properties such as confining stress, fine content, plasticity index and over consolidation ratio are evaluated through developed correlations. The ratio of coefficients between N and V_s, fine content influences N and V_s most differently, followed by overburden stress, plasticity index and over consolidation ratio (Tsai *et al.* 2019). Some researchers have developed the correlations between V_s and energy corrected SPT-N values (Pitilakis *et al.* 1999; Hasancebi and Ulusay 2007; Maheshwari *et al.* 2010; Thaker 2012). Literature reveals that the correlations have been developed between shear wave velocity and SPT blow count considering various parameters such as overburden stress, plasticity index, fine content, confining stress, over consolidation ratio. The correlation between V_s and SPT-N have been developed for Indian condition and gaining popularity due to the simplicity in the equation. In this present study, an attempt has been made to develop simpler correlation factoring two parameters V_s and SPT-N (uncorrected and energy corrected) for Vadodara region of Gujarat, India and compared with the existing correlations.

In this present study, the correlations between shear wave velocity and standard penetration test number (uncorrected and energy corrected) have been developed for Vadodara region, which is located in the western part of India as shown in Fig. 1. These correlations are developed for three categories of soil, *i.e.,* all soil, clay and sand. The shear wave velocity profiles have been generated through MASW test conducted in a grid size of 2 km × 2 km at 67 locations in and around the city. Total 430 boreholes data have been complied through private and government organizations. SPT-N data set have been extracted from those boreholes data. The accuracy of proposed empirical correlations has been validated through graphical statistical tools. The predicted equations are also compared with the correlations developed by other researchers and found to be in good agreement.

2. GEOLOGICAL & GEOTECHNICAL CHARACTERISTICS OF VADODARA REGION

The geographic extension of the Gujarat state is from 20°02′N to 24°42′N and 68°04′E to 74°30′E covering an area of 1,96,024 sq. km. Gujarat state comprises of geological diversity with Mesozoic and Cenozoic sediments and Precambrian metamorphic soil deposits. Geomorphologically, Gujarat has three distinct parts, *i.e.,*

Fig. 1 Map of Vadodara region with geophysical test locations

Kutch, Saurashtra and Mainland Gujarat. The study region lies in Mainland Gujarat. In Vadodara and Bharuch districts, primarily rocks of Bagh formation are found. In Vadodara, Lameta formation is well exposed. Lameta formation is stratigraphically younger than Bagh formation. This formation occurs mainly below fringes of the Deccan basalts. The Bagh beds have a general ENE-WSW strike which coincides with the major Narmada lineament (Karanth *et al.* 1988). The beds were subsequently covered by flows of basalt. The fracture system can be related to tectonic activities along the Narmada Rift Zone (Murthy and Misra 1981; Das and Patel 1984; Karanth *et al.* 1987). According to soil map generated by Merh and Chamyal (1997), Vadodara soil is of inceptisols type. Inceptisols are generally calcareous in nature and texturally having a sandy-clay loam to clay structure.

Detailed study of the borehole data reveals that variety of soil layers has been observed in Vadodara city. In order to understand the variation of sub-soil layers with depth, maps of soil type at depth of 5 m, 10 m, and 15 m have been prepared and presented in Figs. 2(a) to 2(c). In the northern, central and south-western area of the study region comprises of silty sand at 5 m depth as shown in Fig. 2(a). Silty soil of low to medium plasticity covers eastern, western and southern part of the city at the same depth. Figure 2(b) reveals that the area lies on left side of river comprises of silty soil of low plasticity whereas on right side of river comprises of silty soil of medium plasticity. Figure 2(c) shows the variation of soil type at 15 m depth. Central part of the city comprises of silty soil of low plasticity. Sandy silt and silty soil of low plasticity covers the north and south parts of the city, respectively.

Standard penetration test number (SPT-N) is also an important parameter to determine dynamic soil properties. This parameter helps to understand the sub-surface soil stratum which takes a crucial part in ground motion amplification. SPT-N value maps have been developed at 5 m, 10 m, 15 m and 20 m depths in ArcGIS mapping software as shown in Figs. 3(a) to 3(d). Eastern and western parts of the city are having SPT-N values less than 21 at 5 m depth. In north, south and central parts of the city are having SPT-N values ranging from 21 to 26 and high SPT-N values ranging from 26 to 40 are found at north-western part of the city, areas near Vishwamitri River as shown in Fig. 3(a). Figure 3(b) reveals that SPT-N values ranging from 28 to 34 cover the areas in south, west and central part of the city at 10 m depth. In north-western and south-western parts of the city are having SPT-N values from 34 to 39. Figure 3(c) reveals that SPT-N values ranging from 29 to 37 cover the areas of eastern, western, south-east and some locations in central part of the city at 15 m depth. The higher SPT-N values above 37 are observed in northern part of the city and near the bank of Vishwamitri River. SPT-N values ranging from 30 to 39 have been observed in east, south-east and southern part of the city at 20 m depth as shown in Fig. 3(d).

3. GEOPHYSICAL CHARACTERISTICS OF STUDY REGION

Geophysical investigations are advantageous for dynamic site characterization of any region. Many invasive and non-invasive techniques are available for measurement of seismic wave velocities. Shear wave velocity profiles have been generated in the study region using MASW test. The field program is set in 2 km × 2 km grid size covering 67 test locations in entire Vadodara city. The locations of geophysical tests are shown in Fig. 1. 48 channelled engineering seismograph of PESI brand is used for acquiring the data. Number of receivers, spacing between the receivers, source increment and total survey length are the parameters taken into consideration for the survey configuration. In the present field testing program, 24 geophones were used with a space interval of 3 m. The testing procedure for MASW test is explained in the sections 3.1, 3.2, and 3.3.

3.1 Multichannel Analysis of Surface Waves (MASW)

The MASW test is performed to determine shear wave velocity profile of study region. Generated data at all shot points in this test is displayed in time versus distance format. This technique can easily identify and eliminate non-fundamental mode of Rayleigh waves and other coherent noise during analysis process and gives the accurate profile of shear wave velocities. MASW testing program caters major three activities-acquiring multichannel records, extracting dispersion curves and obtaining shear wave velocity profiles from dispersion curves.

3.2 Data Acquisition

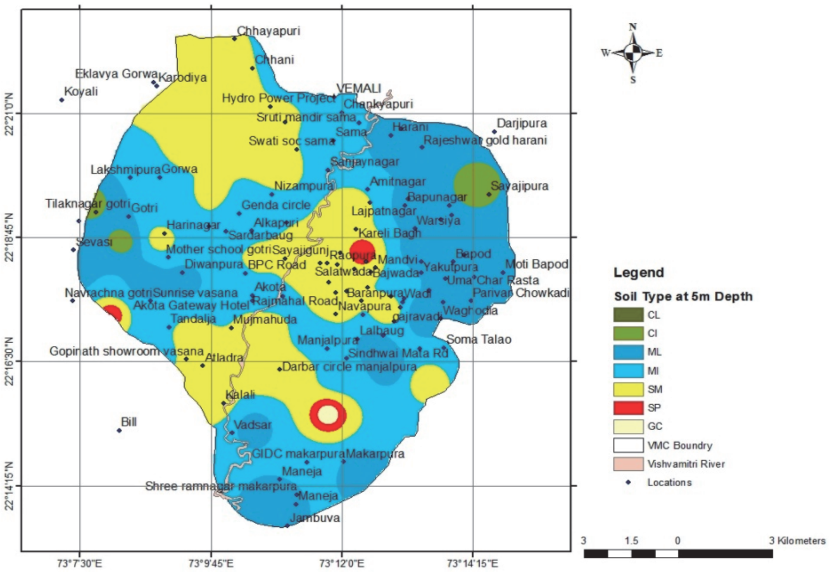
Engineering seismograph of 48 channels with 24 geophones of 4.5 Hz natural frequency is used in present study. These geophones are laid at 3 m space interval. The offset distances, *i.e.,* distance between the source and the nearest geophone, is fixed to 1.5 m. The source is then shifted at 3m intervals. Total survey length is 72 m and 25 shots are made at each location. Sledge hammer of 10.5 kg is used and manually hammered on the steel plate. Fixed receiver configuration is adopted in this survey. A trigger geophone is used to initiate the recording. The generated data for each shot are recorded and saved in the seismograph. The acquired data have been analyzed through SeisImager/SW software (SeisImager/SWTM Manual 2009).

3.3 Data Analysis

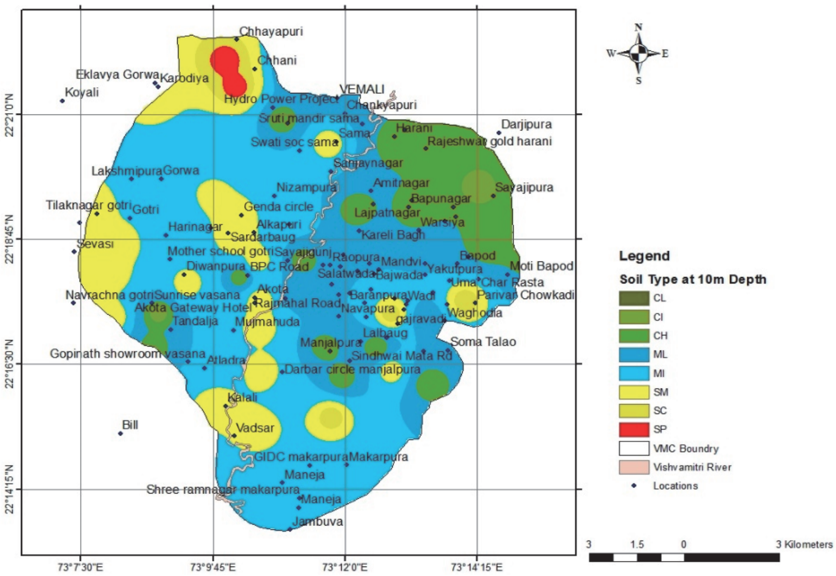
SeisImager/SW software (SeisImager/SWTM Manual 2009) consists of three more software, *i.e.,* PickWin95, WaveEq and Geoplot, which are used for data analysis. Data analysis consists of six steps, which includes making of file list, calculating Common Mid Point (CMP) Gathers, generation of dispersion curves, initial model development, non-linear inversion of dispersion curves and generation of 2D shear wave velocity profile.

Figures 4(a) to 4(f) present shear wave velocity profiles for 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m depth, respectively. Figures 4(a) to 4(c) indicate that eastern part of the city have registered very low velocity of 165 m/s to 215 m/s and 165 m/s to 245 m/s at 5 m and 10 m depth, respectively. These areas are having the pockets of loose soil with low penetration resistance value of less than 20. Central and north-east locations of the city posses medium shear wave velocity ranging from 215 m/s to 240 m/s, 245 m/s to 285 m/s, and 275 m/s to 310 m/s at 5 m, 10 m, and 15 m depth, respectively. It is observed that the areas located in north, south and south-west part of the city are having V_s ranging from 240 m/s to 355 m/s, 285 m/s to 365 m/s and 275 m/s to 380 m/s at 5 m, 10 m and 15 m depth, respectively.

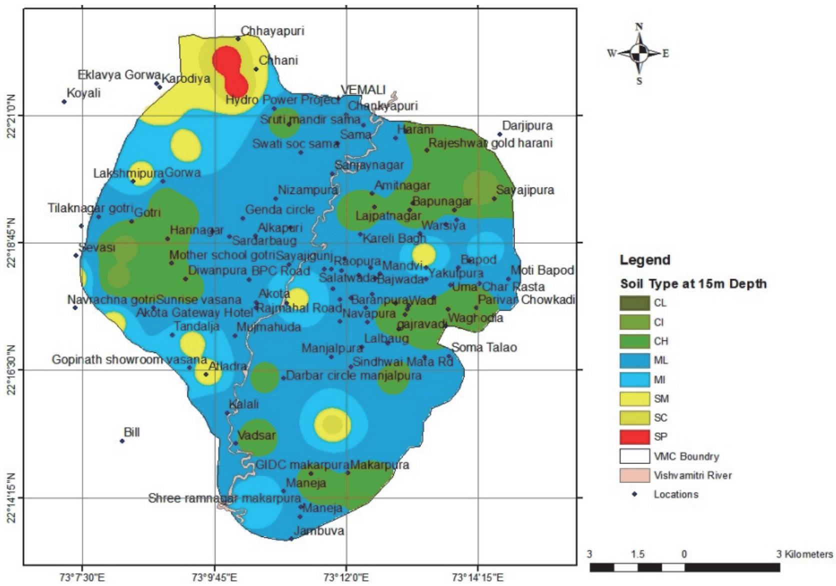
The study of Figs. 4(d) to 4(f) reveals that eastern part of the city is having V_s ranging from 170 m/s to 245 m/s at 20 m, 25 m and 30 m depths. On other hand, the locations in central and southern part of the city are having V_s ranging from 245 m/s to 285 m/s at 20 m, 25 m, and 30 m depths. V_s values observed comparatively



(a) 5 m



(b) 10 m



(c) 15 m

Fig. 2 Variation of soil type at: (a) 5 m; (b) 10 m; (c) 15 m

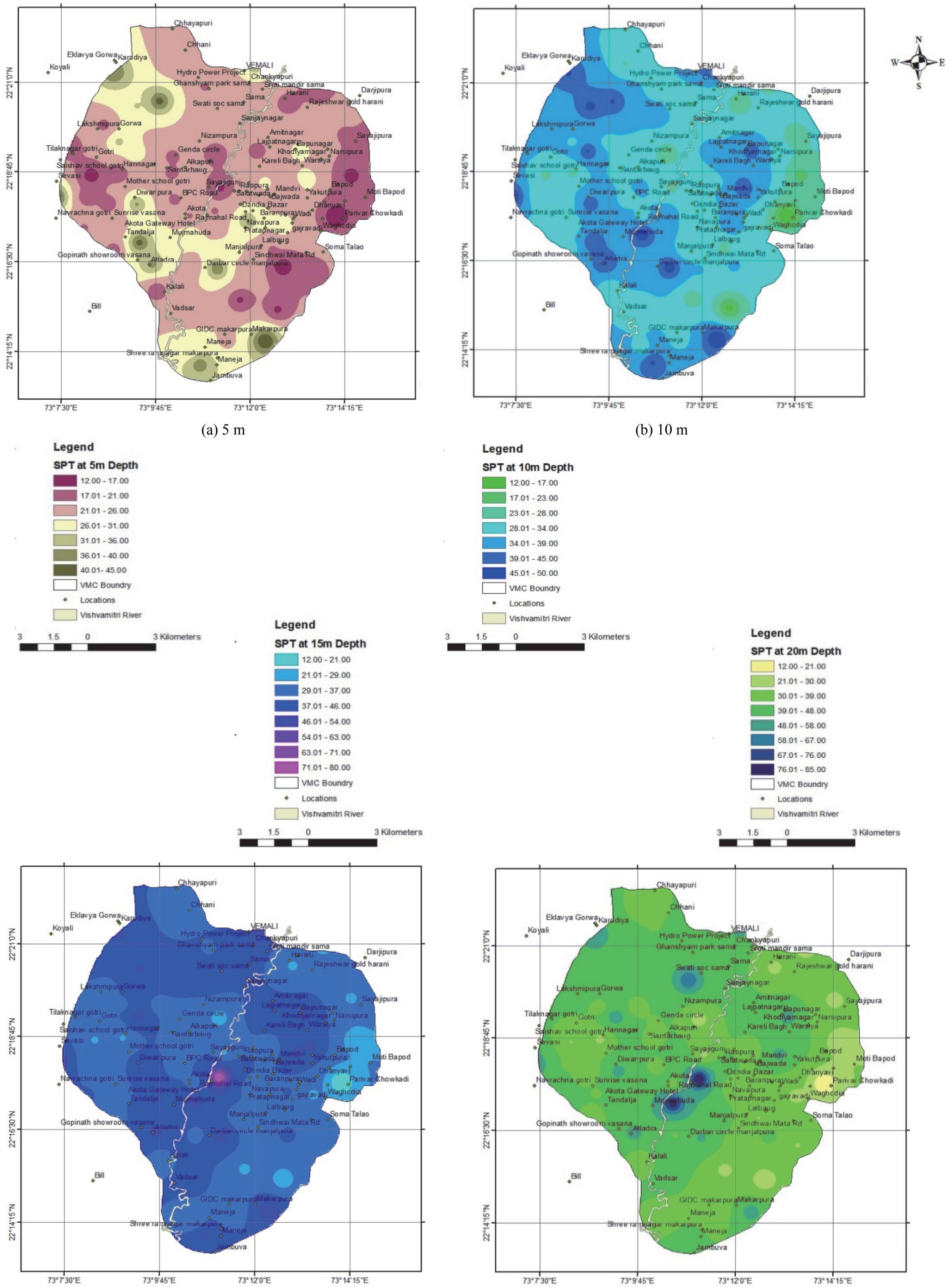


Fig. 3 SPT-N value maps at: (a) 5 m; (b) 10 m; (c) 15 m; (d) 20 m

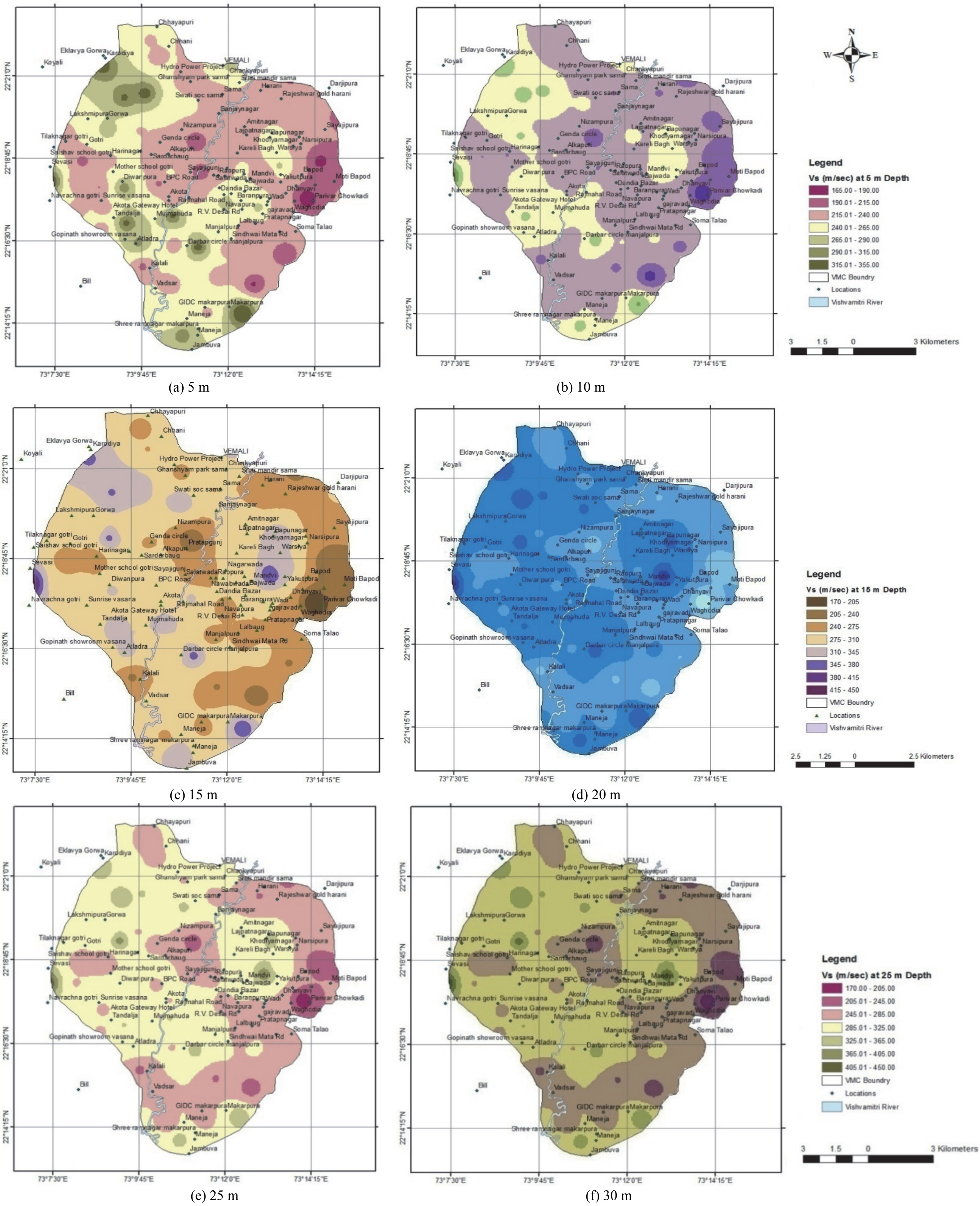


Fig. 4 Shear wave velocity profiles at: (a) 5 m; (b) 10 m; (c) 15 m; (d) 20 m; (e) 25 m; (f) 30 m depth

higher ranging from 285 m/s to 325 m/s at northern and western part of the city at 20 m, 25 m and 30 m depths. The study of Figs. 4(d) to 4(f) reveals that after 20 m depth soil is found to be medium to very stiff and it is also observed that variation of V_s with depth is not significant after 20 m depth. Results also indicate that shear wave velocity models are reconciled well with SPT-N values of the region.

4. CORRELATIONS BETWEEN V_s AND UNCORRECTED SPT-N

MASW is an efficient technique to evaluate shear wave velocity profiles at various depths. However, it is not feasible and economical to conduct this test in city's dense locations due to high noise level and space constraints. In the present study, the empirical correlations have been developed between uncorrected SPT-N and V_s for different categories of soils (*e.g.,* all soils, clay and sand) for Vadodara city. Total 430 dataset have been used to develop the correlations considering simple regression analysis. The correlation curves for the dataset of three types of soils are presented in Figs. 5(a) to 5(c). The proposed correlations with its root-mean-square (RMS) value are as follows:

$$V_s = 81.71\ N^{0.346} \quad (R^2 = 0.759\text{, for all soil}) \tag{1}$$

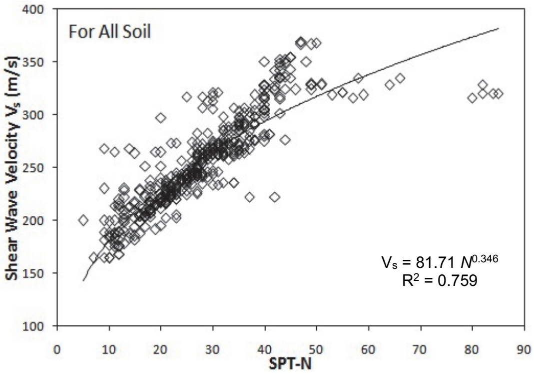
$$V_s = 83.65\ N^{0.336} \quad (R^2 = 0.784\text{, for clay}) \tag{2}$$

$$V_s = 79.81\ N^{0.355} \quad (R^2 = 0.739\text{, for sand}) \tag{3}$$

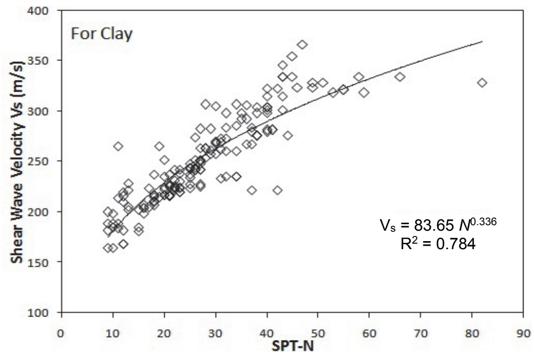
The validation of proposed relations through root-mean-square (RMS) provides information for whole dataset used in analysis. Hence, different graphical statistical methods have been adopted for the assessment of the predicted correlations.

4.1 Comparison between Measured and Predicted V_s

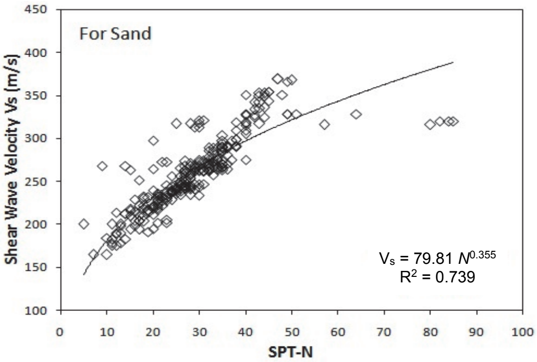
The comparison between measured and predicted V_s is presented in Figs. 6(a) to 6(c). All the data are scattered between the lines with 1:0.25 and 1:1.25 slopes with most of the points falling close to the line 1:1 slope. It shows that regression equations are reasonably fit for the investigated soils.



(a) All soils

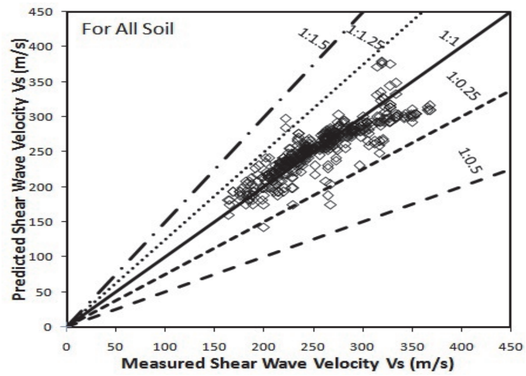


(b) Clay

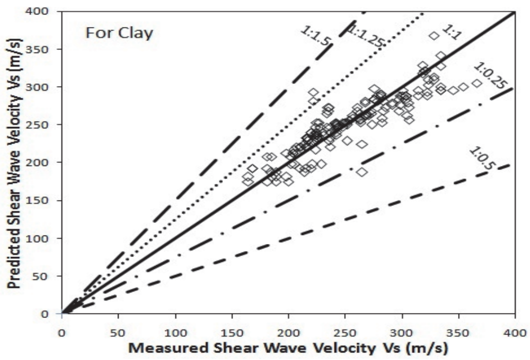


(c) Sand

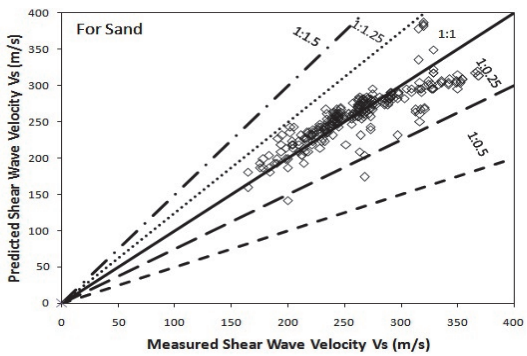
Fig. 5 Correlation between SPT-N and shear wave velocity V_s for (a) all soils; (b) clay; (c) sand



(a) All soils



(b) Clay



(c) Sand

Fig. 6 Measured and predicted shear wave velocity for (a) all soils; (b) clay; (c) sand

4.2 Comparison of the Proposed Correlations with the Existing Relations

The existing correlations between Vs and SPT-N for all categories of soils are depicted in Table 1. These equations are based on uncorrected SPT-N values. These equations are not dependent on depth criteria. Most of the correlations are developed for Japanese conditions (Ohba and Toriumi 1970; Imai and Yoshimura 1970, 1975; Ohta *et al.* 1972; Ohsaki and Iwasaki 1973; Imai and Yoshimura 1975; Imai 1977; Ohta and Goto 1978; JRA 1980), while other correlations have been developed for Indian conditions (Maheshwari *et al.* 2010; Thaker *et al.* 2011; Anbazhagan *et al.* 2013; Kirar *et al.* 2015, Thokchom *et al.* 2017). The proposed correlations are compared with the existing relations as shown in Figs. 7(a) to 7(c). Comparison for all soils suggest that the proposed regression equation is matched well with the relationships developed by Fujiwara (1972), Imai and Yoshimura (1975), Imai (1977), Ohta and Goto (1978), Imai and Tonouchi (1982), Hasancebi and Ulusay (2007), Maheshwari *et al.* (2010), Thaker *et al.* (2011). Fatehnia *et al.* (2015), Ohsani and Iwasaki (1973), Seed and Idriss (1981), Jinan (1987), Athanasopoulos (1995), Iyisan (1996), Jafari *et al.* (1997), Hanumantharao and Ramana (2008), Anbazhagan *et al.* (2013), Kirar *et al.* (2015), and Thokchom *et al.* (2017) give higher V_s values with incremental SPT-N values for all soils as compared to the cited literary works as depicted in Fig. 7(a). It is also observed that relationships presented by Kanai (1966), Imai and Yoshimura (1970), Ohba and Toriumi (1970), Sisman (1995), Kiku *et al.* (2001), and Dikmen (2009) predict lower V_s as compared to proposed relation for all soil types.

Figure 7(b) presents the comparison between the proposed empirical equations with the previous equations suggested by various researchers for clayey soil. It is observed that Dikmen (2009) and Thaker *et al.* (2011) relationships are in good agreement with the proposed relation for clayey soil. Hasancebi and Ulusay (2007) and Imai (1977) predict lower values while JRA (1980), Lee (1990), Athanasopoulos (1995), Jafari *et al.* (1997), Maheshwari *et al.* (2010), Anbazhagan *et al.* (2013), and Kirar *et al.* (2015) shows comparatively higher values for clayey soil. The correlation developed by Thokchom *et al.* (2017) forecasts similar values of V_s for SPT-N value less than 45; thereafter it predicts higher values in comparison to proposed correlation for clays.

The comparison for sandy soil is shown in Fig. 7(c). The study reveals that Imai (1977), Ohta and Goto (1978), JRA (1980), Sykora and Stokoe (1983), Hasancebi and Ulusay (2007), Thaker *et al.* (2011), and Thokchom *et al.* (2017) compare well with the proposed relationship for sandy soil. Relationships proposed by Shibata (1970), Ohta *et al.* (1972), Dikmen (2009), Maheshwari *et al.* (2010), Anbazhagan *et al.* (2013), and Kirar *et al.* (2015) under-predict whereas Lee (1990) over-predicts the shear wave velocity.

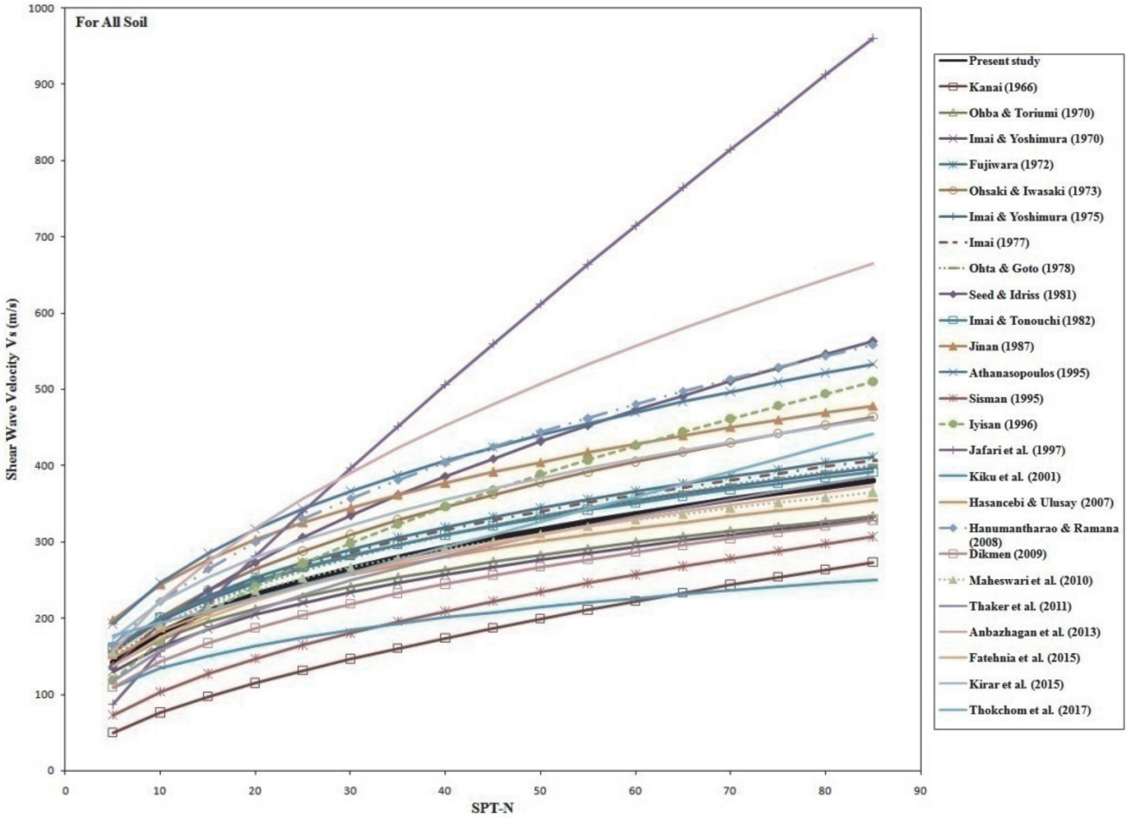
4.3 Scaled Relative Error and Cumulative Frequency

The plots of scaled relative error and cumulative frequency have been developed for all categories of soils to check the capabilities of proposed correlations. These plots are presented in Figs. 8(a) to 8(c). The scaled relative error (E_r) is given by,

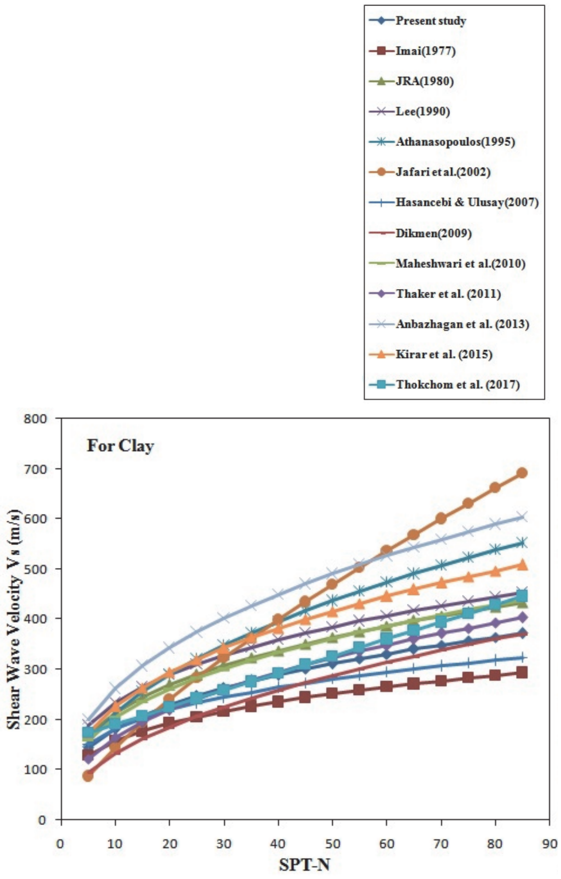
$$E_r = \frac{V_{SC} - V_{SM}}{V_{SM}} \times 100 \qquad (4)$$

Table 1 Existing correlations between V_s and SPT-N

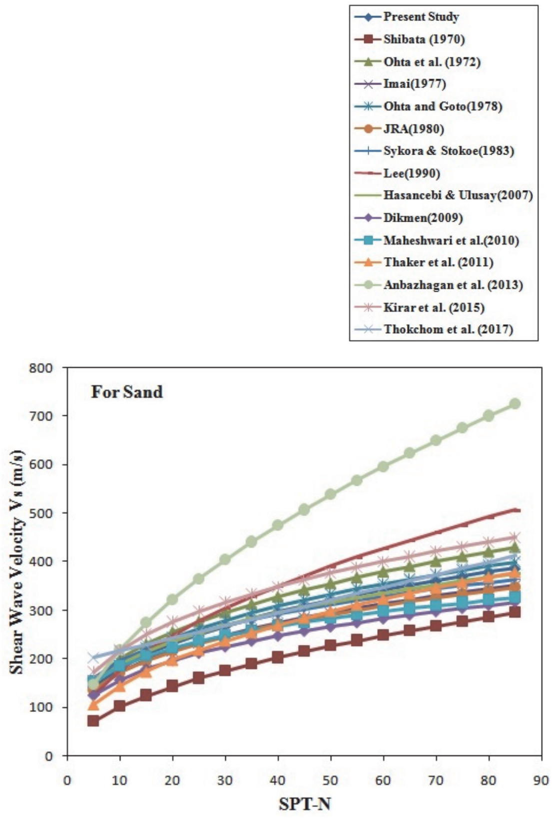
Authors	Correlations	Type of soil
Kanai (1966)	$V_s = 19N^{0.6}$	All soils
Ohba and Toriumi (1970)	$V_s = 84N^{0.31}$	All soils
Shibata (1970)	$V_s = 32N^{0.5}$	Sand
Imai and Yoshimura (1970)	$V_s = 76N^{0.33}$	All soils
Fujiwara (1972)	$V_s = 92.1N^{0.337}$	All soils
Ohta *et al.* (1972)	$V_s = 87N^{0.36}$	Sand
Ohsaki and Iwasaki (1973)	$V_s = 82N^{0.39}$	All soils
Imai and Yoshimura (1975)	$V_s = 92N^{0.329}$	All soils
Imai (1977)	$V_s = 91N^{0.337}$	All soils
	$V_s = 80.6N^{0.331}$	Sand
	$V_s = 80.2N^{0.292}$	Clay
Ohta and Goto (1978)	$V_s = 85.35N^{0.348}$	All soils
	$V_s = 88N^{0.34}$	Sand
JRA (1980)	$V_s = 80N^{0.33}$	Sand
	$V_s = 100N^{0.33}$	Clay
Seed and Idriss (1981)	$V_s = 61N^{0.5}$	All soils
Imai and Tonouchi (1982)	$V_s = 97N^{0.314}$	All soils
Sykora and Stokoe (1983)	$V_s = 100.5N^{0.29}$	Sand
Jinan (1987)	$V_s = 116.1(N + 0.3185)^{0.202}$	All soils
Lee (1990)	$V_s = 57.4N^{0.49}$	Sand
	$V_s = 114.43N^{0.31}$	Clay
Sisman (1995)	$V_s = 32.8N^{0.51}$	All soils
Athanasopoulos (1995)	$V_s = 107.6N^{0.36}$	All soils
	$V_s = 76.55N^{0.445}$	Clay
Iyisan (1996)	$V_s = 51.5N^{0.516}$	All soils
Jafari *et al.* (1997)	$V_s = 22N^{0.85}$	All soils
Kiku *et al.* (2001)	$V_s = 68.3N^{0.292}$	All soils
Jafari *et al.* (2002)	$V_s = 27N^{0.73}$	Clay
Hasancebi and Ulusay (2007)	$V_s = 90N^{0.308}$	All soils
	$V_s = 90.82N^{0.319}$	Sand
	$V_s = 97.89N^{0.269}$	Clay
Maheshwari *et al.* (2010)	$V_s = 95.64N^{0.301}$	All soils
	$V_s = 100.53N^{0.265}$	Sand
	$V_s = 89.30N^{0.358}$	Clay
Thaker *et al.* (2011)	$V_s = 59.72N^{0.42}$	All soils
	$V_s = 51.21N^{0.45}$	Sand
	$V_s = 62.41N^{0.42}$	Clay
Anbazhagan *et al.* (2013)	$V_s = 68.96N^{0.51}$	All soils
	$V_s = 60.17N^{0.56}$	Sand
	$V_s = 106.63N^{0.39}$	Clay
Fatehnia *et al.* (2015)	$V_s = 77.1\ N^{0.355}$	All soils
Kirar *et al.* (2015)	$V_s = 99.5N^{0.345}$	All soils
	$V_s = 100.3N^{0.338}$	Sand
	$V_s = 94.4N^{0.379}$	Clay
Thokchom *et al.* (2017)	$V_s = 3.311 \times$ SPT-N + 160.5	All soils
	$V_s = 2.641 \times$ SPT-N + 189.6	Sand
	$V_s = 3.395 \times$ SPT-N + 156.8	Clay



(a) All soils

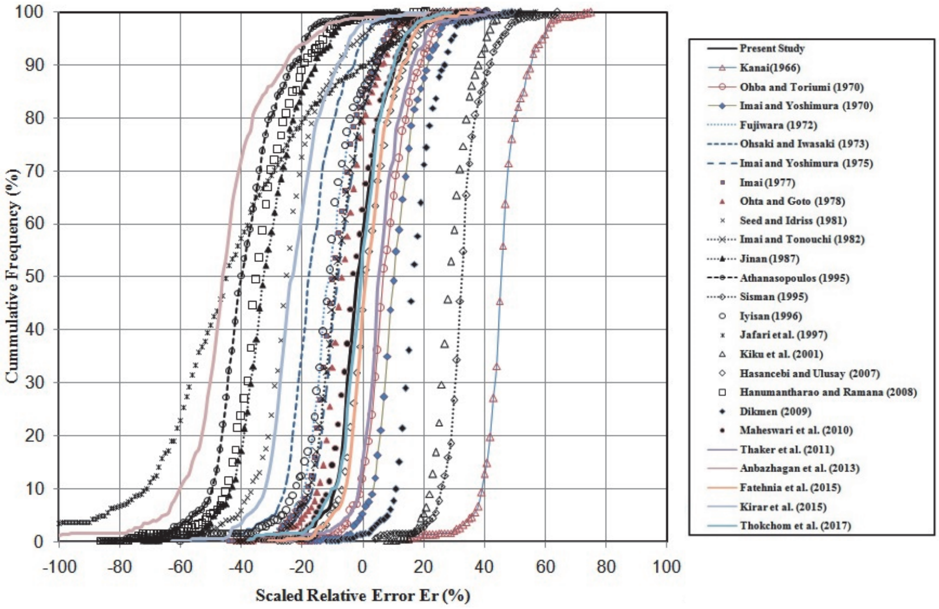


(b) Clay

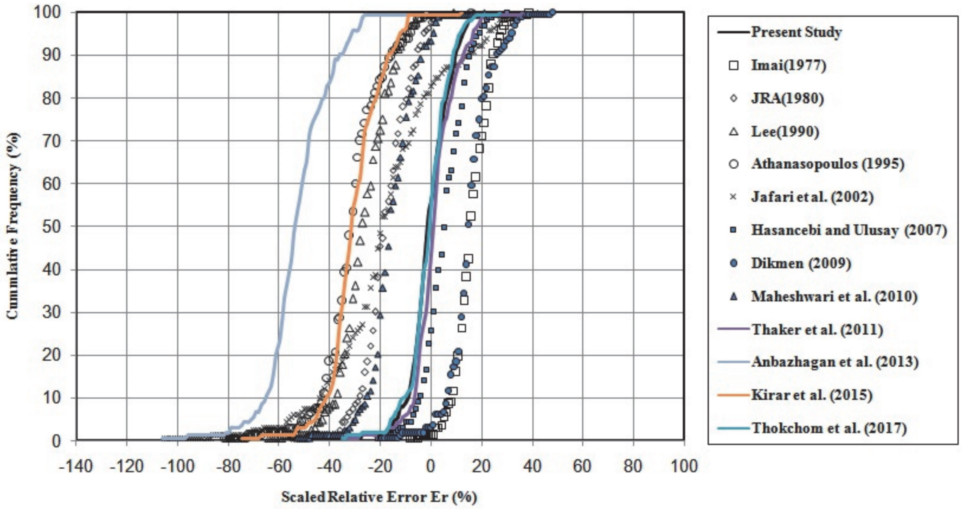


(c) Sand

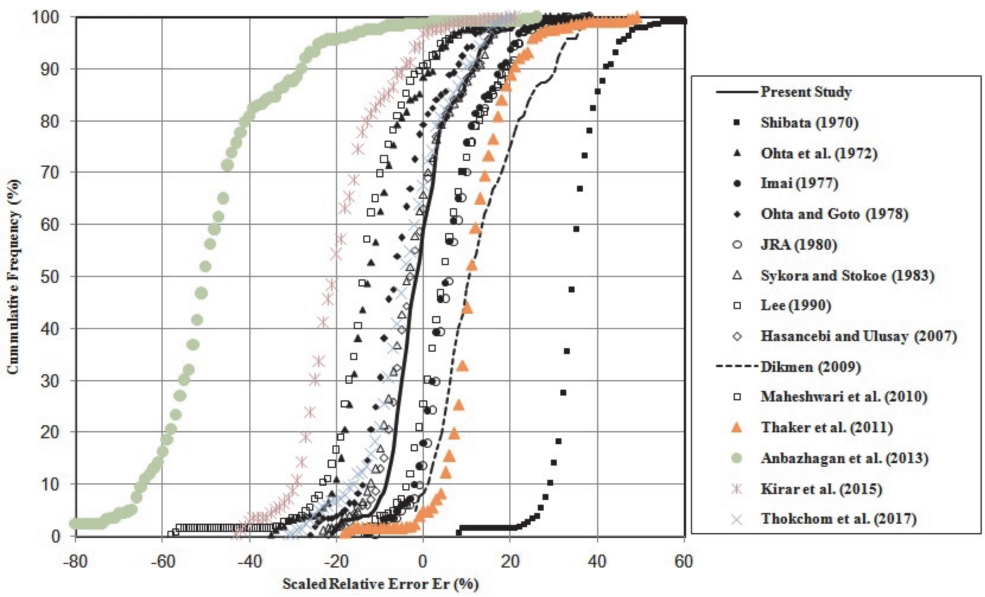
Fig. 7 Comparison between proposed and existing relationships for: (a) all soil; (b) clay; (c) sand



(a) All soils



(b) Clay



(c) Sand

Fig. 8 Scaled relative error for predicted V_s: (a) all soil; (b) clay; (c) sand

where, V_{SC} and V_{SM} are calculated and measured shear wave velocities, respectively. Figures 8(a) to 8(c) present that the proposed relationships give the better estimation than those from the previously published correlations for all soils, clay and sand type of soils.

5. CORRELATIONS BETWEEN V_s AND ENERGY CORRECTED SPT-N (N_{60})

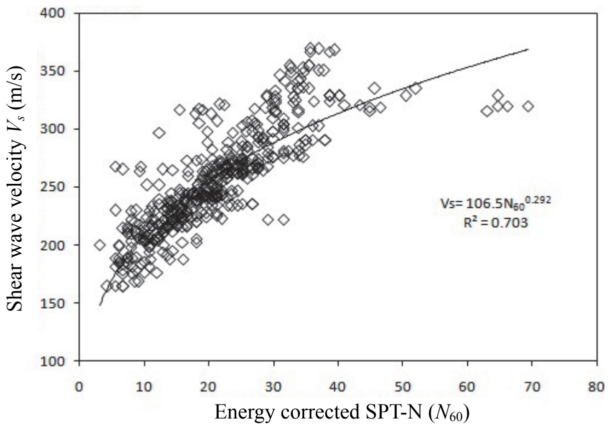
The relationships between V_s and energy corrected blow count N_{60} have been established for all soil, clay and sand. Donut type of hammer is generally used and raised and dropped by two turns of rope for striking the blow. In the present study, SPT blow counts were corrected for hammer energy. The developed correlations for different soils are given in Fig. 9. The relationships developed are presented in Eqs. (5) ~ (7).

$$V_s = 106.5N_{60}^{0.292} \quad (R^2 = 0.703, \text{ for all soil}) \tag{5}$$

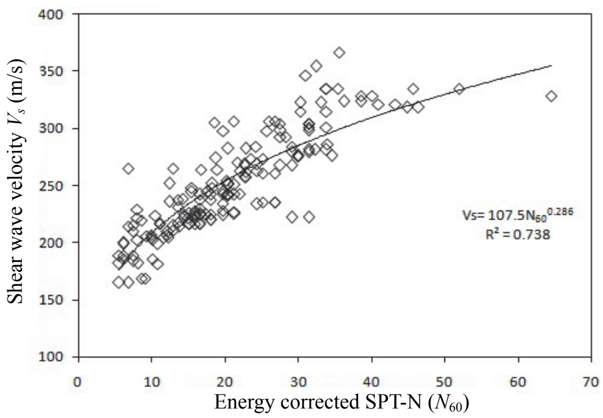
$$V_s = 107.5N_{60}^{0.286} \quad (R^2 = 0.738, \text{ for clay}) \tag{6}$$

$$V_s = 109N_{60}^{0.288} \quad (R^2 = 0.684, \text{ for sand}) \tag{7}$$

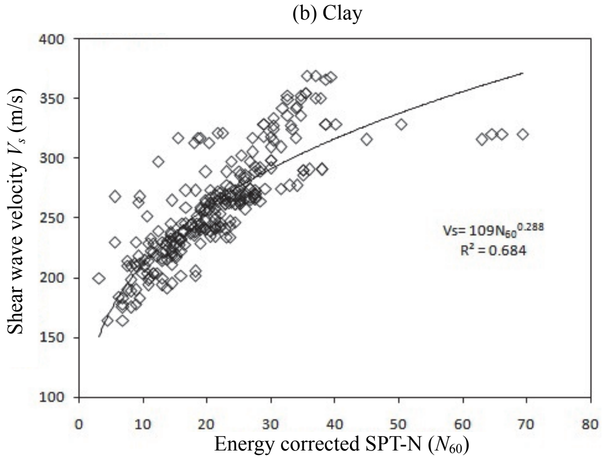
Comparison between the proposed equations based on N_{60} data and existing relationships for different categories of soil are presented in Fig. 10. It has been observed that correlations developed by Thaker (2012) compare well with the proposed equation for all soil and for clayey soil. Relationships given by



(a) All soils

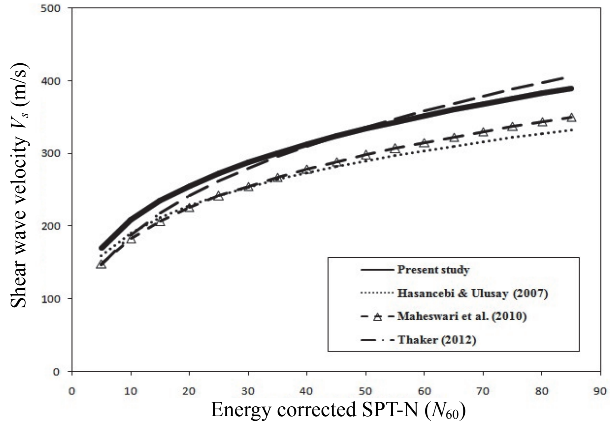


(b) Clay

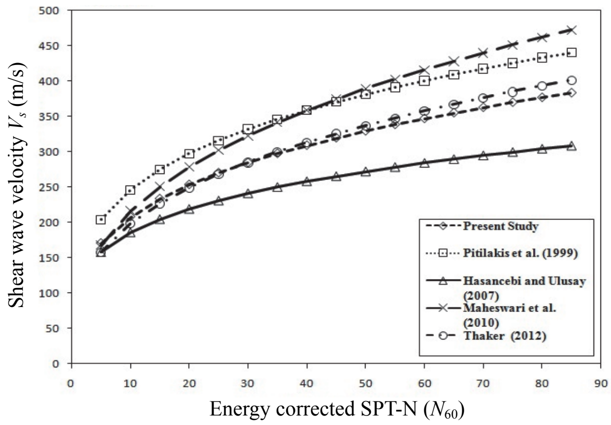


(c) Sand

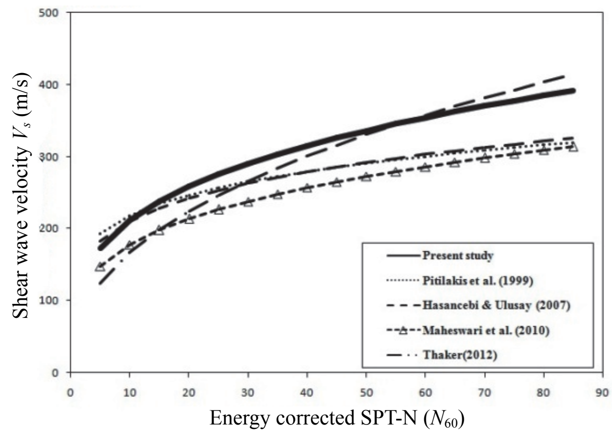
Fig. 9 Correlation between SPT-N_{60} and shear wave velocity V_s for (a) all soils; (b) clay; (c) sand



(a) All soils



(b) Clay



(c) Sand

Fig. 10 Comparison between proposed and existing relationships for (a) all soils; (b) clay; (c) sand

Hasancebi and Ulusay (2007) and Maheswari *et al.* (2010) predict relatively low V_s for SPT-N_{60} >15 for all soil category as depicted in Fig. 10(a). Correlations developed by Pitilakis *et al.* (1999) and Maheswari *et al.* (2010) predict relatively low V_s and Hasancebi and Ulusay (2007) predict relatively high V_s for clayey soil as presented in Fig. 10(b). It is also observed from Fig. 10(c) that the correlations proposed by Pitilakis *et al.* (1999), Hasancebi and Ulusay (2007) and Maheswari *et al.* (2010) predict relatively low V_s for sandy soil. Relationship developed by Thaker (2012) for sandy soil predict relatively low V_s for $N_{60} < 50$.

In addition to the above, comparison of correlation coefficient (R^2) for proposed correlations based on uncorrected and energy corrected SPT-N shows that the equations based on uncorrected SPT-N values provide a marginal better fit than energy corrected values. It is suggested from such assessment that the correlations based on uncorrected SPT-N values are more preferable for indirect estimation of V_s.

6. CONCLUSIONS

The study shows geotechnical and geophysical characteristics of Vadodara region, India. Soil profiles are developed through geotechnical sections in various parts of the city. Soil type is deep black soil in southern part of the city and alluvial sandy loam to sandy clay loam in other parts of the city. Total 67 MASW tests were carried out to develop shear wave velocity (V_s) profiles of the study region. The developed profiles show a good degree of correlations with standard penetration test number (SPT-N) maps at various depths. It is very difficult to carry out field investigation at each location of the active city due to restricted space. Total 430 data pairs have been considered to develop the correlations between V_s and STP-N with and without energy corrections for different categories of soils (all soil, clay and sand). The plots of scaled relative error versus cumulative frequency reveal that 90% predicted velocities from developed correlations between uncorrected SPT-N and V_s for different categories of soils are within ±20% of error. The proposed equations are also compared with previous relations developed for other regions worldwide including India. The comparison shows that the proposed relations are in good agreement with the existing relations for uncorrected SPT-N. The equations based on uncorrected SPT-N values provide higher correlation coefficient than energy corrected SPT-N values. Therefore, the use of uncorrected SPT-N and V_s correlations is recommended for practical purposes. The proposed relations can be further used for other regions having similar site conditions after proper validation. The results are further useful for seismic ground response studies and also for seismic microzonation of the region.

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DATA AVAILABILITY

No new data or no new computer codes.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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