Development of Empirical Correlation between Standard Penetration Test and Shear Wave Velocity

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Abstract. Bhuj 2001 earthquake was the alarmed for the seismic hazard assessment of different regions of the country. Detailed geotechnical and geophysical study provide important inputs for the seismic micro zonation study. In the present paper, the correlation has been developed between standard penetration test number and shear wave velocity for different categories of soil in Vadodara city. The shear wave velocity models have been obtained through Multichannel Analysis of Surface Wave (MASW), which is an effective technique for geophysical site characterization. The field program is set in 2 km x 2 km grid size covering 67 test locations in the entire Vadodara city. The test data are analyzed through the package of SeisImager/SW software. Further, 430 borelog data were collected from various private and government agencies for the investigation of soil properties. Normalized consistency ratio and residual plots have been generated for the validation of the predicted correlations. These correlations are also compared with the relations developed by other researchers. The capability of the proposed correlation is also checked by plotting the map of the scaled relative error versus cumulative frequency. It is found that developed correlations give good prediction performance. The proposed correlations will be the advantageous for the dense locations of the busy city where testing is not feasible and economical. These empirical relations will be further used for similar geotechnical and geological site conditions after proper validation. The proposed correlations can be further used for the ground response analysis and vulnerability assessment of the study region.
Keywords: Shear Wave Velocity, Standard Penetration Test Number, Correlation, Seismic Hazard

1 Introduction

Subsurface soil properties are significantly affected the ground motion during an earthquake event. Shear wave velocity (V_s) is an important soil property to carry out seismic hazard study of any region. Multichannel analysis of surface waves (MASW) is one of field testing method to evaluate shear wave velocity of local soil. MASW field testing program also needs expertise to perform and analyze the data. However, borelog data are easily available from geotechnical investigations at various locations of the region. Standard penetration resistance (SPT-N) value can be easily extracted from these borelog data. Shear wave velocity can also be evaluated from SPT-N value by developing empirical correlations. Study has been carried out to develop the relations between V_s and SPT-N for various types of soil in all over the world (Kanai 1966; Shibata 1970; Ohba and Toriuma 1970; Ohta et al. 1972; Fujiwara 1972; Ohasaki and Iwasaki 1973; Imai and Yoshimura 1975; Imai 1977; Ohta and Goto 1978; Seed and Idriss 1981; Imai and Tonouchi 1982; Jinan 1987; Lee 1990; Athanasopoulos 1995; Dikmen 2009). Many researchers have generated the empirical correlations between Vs and SPT-N for different cities of India. Maheswari et al. (2010) have used 300 borehole data and 20 MASW test data to develop the correlations between V_s and uncorrected SPT-N and also V_s and energy corrected SPT-N for Chennai city. Site classification map was also developed for Chennai city considering NEHRP standards. Seismic site classifications have been carried out for Lucknow city based on NEHRP standards (Anbazhagan et al. 2013). Thokchom et al. 2017 have measured shear wave velocity by performing MASW test at 42 sites and PS logging test at 16 sites for Dholera region, Gujarat.

Present paper is an attempt to develop the correlations between shear wave velocity and uncorrected SPT-N value for different categories of soil for Vadodara region. Shear wave velocity maps have been developed at different depths for the city. Total 430 borehole data were used to develop the correlations for all soils, sand and clay. Different statistical analyses were carried out to examine the developed correlations. The obtained results were also compared with other correlations developed by other researchers in all over the world including India.

2 Study Region and Seismicity

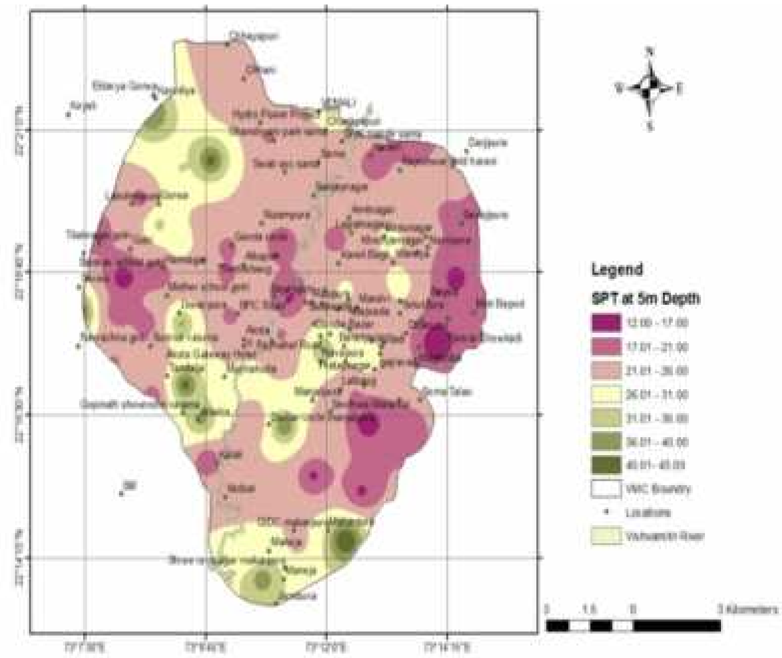
Vadodara, the cultural capital of Gujarat, is having moderate seismic intensity with zone factor 0.16 g under seismic zone III (IS:1893-2016). Vadodara sits on bank of Vishwamitri River and located at 22.30°N 73.19°E in western India with population of 2.1 million people as per 2011 census. The city is the hub of many historical buildings of Maharaja Sayjirao Gayakwad, industries and educational institutes. As Vadodara is developing city, many upcoming constructions near the bank of river may add the vulnerability to the city. Further, the city is having risk from far-field seismic sources like Kutch Mainland Fault, Allah Bund Fault and Island Belt Fault. East Cambay fault, West Cambay fault and Son Narmada fault are near field seismic sources located at distance of 15 km, 90 km and 60 km respectively. 1819 Kutch (M_w 7.8); 2001 Bhuj (M_w 7.7); 1956 Anjar (M_w 6.1); 1938 Satpura (M_w 6.0); 1935 Surat (M_w 5.7); 1969 Mount Abu (M_w 5.5); 1970 Bharuch (M_w 5.4) and 1864 Ahmedabad (M_w 5.0) are some of the past earthquakes, which reveal that seismicity of the study region has increased in last few decades. Hence, the hazards of Vadodara city need to study considering various aspects like seismological, geotechnical, geophysical investigations with local site effects.

3 Standard penetration test number (SPT-N)

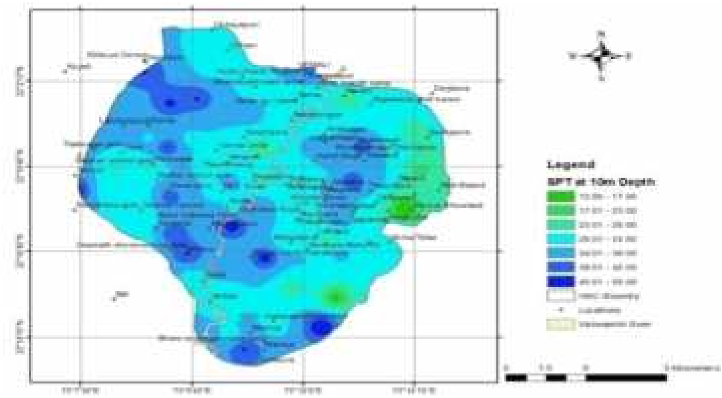
Standard penetration test number (SPT-N) is an important parameter to understand the dynamic properties of sub-soil strata. Around 430 borehole data have been used to develop the map of standard penetration test number (SPT-N) at various depths as depicted in Fig. 1(a)-(d). Fig. 1(a) reveals that east and south-east locations are having the least SPT-N value ranging from 12 to 21 at 5 m depth. The locations like Amitnagar, Nizampura, Karelibaug, Lalbaug, Vadsar are observed medium range of SPT-N value (21-26) at the same depth. The maximum value of SPT-N ranging from 26 to 45 covers the locations like Vasna, Tandalja, Mujmahuda, Makarpura, Gorwa and Karodiya at 5 m depth. At 20 m depth, the locations like Bapod, Harni, Sayajipura, Parivar Chokdi are having SPT-N value from 12 to 23 as shown in Fig. 1(b). The higher range of penetration resistance value from 34 to 50 have been observed in locations like Gorwa, Karodiya, Akota, Maneja, Makarpura.

It has been observed from Fig. 1(c) that the areas like Bapod, Parivar Chokdi and Waghodia are associated with lowest SPT-N value (12-29) at 15 m depth. The north-east, south-east, western part and some locations in central areas like Harni, Sayajipura, Narsipura, Lalbaug, Manjalpur, Pratapnagar, Nizampura, Genda circle, Alkapuri, Gotri, Gorwa have registered penetration resistance value ranging between 29 to 37 at 15 m depth. The higher SPT-N values from 37 to 54 are observed in areas like Sama, Diwanpura, Vasna, Akota, Tandalja, Altadra, Vadsar, Jambuva at same depth. The eastern most part of the city is associated with the lowest penetration resistance value of 12-30 at 20 m depth as depicted in Fig. 1(d). The locations of north-east, south-east and western region of the city have registered medium range of SPT-N value from 30 to 39 at same depth. The areas like Sama, Amitnagar, Karelibaug, Manjalpur, Vadsar, Atladra, Gotri, Gorwa have observed highest SPT-N value ranging from 39 to 85.

a)



b)



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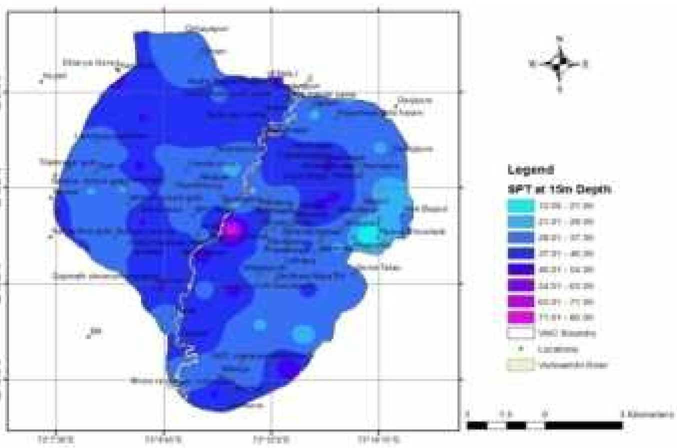


d)

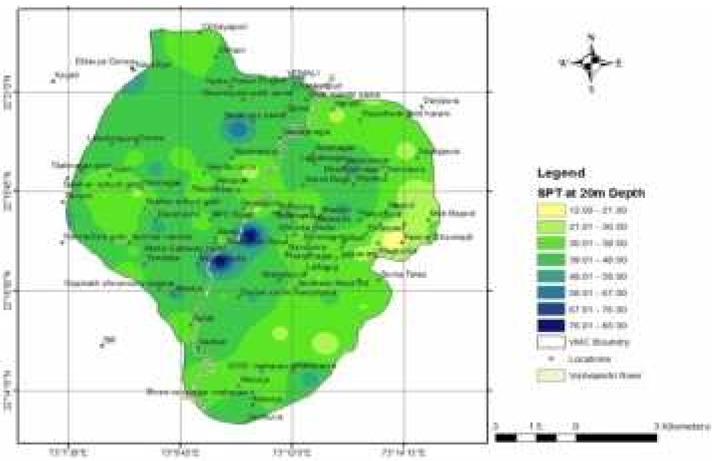


Fig. 1. SPT-N value maps at (a)5 m (b)10 m (c)15 m (d)20 m depth

4 Acquisition of Geophysical Data

Multichannel analysis of surface waves (MASW) method is the most reliable and non-invasive technique to determine shear wave velocity of the local soil of any region. In present study, field investigation program is set in 2 km x 2 km grid size and 67 tests were performed to cover the entire Vadodara city. Field testing program has been performed with 24 geophones of 4.5 Hz natural frequency. Geophone spacing is set as 3 m interval with 72 m survey length. The data have been acquired in 48 channeled engineering seismograph by generating 25 shots with the manually operated sledge hammer of 10.5 kg.

Analysis of the acquired data has been performed with SeisImager/SW software. File lists are made for all wave form files with source receiver configuration in the first step of analysis. In next step Common Mid Points (CMP) of all traces are gathered and calculated. Then most important step is to generate dispersion curves. Initial velocity model is generated from dispersion curves. After that, a non-linear inversion is performed to generate 1D shear wave velocity profiles. In last step 2D velocity model is generated. Finally, V_s maps are constructed at various depths for the study region. Fig. 2 depicts dispersion curve and 2-D shear wave velocity profile of typical location of the study region.

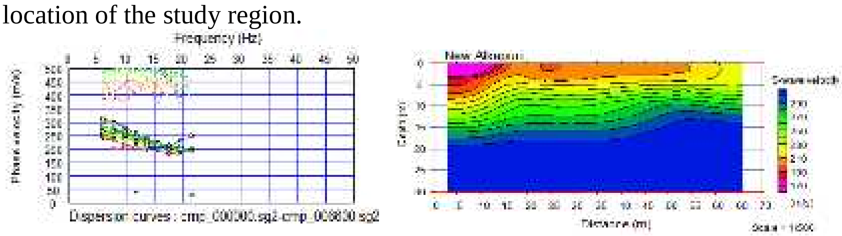


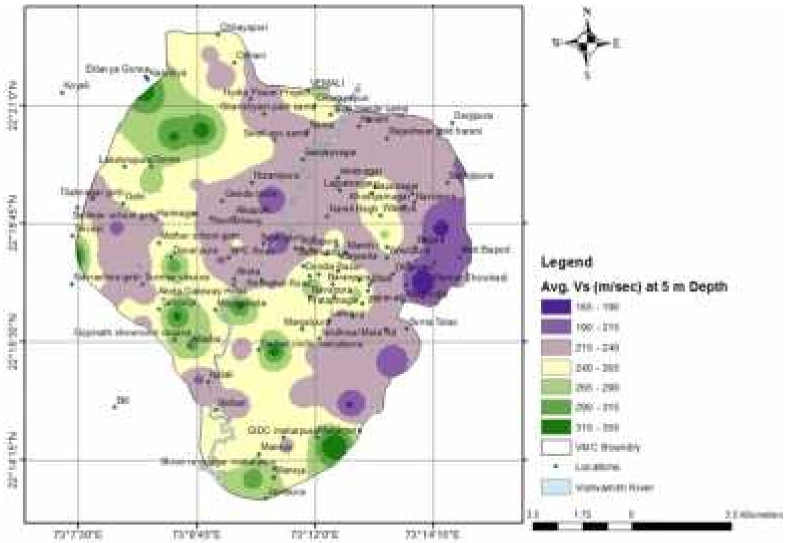
Fig. 2. Dispersion curve and Shear wave velocity profile at typical location

4.1 Shear wave velocity (V_s)

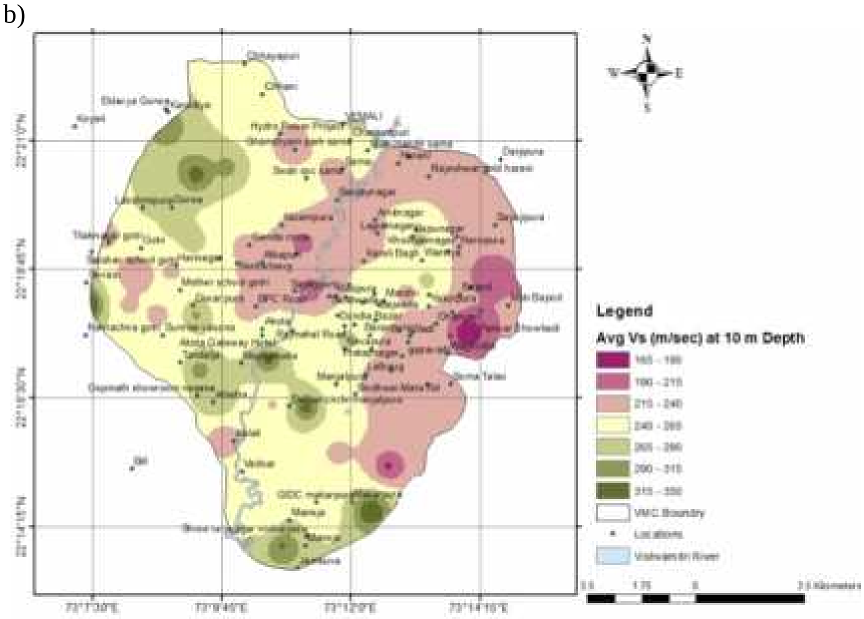
Fig. 3(a)-(f) represents average shear wave velocity profiles at 5 m, 10 m, 15 m, 20 m, 25 m and 30 m depths. The locations like Bapod, Pariwar Chowkadi, Waghodia have registered lowest range of shear wave velocity of 165-215 m/s at 5 m depth as shown in Fig. 3(a). The medium range of V_s from 215 m/s to 240 m/s is observed at locations like Sama, Sanjaynagar, Nizampura, Genda circle, Alkapuri, Akota, Amitnagar, Karelibaug at same depth. The highest shear wave velocity has been registered at locations like Gorwa, Diwanpura, Vasana, Atladra, Mujmahuda, Darbar circle, Maneja, Jambuva ranging from 265-355 m/s at 5 m depth. Fig. 3(b) reveals that lowest average shear wave velocity of 165-190 m/s is registered at eastern most part of the city at 10 m depth. The locations like Harni, Sanjaynagar, Nizampura, Genda circle, Alkapuri, Gajrawadi, Lalbaug have observed V_s of 215-240 m/s at same depth. Average shear wave velocity of 240-265 m/s has been registered at locations like Sama, Gotri, Akota, Karelibaug, Mandvi, Dandia Bazar, Pratapnagar, Manjalpur. The north-west, south and some areas of south-west like Gorwa,, Sevasi, Tandalja, Atladra, Munjmahuda, Maneja, Makarpura, Jambuva are having highest shear wave velocity of 265-350 m/s at 10 m depth.

Average shear wave velocity of 165-225 m/s and 170-235 m/s is observed at eastern most part of the city at 15 m and 20 m depth respectively. As shown in Fig. 3(c)-(d), the northern part, north-east, south-east and some areas of central part are having the shear wave velocity of 225-255 m/s and 235-265 m/s at 15 m and 20 m depth respectively. The locations like Chhani, Karodiya, Gorwa, Gotri, Vasna, Akota, Tandalja, Mujmahuda, Warasiya, Mandvi, Maneja, Makarpra have registered V_s ranging from 255 m/s to 370 m/s and 265 m/s to 395 m/s at 15 m and 20 m depth respectively.

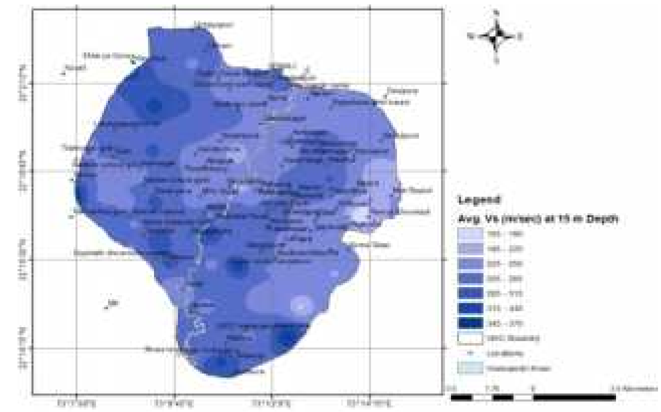
(a)



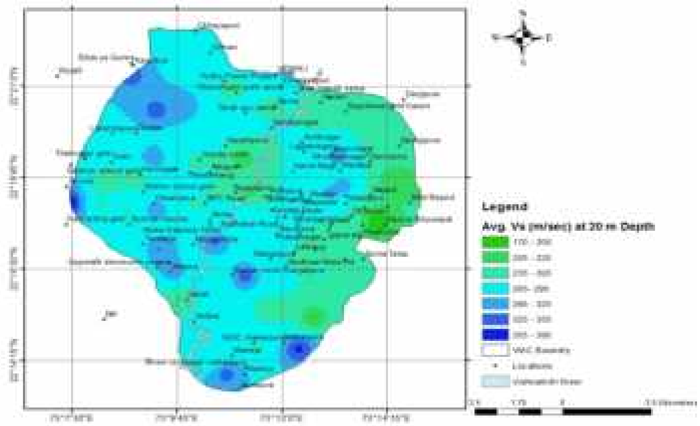
b)



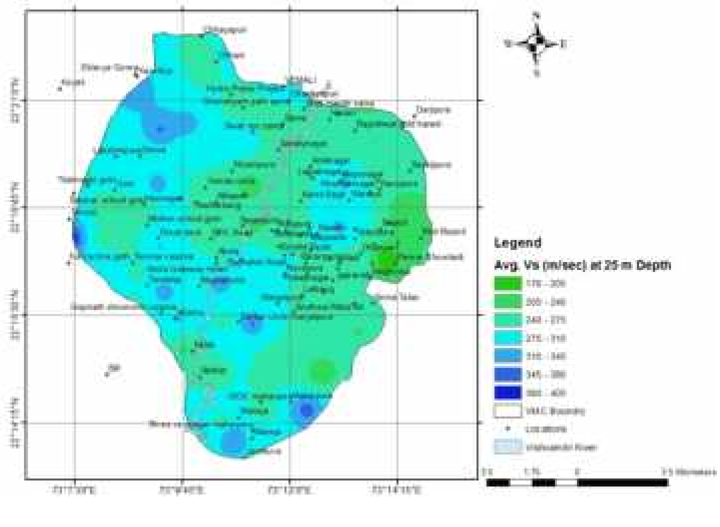
c)


Legend
Avg. Vs (m/sec) at 15 m Depth

d)


Legend
Avg. Vs (m/sec) at 20 m Depth

e)


Legend
Avg. Vs (m/sec) at 25 m Depth

f)

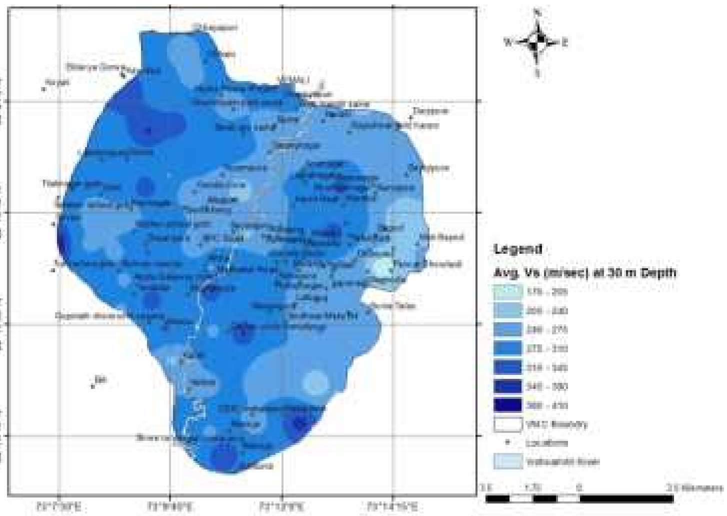


Fig. 3. Average shear wave velocity models at (a)5 m (b)10 m (c)15 m (d)20 m (e)25 m (f)30 m

Fig. 3(e)-(f) presents average shear wave velocity of Vadodara region at 25 m and 30 m depth respectively. Eastern most parts of the city have registered lowest shear wave velocity of 170-240 m/s at 25 m and 30 m depths. The locations like Harni, Sama, Sanjaynagar, Amitnagar, Alkapuri, Genda circle, Gajrawadi, Lalbaug have observed shear wave velocity of 240-275 m/s at same depths. Highest shear wave velocity ranging from 275 m/s to 405 m/s is registered at locations like Gorwa, Karodiya, Diwanpura, Vasna, Tandalja, Akota, Atladra, Warasiya, Manjalpur, Maneja, Makarpura at depths of 25 m and 30 m.

5 Development of V_s-SPTN correlations

Shear wave velocity is an important input to assess the hazard of any region. MASW is one of the techniques to determine shear wave velocity of local soil of the study region. But it would be difficult to conduct this test at every location of the busy city. Hence, this paper aims to develop the correlations for evaluating the shear wave velocity from standard penetration test number for Vadodara city. Simple regression analysis has been carried out to develop the correlations considering 430 dataset for different categories of soil. Fig. 4 presents the correlation curves for all soils, sand and clay. The predicted equations with its RMS value are as follows:

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

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

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

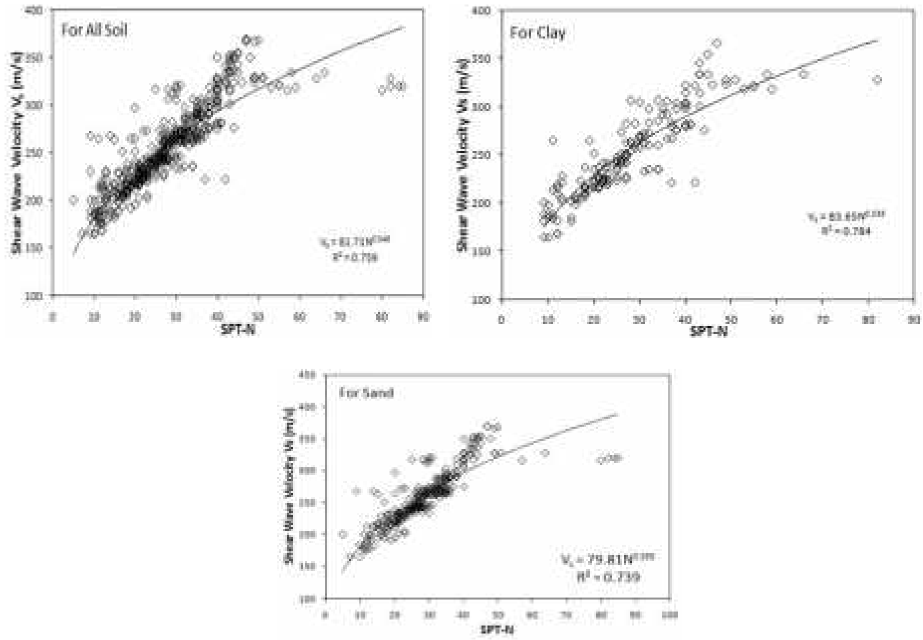


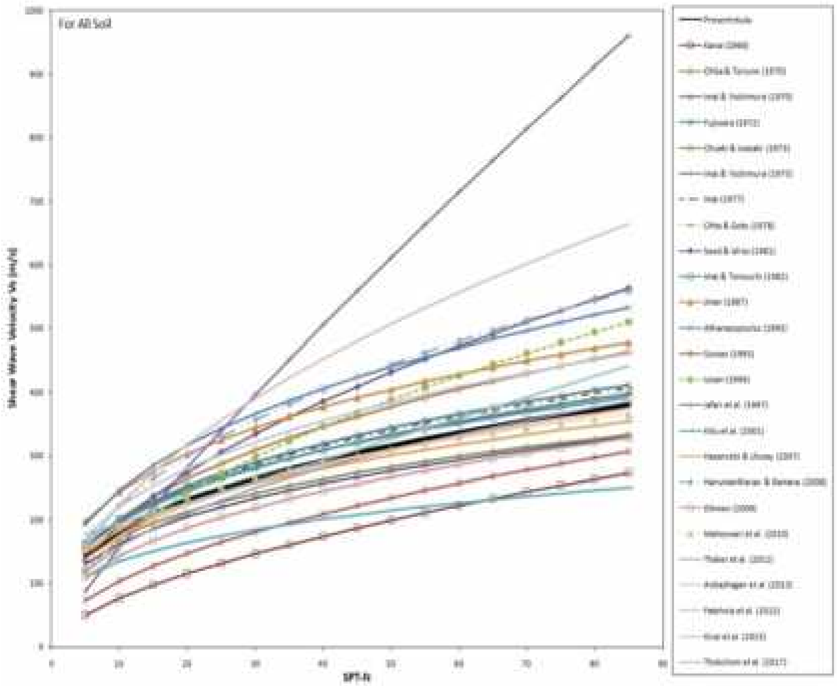
Fig. 4. Correlations between shear wave velocity V_s and penetration resistance (SPT-N) for different categories of soils

Many statistical tools are available for the validation of predicted correlations. Residual analysis has been carried out to assess the adequacy of model. The analysis reveals that residuals are scattered uniformly at horizontal line with equal variance from horizontal axis. The comparison has been done between measured and predicted shear wave velocity, which shows that most of the data are reasonably fit with measured velocity for the investigated soil. Further, predicted correlations are also compared with the correlations developed by other workers for various categories of soil.

Fig. 5(a) depicts the comparison of proposed correlations with other literatures for all soils, which suggest that predicted equation is in good agreement with relations 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) and Kirar et al. (2015). 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) under predict V_s as compare to proposed relation for all soils type. Dikmen (2009) and Thaker et al. (2011) relationships are matched very well with predicted relationship for clay as depicted in Fig. 5(b). Hasancebi and Ulusay (2007) and Imai (1977) under predict shear wave velocity while JRA (1980); Lee (1990); Athanasopoulos (1995); Jafari et al. (1997); Maheshwari et al. (2010); Anbazhagan et al. (2013) and Kirar et al. (2015) over predict shear wave velocity for clayey soil. Fig. 5(c) 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) are reconcile well with proposed relation for sandy soil. Correlation developed by Shibata (1970); Ohta et al. (1972); Dikmen (2009); Maheshwari et al. (2010); Anbazhagan et al. (2013) and Kirar et al. (2015) forecasts lesser value and Lee (1990) predicts higher value as compared to proposed relation for sandy soil.

a)



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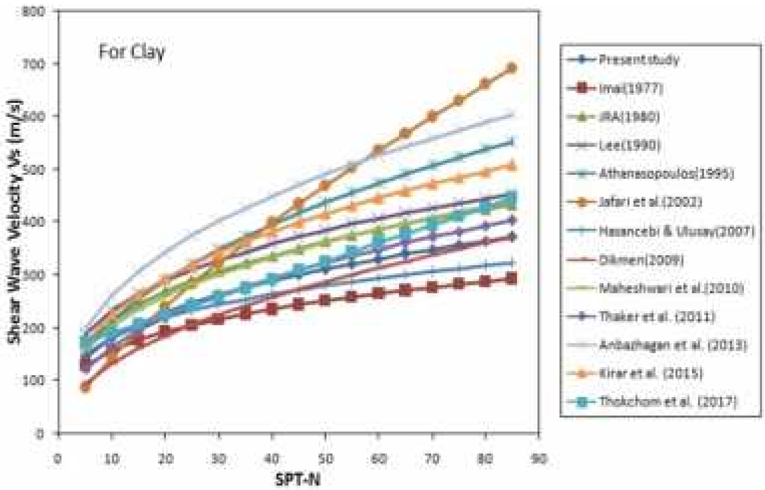

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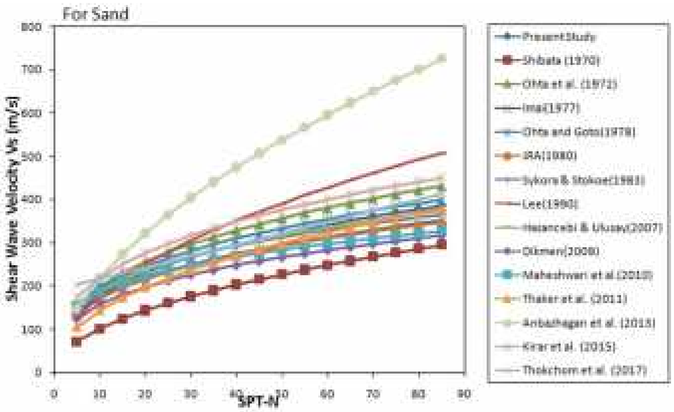

Fig. 5. Comparison between proposed and existing relationships for (a) All soil (b) Clay (c) Sand

6 Conclusion

Dynamic soil property like shear wave velocity is an essential input to investigate the hazard of any region. MASW is the direct approach to evaluate shear wave velocity. Extensive field investigations have been carried out by performing MASW test at 67 locations in and around the Vadodara city. MASW test requires large space to conduct the test but that would not be possible at every location of the populated city. Hence, the correlations have been developed to evaluate V_s from SPT-N value, which is extracted from borehole data. Developed correlations are reconciled well with other published correlations for all categories of soils. The obtained results will be further useful to evaluate the amplification factor of ground motions at surface level. The results are also useful in seismic microzonation study of the region.

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