


Empirical correlation of SPT blow counts versus shear wave velocity for different types of soils in Dholera, Western India

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Abstract In the present study, a set of correlation relations between standard penetrations tests (SPT-N values) and shear wave velocity (V_s) for different categories of soils is developed for Dholera region, Gujarat state, Western India. Shear wave velocities were measured using multichannel analysis of surface wave (MASW at 42 sites) and by PS logging (at 16 sites). SPT-N values were taken in total 87 geotechnical boreholes at depth interval of 3 m. Seismic site classification is done as per National Earthquake Hazards Reduction Program of the USA. Total 336 pairs of SPT-N values and V_s data at different depths are used to develop the regression correlation between uncorrected SPT-N value and V_s and compared with the results of other workers from India and worldwide for all soils type. It is found that regression correlations developed for clay and all soils are almost similar to each other, for sand, the coefficient value is less and for silt, it is higher. The new regression equation gives good prediction performance. The present correlation can be used for the seismic hazard study for the study area and also for the other areas having similar soil strata using a process of validation.

Keywords Shear wave velocity · Dynamic properties of soil · Geophysical testing · Standard penetrations tests · Multichannel analysis of surface wave · Regression correlation

1 Introduction

Detailed studies of subsurface soil characteristics and stratigraphy are necessary to understand the local site effects during earthquake and prediction of seismic site effects for future earthquake. In geotechnical earthquake engineering, the dynamic properties of

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soil such as density, stiffness, damping and maximum shear modulus are important for response analysis of soil. These dynamic properties of shallow subsurface soils can be estimated using shear wave velocity (V_s). For evaluation of seismic site characteristic, average shear wave velocity of upper 30 m (V_{s30}) is essential. The US National Earthquake Hazards Reduction Program (NEHRP) and International Building Code (IBC 2009) classified six different categories of soils based on V_{s30} . Since the shear wave velocity is one of the most important geotechnical parameters that acts as the input for quantitative earthquake engineering and is the main controller of site response, it is important to determine it for estimation of the ground motion parameters at the surface. There are many literatures, international and national standards, which provide methodology to measure precise shear wave velocity (Fabbrocino et al. 2015). Determination of V_s can be done both in situ as well as in laboratory. Field methods include seismic refraction test, spectral analysis of surface wave (SAWS) test, multichannel analysis of surface wave (MASW) test, suspension logging and seismic cross-hole test (Kramer 1996) which can measure large volume of soil in its natural condition of a particular region with minimal disturbance. On the other hand, laboratory tests such as resonant column test, ultrasonic pulse test and piezometric bender element test require undisturbed samples. It is, however, difficult to restore the natural field conditions in the laboratory. Hence, due to advantages of the in situ methods over laboratory, it is preferred to use the V_s determined from field measurements. Surface wave method for determining V_s is widely used all over the globe. However, geophysical testing for measurement of V_s is time-consuming and costly, and sometimes it is difficult to measure V_s in all the locations for microzonation studies in cities. On the other hand, standard penetration test is the in situ geotechnical test which provides indirect measure of the soil resistance as well as disturbed drive samples. It can be performed in a wide variety of soil types. On the other hand, sometimes the penetration test cannot be performed conveniently and reliably at all depths and in all soils such as those with large grain size, i.e., gravels. Sometimes, the presence of even a few small boulders may give unrealistic high N -value. Hence, a correlation between SPT- N and V_s represents an indirect correlation between initial strength and stiffness for a soil. The correlation between the SPT- N and V_s was largely investigated in the last decades. 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), Hansancebi and Ulusay (2007) reported empirical correlation of V_s with standard penetration tests for evaluation of dynamic properties of soil.

The three main advantages of empirical regression equation are convenience, efficiency and economy. Although the empirical correlation between SPT- N and V_s is convincing with notably worldwide agreement, it is region specific and not applicable to other site. So it is required to perform thorough process of validation before using them. The present paper deals with the development of empirical correlation between SPT- N and V_s for different soil types of Dholera region in western part of India. Subsurface investigation of the study area was done using seismic surface wave technique of MASW, PS logging and drilled boreholes. MASW test has been carried out at 41 sites in Dholera region. Total 87 boreholes were drilled covering almost the entire study area. SPT- N values were measured at 3 m depth interval. Sixteen PS logging tests up to 70 m depth were carried out in selected 16 boreholes.

2 N_{SPT} – V_s empirical correlation: literature review

Many researchers from different countries have proposed sets of regression correlation between SPT-N values and V_s for different soils. They tried to correlate V_s in terms of various soil indices including depth, geological epoxy and soil type with SPT-N value (Kuo et al. 2011). The correlation of V_s and N -value was started in early 1970s based on several datasets collected in different regions of Japan (Imai and Yoshimura 1970; Ohba and Toriumi 1970; Shibata 1970; Otha et al. 1972; Fujiwara 1972; Ohshaki and Iwashaki 1973; Imai 1977). Ohta and Goto (1978) considered all the four indices, i.e., SPT-N, depth from the ground surface, geological age and soil type to develop the empirical correlation using about 300 data derived by characterization of the alluvial deposits in Japan. The empirical correlation studies using largest dataset (1654 data pairs) were done by Imai and Tonouchi (1982) based on N -value, soil type and geological age. They analyzed most wide ranging database of Japanese survey and reported that the clayey layer has higher V_s value than sandy layer.

To determine the liquefaction susceptibility of alluvium and marine sands in California, a similar correlation study of SPT-N and V_s is done by Seed and Idriss 1981, Seed et al. 1981, Sykora and Stokoe 1983, Rollins et al. 1998, Brandenberg et al. 2010 using SPT blow counts N_{60} and $(N_1)_{60}$ (60% effective reduction energy ratio) for the evaluation of cyclic resistance ratio (CRR). Seed et al. (1985) modified the existing equation of Ohta and Goto (1978) and developed a relationship for Quaternary soils and granular soils using N_{60} , which are generally used for the evaluation of the cyclic strength ratio CRR in the liquefaction simplified analysis.

Similar studies are carried out by different scientists of different parts of the globe like in Greece (Kalteziotis et al. 1992; Pitilakis et al. 1992, 1999; Athanasopoulos 1995; Raptakis et al. 1995; Tsiambaos and Sabatakakis 2011), Turkey (Iyisan 1996; Kayabali 1996; Hansancebi and Ulusay 2007; Koçkar and Akgün 2008; Dikmen 2009; Akin et al. 2011), India (Anbazhagan and Sitharam 2008a, b, 2010; Anbazhagan et al. 2011, 2012; Hanumantharao and Ramana 2008; Uma Maheshwari et al. 2010) and Iran (Jafari et al. 2002) in last decades, mainly for alluvial formations. Piratheepan (2002) reported the work of Yoshida et al. (1988) in which he mentioned about the laboratory test for V_s measurement in 2 m diameter and 1.5 m height samples. Hansancebi and Ulusay (2007) investigated SPT-N– V_s correlation based on N and N_{60} for all soils, sand and clay in Yenisehir area, Turkey. Power type data regression relation such as $V_s = aN^b$ was mostly used for empirical study in which, V_s = shear wave velocity at particular depth and N = SPT-N value at the same depth, except in a few cases, linear type correlations were used (Kayabali 1996; Lee 1992), with low regression coefficient r . Both corrected N values (corrected for overburden pressure, sampling tool and drilling conditions) and uncorrected values are used. Hansancebi and Ulusay (2007) noted that the best relationships were achieved using uncorrected SPT-N values. However, Tsiambaos and Sabatakakis (2011) argued that the use of uncorrected SPT-N values may provide worse regression models, possibly due to uncertainties related to the definition of correction coefficients. Majority of the relations have used uncorrected SPT-N values for regression correlation study. Uma Maheshwari et al. (2010) estimated V_s with equal precision using both corrected and uncorrected SPT-N values. Geological age is considered in correlation study by some geologists while others (e.g., Sykora and Stokoe 1983) state that geological age and soil types are not important. Earthquake geotechnical engineers considered it as a soil dependent and region specific.

3 Geology and geotechnical characteristics of the study area

The study area is located along the western margin of Gulf of Cambay which extends between latitude 22°00'N to 22°27'N and longitude 72°03'E to 72°22'E (Fig. 1). The western margin Cambay fault (WCMCF) lies 10 km east of Dholera (Biswas 1982). Geomorphologically, the area can be divided into three major zones; these are the (i) active mud flats/tidal flats, (ii) relict mud flats and (iii) salt waste (Fig. 1). Sedimentation in the western coastal margin is ascribed to the multiple events of transgression and regression during the late Quaternary (Allchin et al. 1978; Nigam et al. 1993; Merh and Chamyal 1993; Wagle et al. 1994). In the borehole data (subsurface), these events are represented by

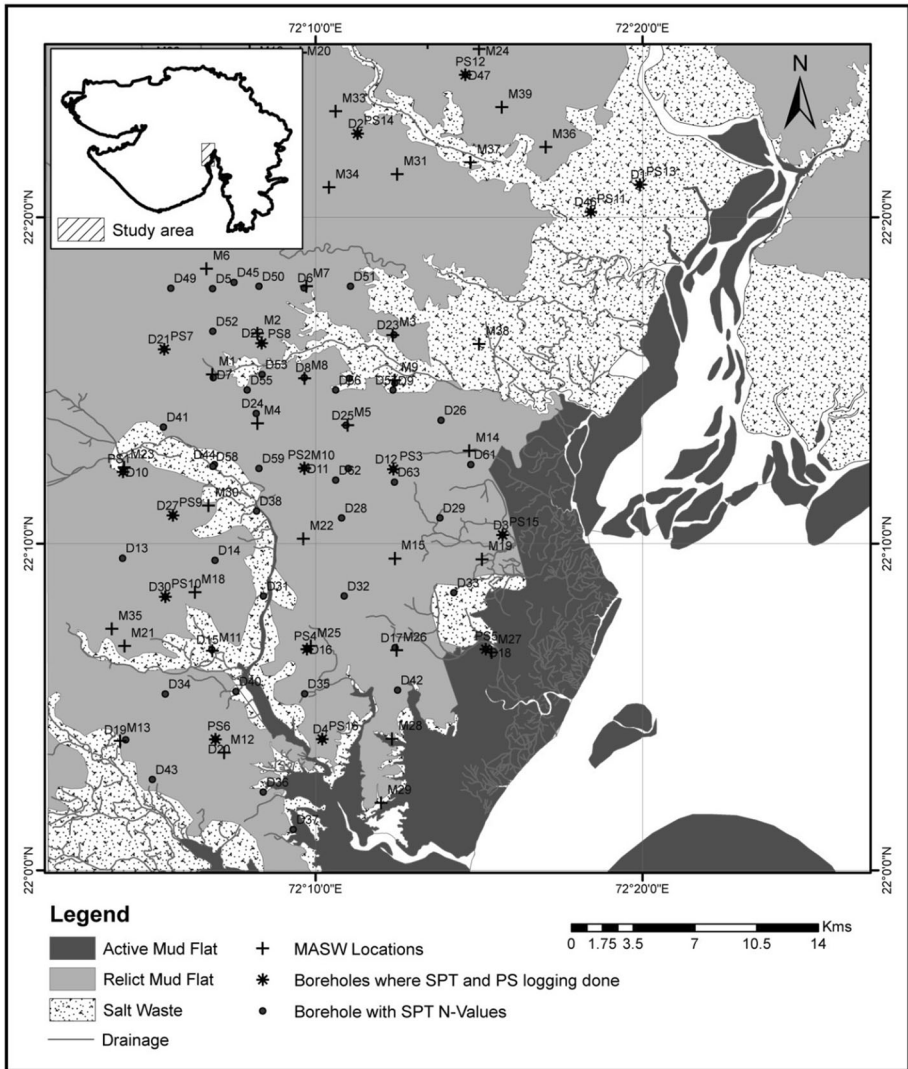


Fig. 1 Geomorphological map of the study area showing locations of boreholes, PS logging and MASW sites

the silty–clay rich layers (transgression), whereas the regression is represented by sand and silt facies.

4 Data used

SPT were conducted in accordance with IS: 2131 (1981) in boreholes at an interval of 3 m depth. The test gives *N*-value; the blow counts of last 30 cm of penetration of the split-spoon sampler with 65 kg hammer falling freely from 75 cm height. The rods to which the sampler is attached for driving are straight and tightly coupled in alignment. Thereafter, the split-spoon sampler is further driven by 30 cm. The number of blows required to drive each 15-cm penetration is recorded. The first 15-cm penetration is termed as a “Seating Value.” The no. of blow counts for last 30-cm penetration is termed as the “*N*-value.”

V_s is obtained from PS logging and MASW for obtaining high-resolution P and S wave velocity profile directly till 70 m depth. The suspension PS logging probe is about 8-meter long, which contains a weight, source driver, source (trigger), filter tube, lower and upper geophone, head reducer, cable head, 4-conductor cable, winch and logger/recorder. The interval between upper and lower receiver is usually 1 m, and distance from PS Source to lower receiver is 4 m. Three to nine stacks of triggers are used as an energy source to generate a pressure wave in borehole fluid. This pressure wave is received by the geophones, which send the data to the recorder on the surface. The acquired data were processed by MCS SUS acquisition software of OYO Inc, Japan.

MASW is relatively a recent technology in Geotechnical Engineering and Engineering Geophysics and is gaining a greater importance. It is based on the acquisition of the surface wave data, construction of dispersion curve and inversion of the *V_s* from the dispersion curve. Integrating the MASW technique with CMP (Common Mid Point) style data acquisition permits the generation of laterally multiple cross sections of the *V_s*. Vertically stacked 20 impacts of a 30 kg hammer on a metal plate were used as a source to generate seismic waves. These waves were recorded by twenty-four (24) vertical geophones/receivers of 4.5 Hz planted at a 2-m interval along the profile line. This spread is sequentially moved in steps of one geophone distance to get required profile length.

To understand geotechnical characteristics of the subsurface lithology, data of 27 boreholes lying close to MASW sites were used up to the depth of 30 m as the *V_s* values from MASW method are usually down to the depth of 30 m. These sites are covering the entire study area. SPT-*N* value is available at depth intervals of 3 m for all the boreholes.

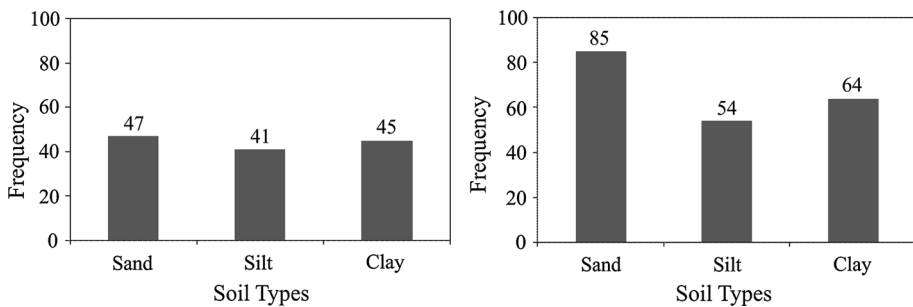


Fig. 2 Frequency of data points based on soil type having (right) *V_s* by PS logging and (left) *V_s* by PS logging and MASW

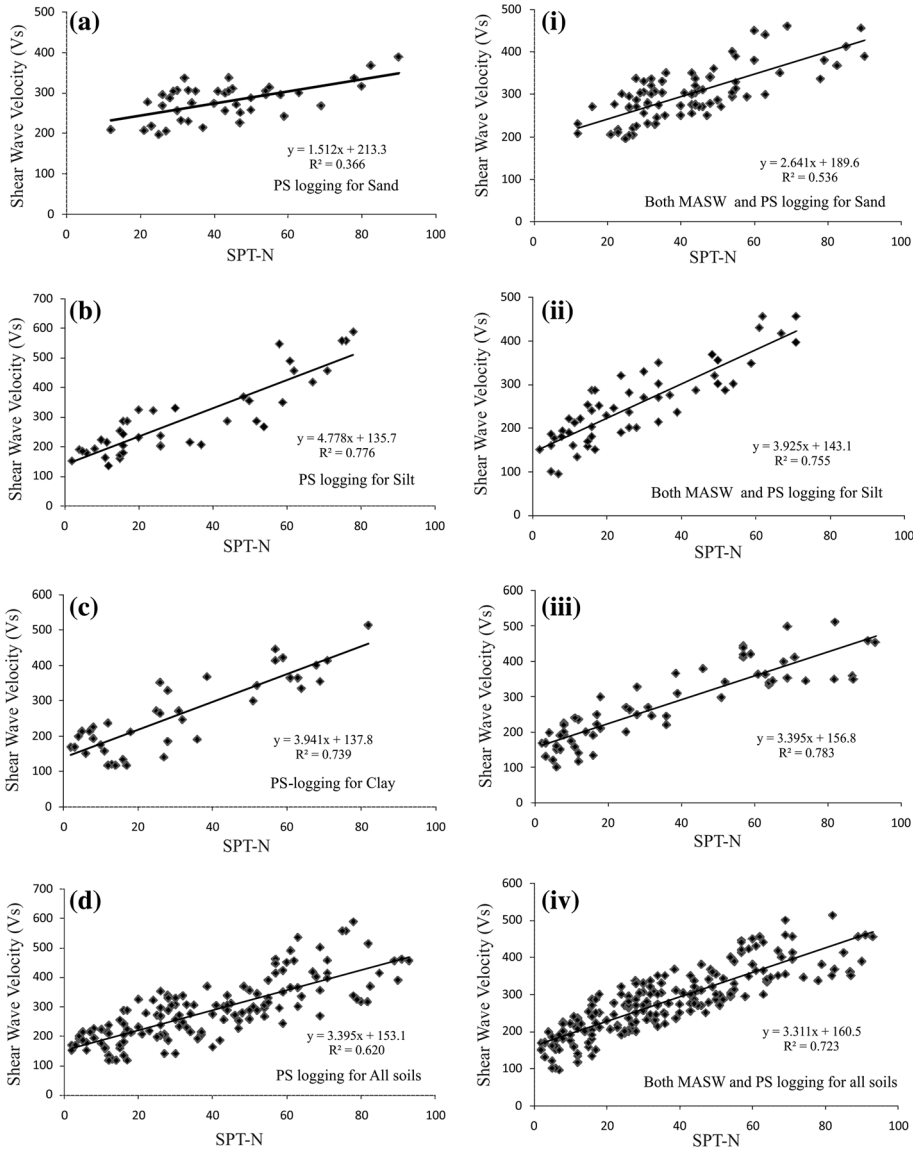


Fig. 3 Correlation between Vs and SPT-N for PS logging data **a** sand, **b** silt, **c** clay, **d** all soils and both MASW and PS logging **i** sand, **ii** silt, **iii** clay, **iv** all soils

SPT were done as per Indian Standards code. Samples collected from the boreholes were used for laboratory analysis to determine the geotechnical properties of the soil such as Atterberg’s limit, grain size analysis, specific gravity, moisture content and density of the subsurface sediments. Vs data were collected from MASW and PS logging test. Out of total 27 boreholes, 16 boreholes have PS logging data and 11 boreholes are near the MASW sites. It may be mentioned that six boreholes have Vs data from both MASW and PS logging. The frequencies of data used for the present N-Vs study are shown as graphical

Table 1 Proposed regression equation between uncorrected SPT-N values and shear wave velocities, V_s , for different categories of soils

Soil types	Proposed regression equation using PS logging data	Proposed regression equation using both MASW and PS logging data
Sand	$V_s = 1.512 \times \text{SPT-N} + 213.3; R^2 = 0.366$	$V_s = 2.641 \times \text{SPT-N} + 189.6; R^2 = 0.536$
Silt	$V_s = 4.778 \times \text{SPT-N} + 135.7; R^2 = 0.776$	$V_s = 3.925 \times \text{SPT-N} + 143.1; R^2 = 0.755$
Clay	$V_s = 3.941 \times \text{SPT-N} + 137.8; R^2 = 0.738$	$V_s = 3.395 \times \text{SPT-N} + 156.8; R^2 = 0.783$
All soils	$V_s = 3.395 \times \text{SPT-N} + 153.1; R^2 = 0.620$	$V_s = 3.311 \times \text{SPT-N} + 160.5; R^2 = 0.723$

form in Fig. 2a for V_s obtained from PS logging and Fig. 2b for V_s from both PS logging and MASW.

The soil classification of the study area is done according to IS code for all the samples collected for laboratory analysis. Geotechnical analysis of the borehole samples indicates that the sediments of the study area consist of both fine-grained and coarse-grained soil. Fine-grained soil ranges from low to high plasticity silt and clay, while coarse-grained soil are classified as silty sand to poorly graded sand. The SPT-N values are less than 10 in most boreholes down to the depth of 6 m. Below 6 m depth, the values increase. SPT-N values greater than 100 are observed at depth of 30 m in most of the boreholes.

Seismotectonically, the area lies in the Seismic Zone III of Seismic Zoning Map of India (BIS 2002) where earthquakes of magnitude up to 6 (Intensity of VIII) can be expected. The region has experienced several earthquakes of magnitude ≤ 6 in the past.

5 Seismic site classification

Seismic site classification can be done based on any one of the following three parameters, i.e., undrained shear strength (S_u), standard penetration resistance (N -value) and shear wave velocity (V_s) values. The design spectrum of each site is determined based on its site class, 30 m average V_s values (Borcherdt 1994), 30 m average standard penetration resistance (N_{30}) and undrained shear strength (S_u). Both the Uniform Building Code (UBC) and Eurocode 8 (EC8) codes use V_{s30} to classify sites, for earthquake engineering design, according to soil types. V_s can be directly measured from field test or can be estimated from existing correlations between N -values and V_s (Hansancebi and Ulusay 2007). V_{s30} are useful for seismic zonation studies (Koçkar et al. 2010). In India, a few cities have been classified considering V_{s30} and many other cities are still under study (Mark et al. 2001; Anbazhagan et al. 2011).

Seismic site classification of the study area is done based on 30 m average standard penetration resistance (N_{30}) and average shear wave velocity (V_{s30}) values. The V_{s30} of the study area ranges from 193 to 341 m/s. According to NEHRP (BSSC 2003), the study area comes under the site class D in which V_{s30} ranges from 180 to 360 m/s. The N_{30} of the study area also comes under the site D ($N_{30} = 15\text{--}50$ blows/0.3 m) of NEHRP site classification except in three boreholes out of total 64 boreholes. It can be mentioned that both the N_{30} value-based and V_{s30} -based seismic site classification gives the similar result.

6 Correlation between SPT-N and V_s

Total 336 data pairs were used for the present regression correlation study using simple regression analysis for the existing database. Three categories of the soils, i.e., sand, silt, clay and all soils together were considered for developing regression equation between

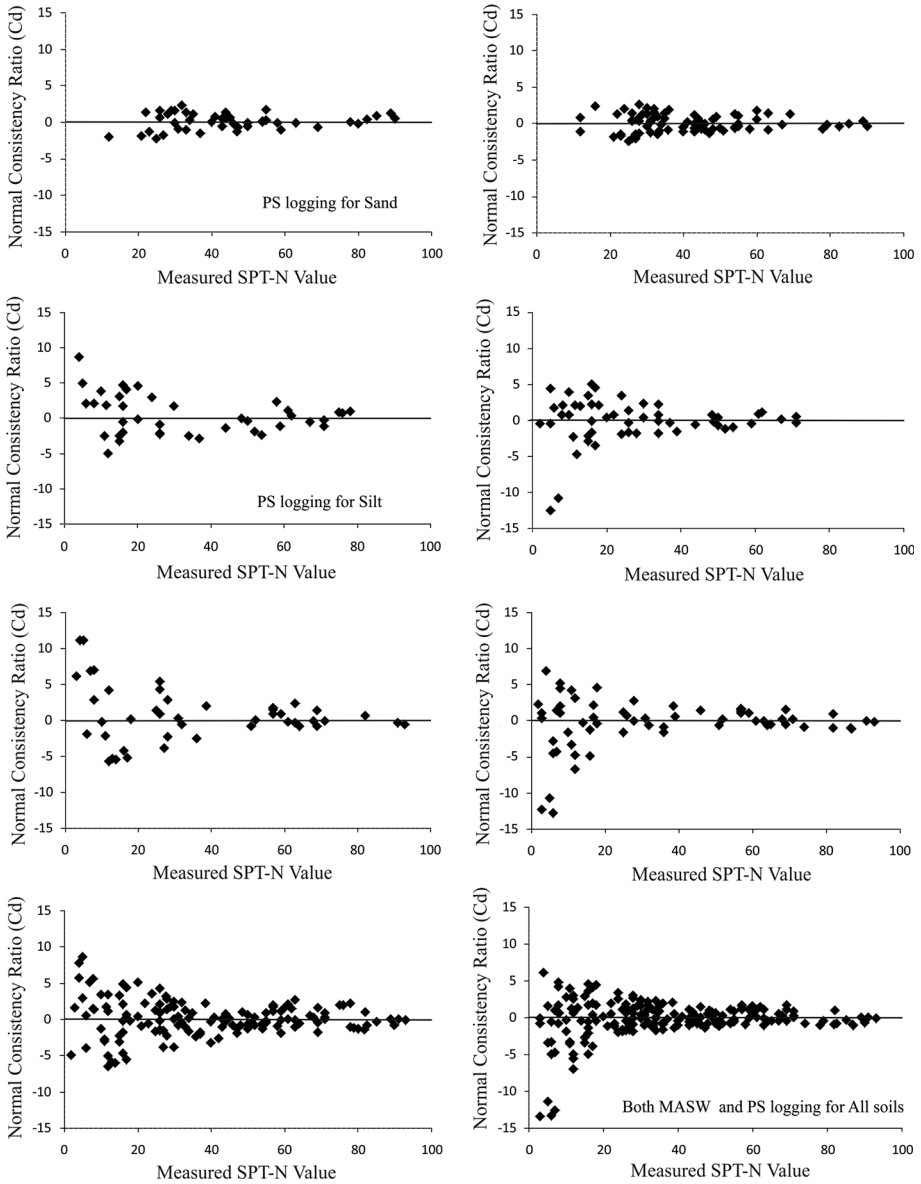


Fig. 4 Normal consistency ratio for sand, silt, clay and all soil of PS logging and both MASW and PS logging

uncorrected SPT-N values and measured Vs (Fig. 3). Regression equations are developed for PS logging data separately and for both MASW and PS logging data taken together. The equations developed for the correlation between SPT-N values and Vs of the study area are shown in Table 1.

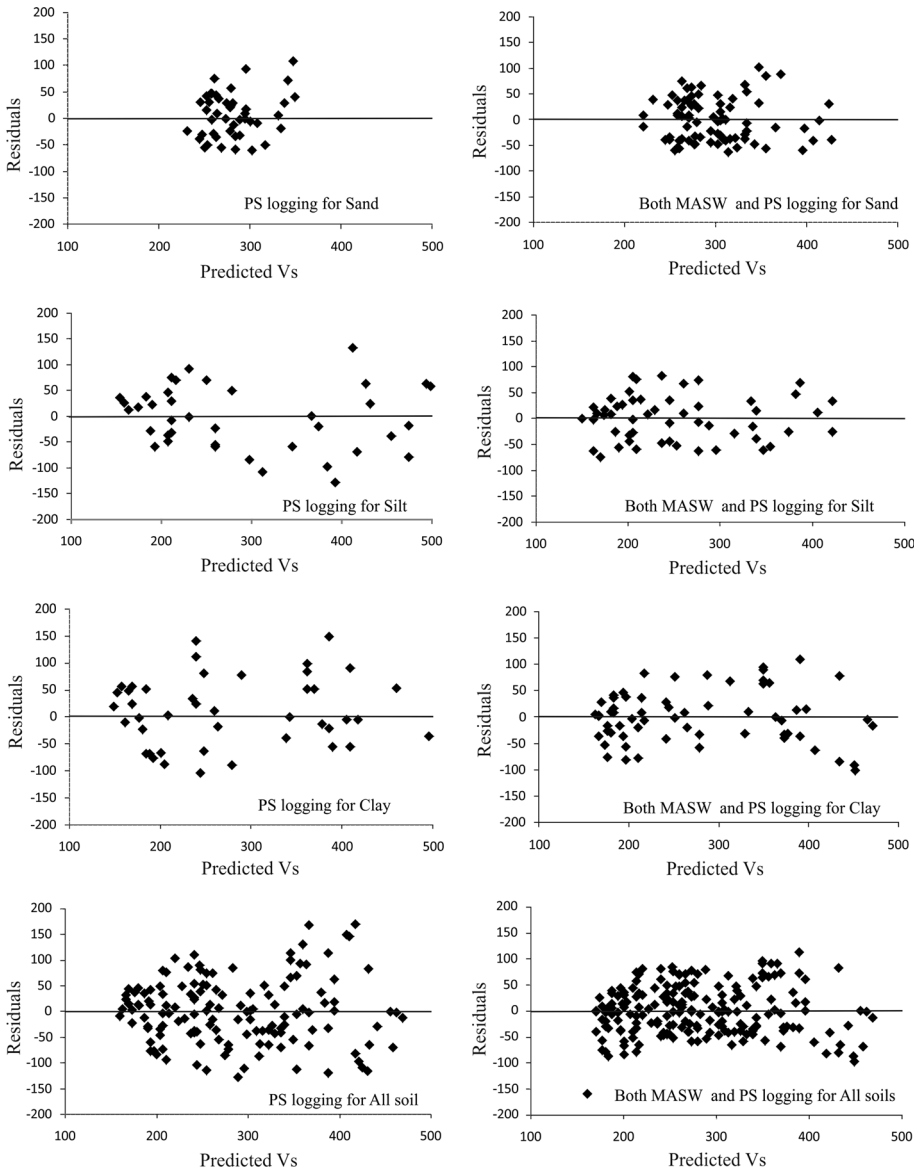


Fig. 5 Residuals plot for the sand, silt, clay and all soil types of PS logging and both MASW and PS logging data

7 Validation of the regression graph using graphical analysis

The proposed regression equation can be validated based on root-mean-square (RMS) values and graphical residual analysis. The equation validated based on RMS value provides only information about the whole set of data used in the analysis. Graphical residual analysis is the primary tool for validating the correlation between the observed and predicted values. The adequacy of different types of regression model is provided by different

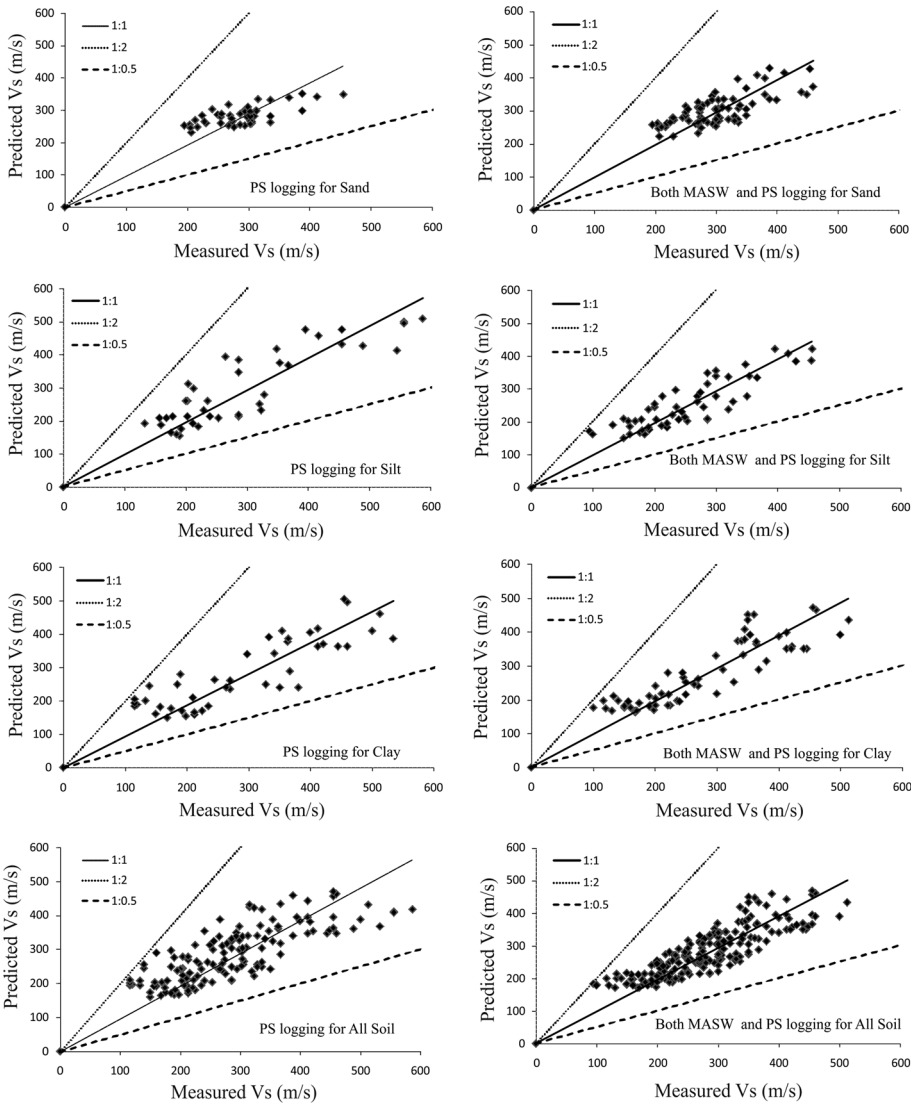


Fig. 6 Comparison between measured versus predicted V_s for sand, silt, clay and all soil of Ps logging and both MASW and PS logging data

types of plots of the residuals from a model. Hence, to validate the proposed regression equation, for the correlation between SPT-N values and V_s , different graphical methods were used for all categories of soils type.

7.1 Normal consistency ratio, C_d

The normal consistency ratio (C_d) is defined as the ratio of the difference of the predicted and observed shear wave velocity to measured SPT-N value. It can be calculated as (Dikmen 2009):

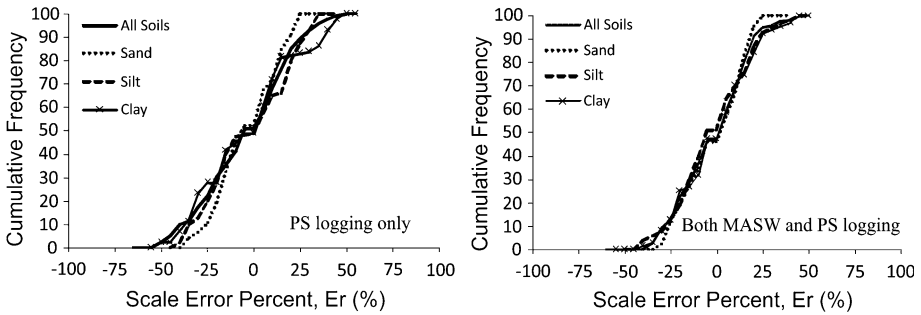


Fig. 7 Scale error for the proposed regression correction

$$Cd = \frac{(Vs_{obs} - Vs_{pre})}{SPT-N} \tag{1}$$

where Vs_{obs} is the measured shear wave velocity, Vs_{pre} is the calculated shear wave velocity using the proposed regression equation, and $SPT-N$ is the measured SPT-N value corresponding to Vs_{obs} . Comparison between the normalized consistencies ratios with SPT-N value for all categories of soils are shown in Fig. 4. It is observed that the average value of Cd is close to zero, which indicates that the predicted Vs values are very close to the measured Vs . When SPT-N value is less than 15, the predicted Vs values have an error range of 5–10% with respect to measured Vs .

7.2 Graphical residual plot

The graphical residual plot of the regression correlation of the SPT-N and Vs for all categories of soil types, i.e., for sand, silt, clay and all soils for PS logging and both MASW and PS logging are shown in Fig. 5. The graphs shows horizontally distributed and uniformly scattered with more or less equal variance from the horizontal axis. This indicates that the regression model is in good agreement.

7.3 Comparison between predicted and measured Vs

Figure 6 shows comparison between the measured Vs and predicted Vs for all newly proposed set of regression equation. All the points lie between the lines with 1:0.5 and 1:2 slope lines with most of the points scattered toward the line 1:1 slope, which suggest a reasonable fit for the present investigated soils.

7.4 Scale error percent, (Er) Vs cumulative frequency

The scale error percent and cumulative frequency were used to compare the performance of the new proposed correlation relationship with measured data. Scale error percent is define as (Dikmen 2009):

$$Er = 100 \times \frac{(Vs_{pre} - Vs_{obs})}{Vs_{pre}} \tag{2}$$

where Vs_{obs} is the measured shear wave velocity, and Vs_{pre} is the calculated shear wave velocity using the proposed regression equation. Scale error percen variation for the set of

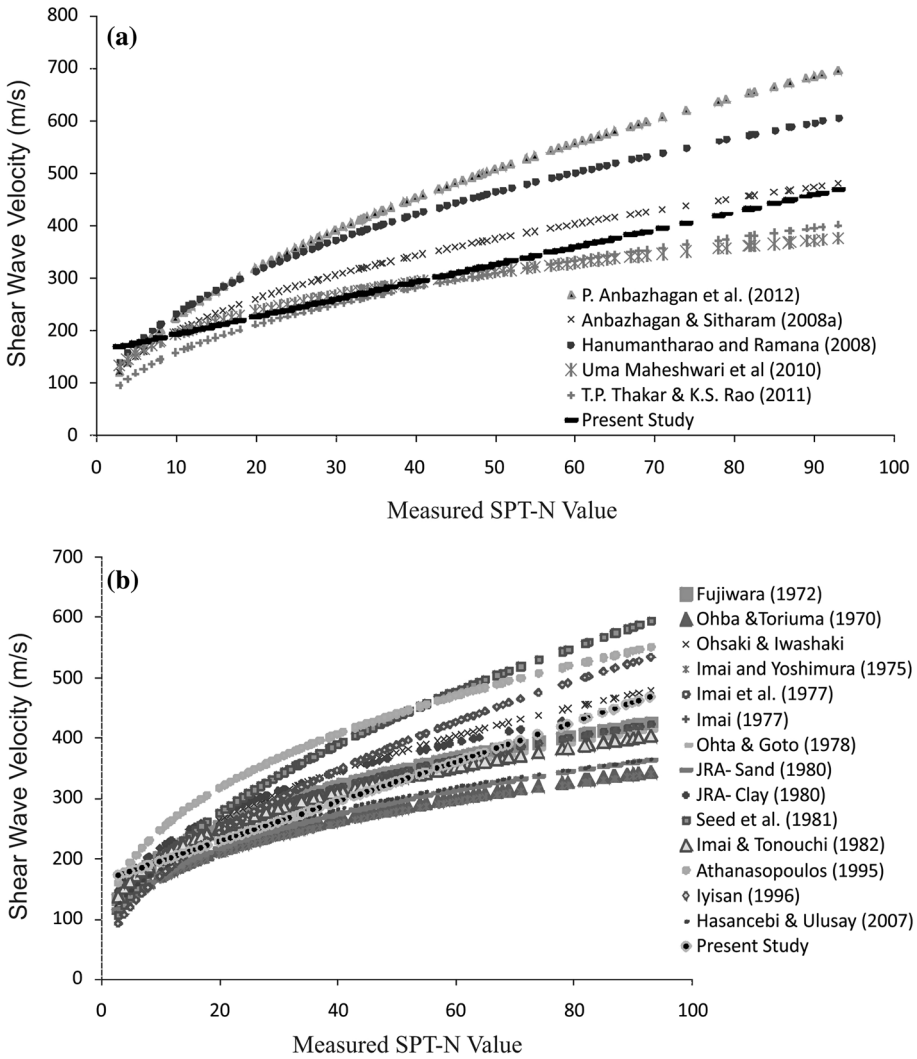


Fig. 8 Comparison of the proposed regression equation with **a** other relations developed in India and **b** worldwide relations for all soils type

regression equation developed for different soil categories is shown in Fig. 7. It shows that 85% of the predicted data falls within $\pm 25\%$ error.

7.5 Comparison of the proposed equation with the existing relations

Figure 8a shows the comparison of the proposed regression equation with other relations developed in India. It is observed that the new regression equation for all soils is similar to Anbazhagan and Sitharam (2008a) and Uma Maheshwari et al. (2010) up to SPT-N value of 20. Hanumantharao and Ramana (2008) and Anbazhagan et al. (2012) give high Vs values with increase in SPT-N values for all soils type.

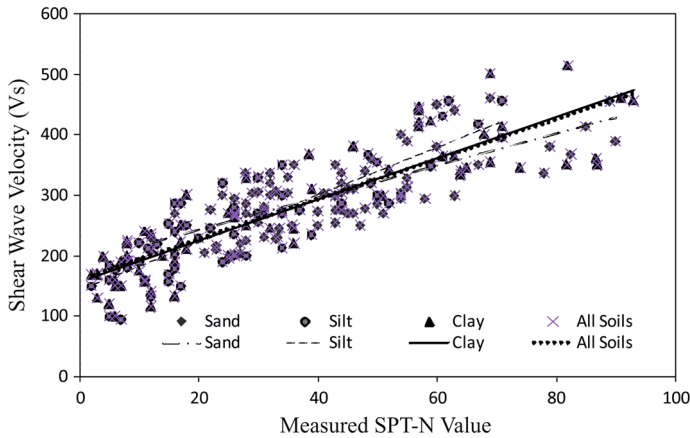


Fig. 9 Comparison of all the proposed regression equation for all type of soils

The proposed relation is also compared with the existing relations developed by global researchers. Comparison of the proposed regression equation with worldwide relations for all soils type is shown in Fig. 8b. It can be observed that the newly proposed equation is comparable for all values of SPT-N with the existing relations developed by Imai and Tonouchi (1982) while Fujiwara (1972) and Imai (1977) reported similar values for SPT-N value up to 25 but little higher values when SPT-N value is greater than 25. Ohshaki and Iwashaki (1973), Seed et al. (1981), JRA-clay (1980) and Athanasopoulos (1995) give much higher Vs values as compared with the present study with increase in SPT-N value. Iyisan (1996) underestimates the Vs value up to SPT-N value 25 and overestimates when SPT-N value greater than 25.

8 Conclusions

Considering 336 pairs of data of uncorrected SPT-N values and V_{s30} , a relation between the two parameters has been determined for Dholera area of Western India. These data were grouped according to the soil types, i.e., sand, silt, clay and all soils to generate the regression correlation for different types of soils. There is not much variation of the relation for different types of soils (Fig. 9). The newly developed relation is found to be statistically and graphically significant. It can be concluded that the soil type does not change much the correlation. Seismic site classification is also done for the study area according to NEHRP soil classification based on V_{s30} and N_{30} . Total 57 sites for V_{s30} and 63 sites for N_{30} were used for seismic site classification of the study area. The study area falls under site D, which is classified as stiff soil. Both the parameters give the same site classification for the present study.

The newly developed regression equation for all categories of soils taken together is comparable with the equations developed by various investigators from different parts of the World including India. Hence, the result obtained from the new correlation can be used for the preliminary seismic microzonation and seismic site response for the study area. It can also be used for the area having similar soil strata as the present area.

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