Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-94

Correlation between Shear Wave Velocity (Vs) and corrected SPT-N for Bharuch Region of Gujarat, India

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ABSTRACT

The assessment of ground motion during an earthquake depends on the shear wave velocity (*Vs*) of the existing soil strata. The *Vs* determines the characteristics of soil layer under earthquake motion at a given site. However, the *Vs* profile of a particular region is not readily available. The correlations of *Vs* with standard penetration (SPT) resistance can be of significant importance in such conditions. The present study discusses the development of a correlation between *Vs* measured by multi-channel analysis of surface waves (MASW) testing and corrected N value measured by SPT at various sites in the Bharuch region of Gujarat, India (located in seismic zone III). These tests were carried out at nine locations within a twenty-kilometer radius of the Bharuch region. An empirical correlation between *Vs* and corrected *N* was developed based on statistical assessments. The regression coefficient (R^2) value of *Vs* with corrected *N* was found to be 0.8752. At each site, roll-along MASW tests were carried out to estimate the two-dimensional (*2D*) *Vs* profile using spatial resolution techniques. According to the NEHRP guidelines, these sites were classified as *C* and *D* based on *Vs30* computed from 1D *Vs* profile using the MASW technique. The proposed relationships can be helpful in seismic microzonation and seismic hazard analysis of this earthquake-prone region.

Keywords: Shear wave velocity, Earthquake, SPT-N, MASW, Seismic zone

1 INTRODUCTION

The presence of soil deposits at a site has a big impact on the characteristics of an earthquake motion. Either a rigorous site-specific ground response study is performed, or a simplified site classification method is used to analyze the ground motion characteristics. Shear wave velocity (*Vs*), which reflects the stiffness of the soil layers, is the most significant parameter for all of these techniques (Sykora, 1987). Typically, wave propagation tests are used to determine the *Vs* profile at a site (Xia et al., 2002). But performing these assessments at every site is frequently not economically feasible. However, at many sites where geotechnical investigations are conducted, the numbers of blows (*N*) from standard penetration tests (SPT) are easily accessible. An accurate empirical correlation between *Vs* and *N* would be highly advantageous in this perspective. The Bharuch region of Gujarat is in seismic zone III on the bank of the Narmada River, which comes in the range of 0.24-0.36g of peak ground acceleration (PGA) according to IS 1893 (Part 1). The Sardar Sarovar dam was affected by 5.4-magnitude earthquakes in Bharuch in 1970 near the Narmada rift zone.

For soil investigation of the Bharuch region, an effort has been made to establish a reliable correlation between *Vs* and SPT-*N*. Multichannel analysis of surface waves (MASW) tests and SPTs were conducted at nine sites within a 20-kilometer radius of Bharuch city to determine the *Vs* profiles. The correlations between *Vs* and SPT-N with and without corrections were developed for the study region.

In past studies, numerous attempts have been made to correlate the values of *Vs* to readily available soil parameters like the *N* value. Anbazhagan & Mahesh (2007) conducted MASW surveys for approximately 38 locations in Bangalore city to establish a correlation between *Vs* and corrected SPT-N values. Hanumantharao & Ramana (2008) developed correlations between *Vs* and SPT-N values for Delhi city up to the depth of 20–32 m. Thaker & Rao (2011) developed a correlation between *Vs* and SPT-N values for the Surat city of Gujarat. Maheshwari et al. (2013) performed MASW and SPT surveys for the Ganga Basin at two places, Dhanauri and Roshnabad, and established correlations between *Vs* and SPT-N values.

Kirar et al. (2016) developed a separate correlation between *Vs* and SPT-N for all types of soils, sands, and clays. They observed that these correlations lie in the range of other correlations for various sites. However, the literature does not include the correlation of *Vs* and SPT N for the Bharuch region, which is of local importance. The *Vs*-corrected SPT-N relationship for nine locations in the Bharuch region has been addressed in the current work. In order to do this, MASW tests were used to determine the *Vs*, and SPTs were used to calculate *N* values.

2 GEOTECHNICAL INVESTIGATION

Standard penetration tests (SPT) in accordance with IS 2131 (1981) and laboratory test of the samples collected from all nine sites were used in the geotechnical investigations. Table 1 details each of the nine sites, including locations, water tables (WT), and borehole depths. The boreholes on the left and right banks of the Narmada River were marked as left-bank boreholes (LBBH) and right-bank boreholes (RBBH). Figure 1 represents the alignment of these boreholes, the distance between two consecutive boreholes, and the direction of MASW tests at respective borehole locations. These boreholes of 150mm diameter were drilled up to 30 m depth or up to the depth of two consecutive refusals in SPT, whichever is earlier. Undisturbed soil samples were collected in 100 mm diameter Shelby tubes in these boreholes. The SPT test setup had an automatic free-fall hammering system, as detailed in Bolton Seed et al., (1985). It was ensured that it strictly followed the weight and height parameters as per IS code (IS 2131) for every blow.

Table 1. *Details of Sites*

Boreholes	Longitude	Latitude (m)	Water Table (m)
RBBH1	E21.66378	N72.80015	6.70
RBBH4	E21.68317	N72.79897	4.95
RBBH5	E21.69247	N72.80934	5.20
RBBH6	E21.70879	N72.80955	5.10
LBBH1	E21.64898	N72.80463	2.95
LBBH4	E21.63835	N72.8069	3.15
LBBH5	E21.62088	N72.8129	4.21
LBBH6	E21.60395	N72.81839	4.50
LBBH7	E21.58575	N72.82261	9.81

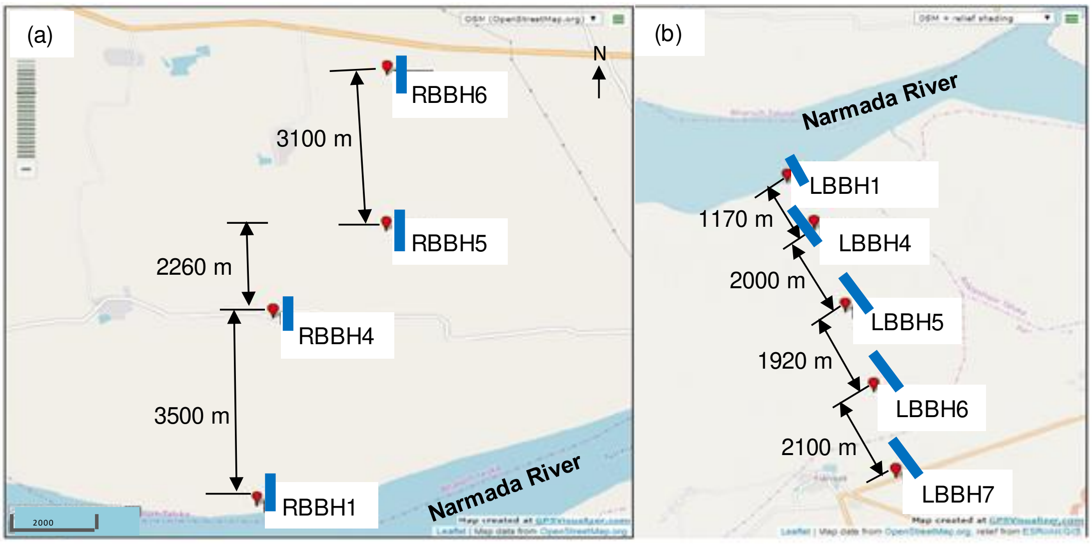

Figure 1. *Location and alignment of (a) Right bank boreholes (RBBH); (b) Left bank boreholes (LBBH) on the bank of Narmada River. MASW locations are marked by blue lines near the respective borehole location.*

Table 2 lists the soil type, fine particle range, uncorrected and corrected SPT-N, and *Vs* for each of the nine sites. The locations RBBH6, LBBH6, and LBBH7 exhibit the SPT-N range of 8 to 26. The fines (%) of these sites lie in the range of 60 to 90 for the clay with intermediate to high plasticity. Except for RBBH1 and RBBH5, fines content is relatively low (20 to 60 %) because of silty sand (SM). The LBBH6 site is the weakest (*N*: 8-11), whereas the LBBH4 sites are the strongest (*N*: 25–51) for the shallow depth (0 to 10 m), as can be seen in Table 2.

Table 2. *Type of soil, range of fine contents, SPT-N, N" and Vs for all the nine sites*

Borehole	Depth (m)	%Fines	Soil type	SPT-N	SPT-N corrected	Vs range (m/s)	Vs30 (m/s)
RBBH1	1-30	89-97	CI-CH[a]	13-52	17-25	150-350	260
RBBH4	1-16	72-97	CI-CH	10-39	14-23	150-450	320
	19-30	40-65	SM[b]	36-53	18-21		
RBBH5	1-5	68-95	CI-CH	10-20	15-25	150-500	300
	7-30	84-96	ML[c]	29-46	16-18		
RBBH6	1-17	67-81	CI-CH	10-26	13-17	150-600	420
	19-25	60-90	CI[d]	38-53	18-20		
	27-29	18-25	SM	47-50	17-19		
LBBH1	1-19	14-76	SM	11-46	13-20	100-300	180
	22-25	57-73	CI	71-83	25-32		
	25-30	28-36	SM	79-88	25-32	100-300	
LBBH4	1-30	13-30	SM	25-51	16-22	100-300	200
LBBH5	1-30	11-89	SM	5-52	11-25	100-300	190
LBBH6	1-7	83-93	ML	8-11	11-14	100-300	190
	9-30	16-58	SM	8-50	11-21		
LBBH7	1-5	68-76	CI	8-26	14-22	150-500	310
	7-11	17-79	SM	28-40	22-24		
	13-30	14-93	CI-CH	26-50	16-21		

[a] Clay with intermediate to high plasticity, [b]Silty sand, [c]Silt with low plasticity, [d]Clay with intermediate plasticity.

3 MASW TEST

The MASW tests were performed at nine locations on the bank of the Narmada River, as marked in Figure 1. This test is generally quick and inexpensive among geophysical techniques (Abhishek & Rangaswamy, 2023). The 24 vertical geophones with a natural frequency of 4.5 Hz were placed in a linear array length of 46 m with a 2 m spacing for the survey. Each geophone was connected to a multi-channel cable, which was further connected to the data acquisition system (Park et al. 2001).

A 10 kg sledge hammer used as the active source (*S*) for striking the metal plate at an 18 m offset distance (X_1). The dispersion images were generated using a phase-shift method after collecting the wave-fields (Park et al. 1998), as shown in Figure 2. The borehole's numbers are written in the respective dispersion images. The phase velocities of maximum spectral amplitudes were extracted from the dispersion image at various frequencies, which provided the experimental fundamental mode dispersion curve. The distinct points of the experimental fundamental mode were used in the inversion process. These fundamental modes were inverted to estimate the *1D Vs* profile along depth for each of the nine sites.

Figures 3a-3b, 3c-3d, 3e-3f, and 3g-3h represent the corrected SPT-N and *1D Vs* profile along the depth for the site located at boreholes RBBH1, RBBH4, RBBH5, and RBBH6, respectively. The variation of SPT-N and *Vs* profiles showed a good comparison along the depths. The multiple MASW tests were also performed at each location in a roll-along arrangement to generate the 1D *Vs* profiles, which were used in establishing the correlations, as shown in Fig 4. These 1D *Vs* profiles were utilized to obtain the 2D *Vs* profile. The soil stratifications were compared using the 2D *Vs* profile and respective SPT-N values.

Figures 5a-5b, 5c-5d, 5e-5f, 5g-5h, and 5i-5j compare the corrected SPT-N and *1D Vs* profile along the depth for the site located at boreholes LBBH1, LBBH4, LBBH5, LBBH6, and LBBH7, respectively. Figure 6 exhibits the 2D *Vs* profile obtained from multiple MASW tests performed in a roll-along arrangement. Each site shows a similar variation of corrected *N* from SPT and soil stratification from the *2D Vs* profile obtained using the MASW test. Except for RBBH5, the regular soil profile is depicted from RBBH1, RBBH4, and RBBH6 by comparing the corrected SPT-N and 1D *Vs* profile along the depth, as shown in Figure 3. For LBBH1, LBBH4, and LBBH5, the *Vs* was in the range of 250-300 m/s at a depth of 10 to 20m. However, it is significantly low (*Vs* 150-200 m/s) for the depth of 0 to 10m. The shear wave velocity for RBBH5, RBBH6, and LBBH7 show the high *Vs* range (400-600 m/s). As a result, findings from MASW tests and those from corrected *N* values are compared with good agreement.

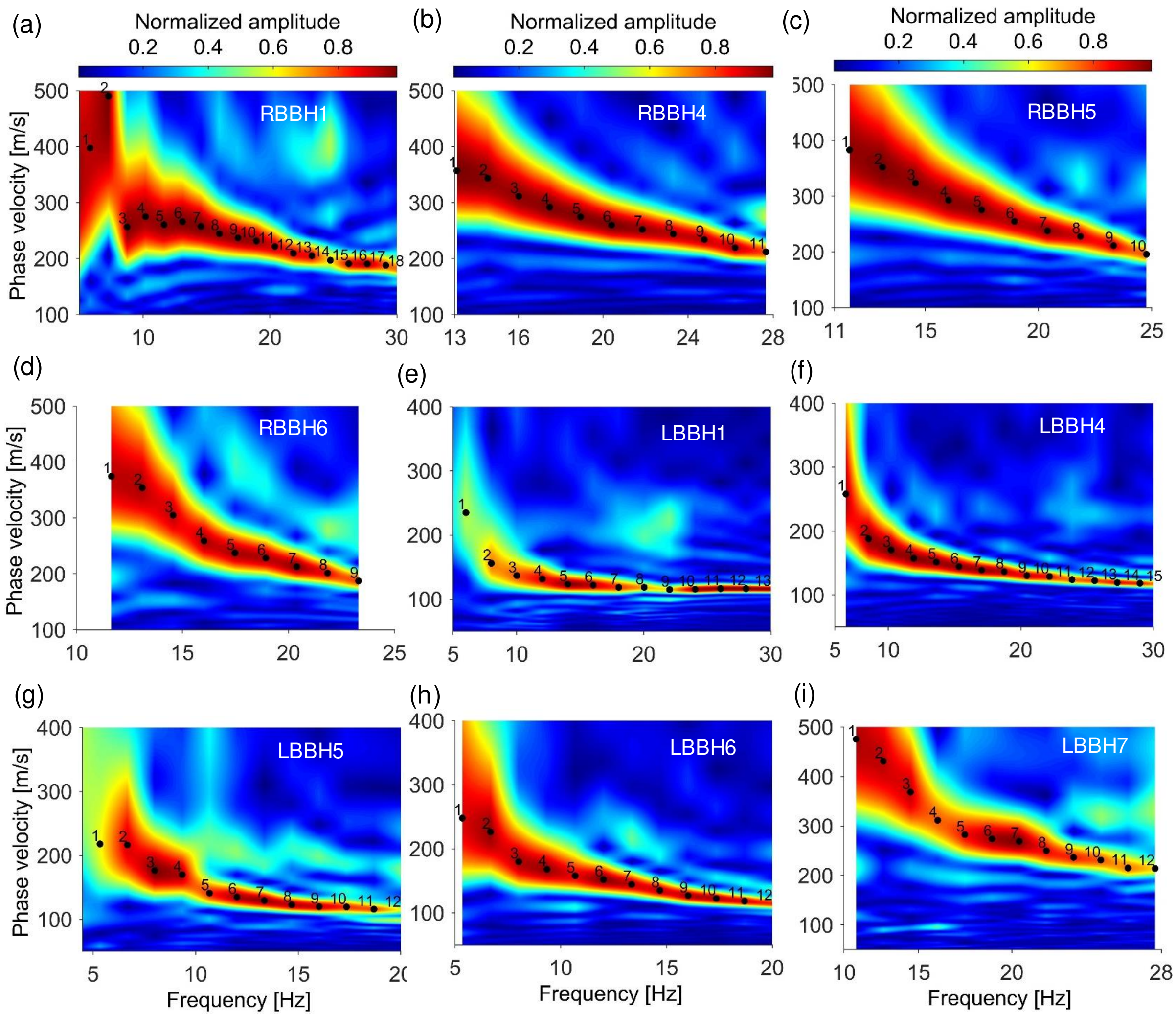

Figure 2. *Dispersion images for the sites located near borehole (a) RBBH1; (b) RBBH4; (c) RBBH5; (d) RBBH6; (e) LBBH1; (f) LBBH4; (g) LBBH5; (h) LBBH6; and (i) LBBH7*

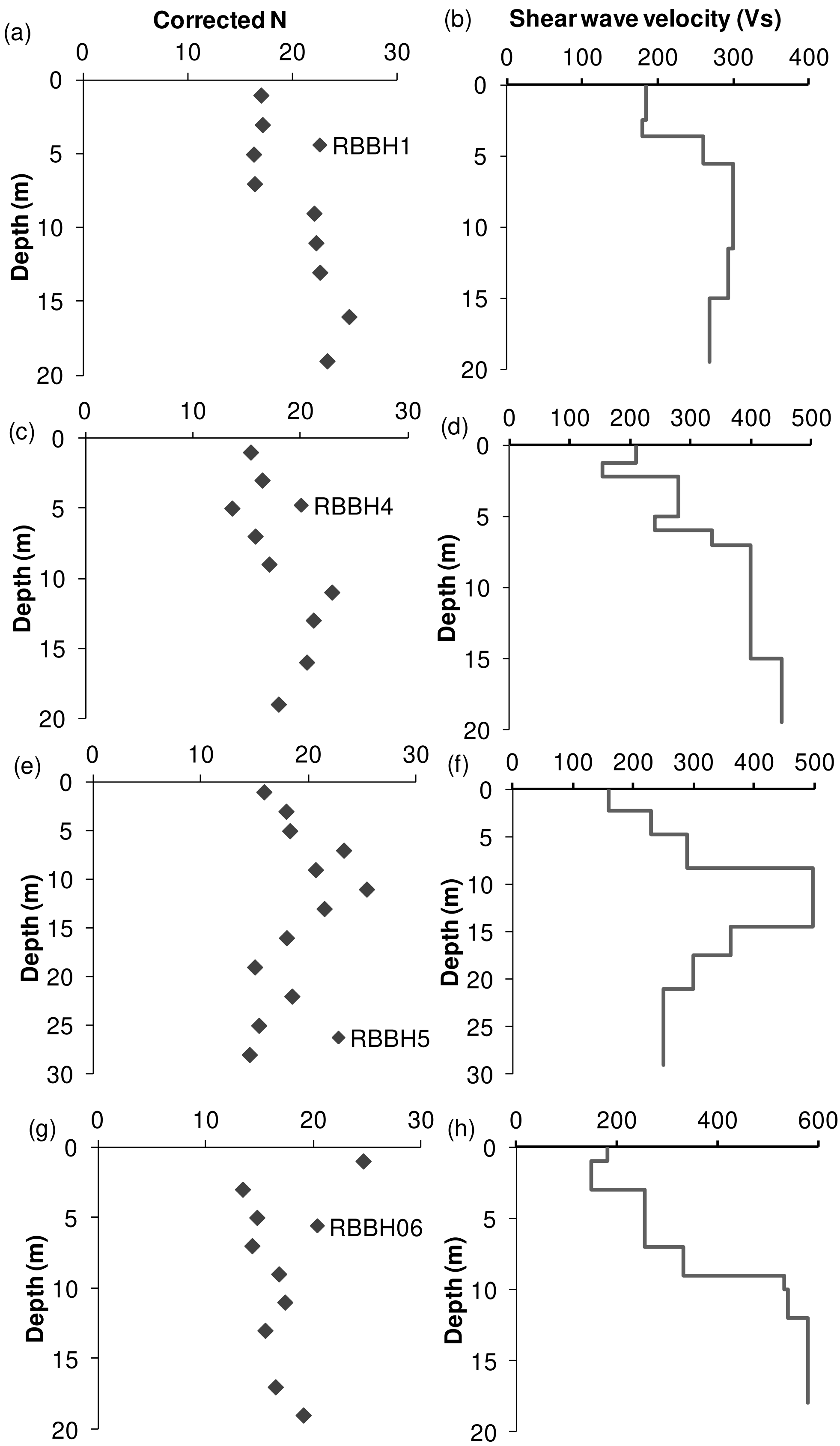

Figure 3. *Variation of corrected SPT-N and 1D Vs for right bank boreholes (RBBH). The corrected SPT-N values are shown on the left side, and 1D Vs profiles are presented on the right side of the respective site.*

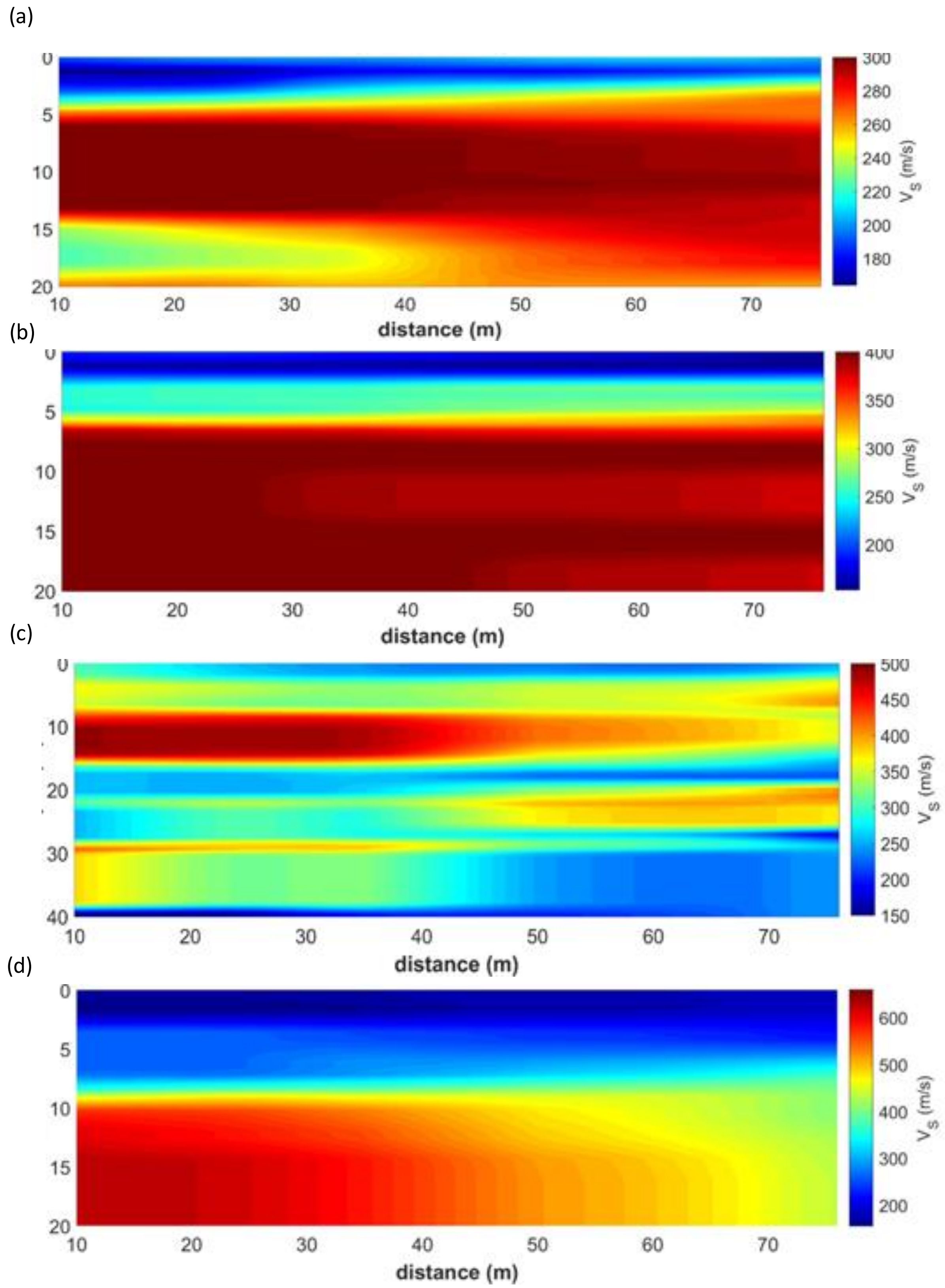

Figure 4. *2D Vs profile for right bank boreholes (a) RBBH1; (b) RBBH4; (c) RBBH5; and (d) RBBH6*

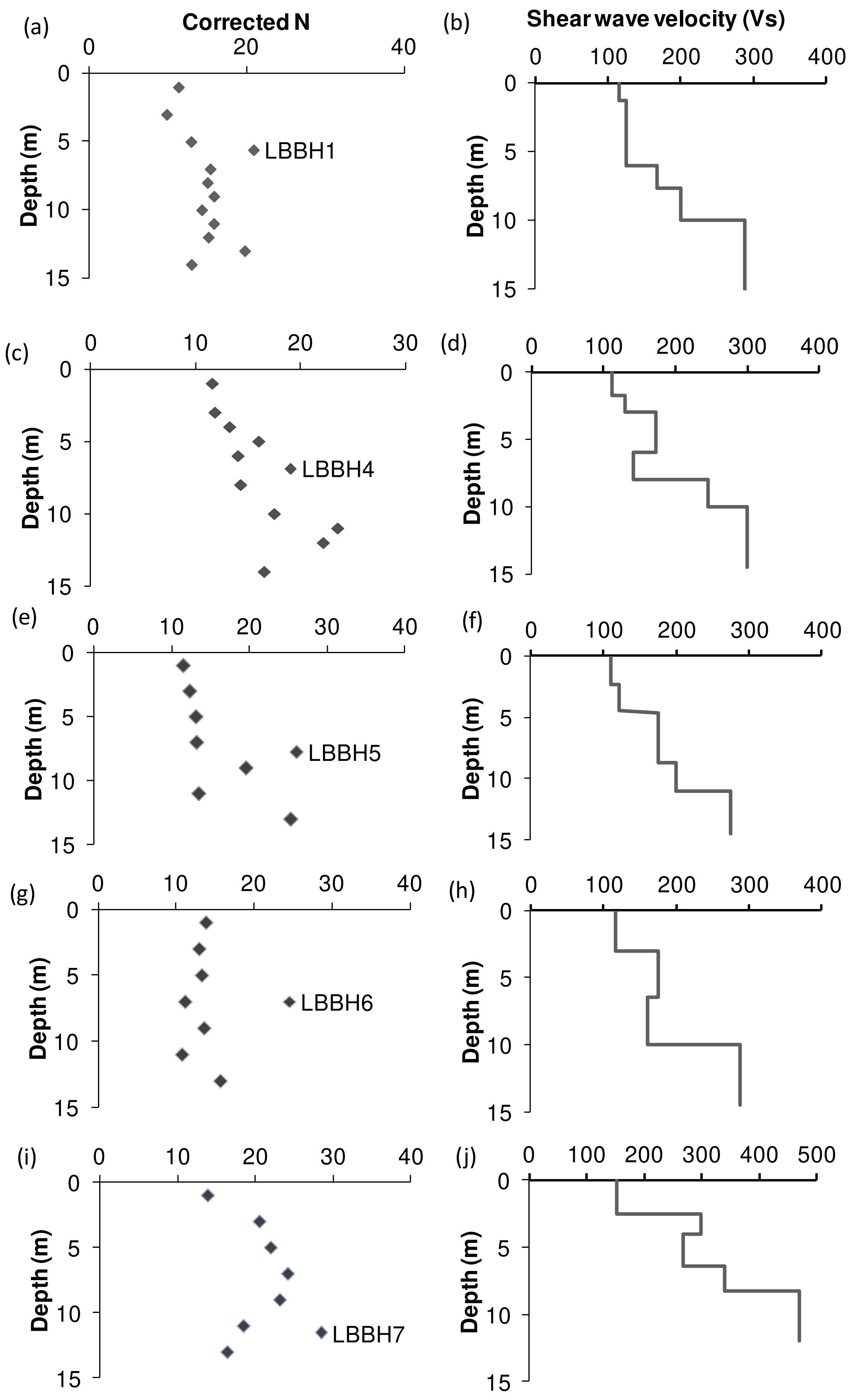

Figure 5. *Variation of corrected SPT-N and 1D Vs for left bank boreholes (LBBH). The corrected SPT-N values are shown on the left side, and 1D Vs values are presented on the right side of the respective site.*

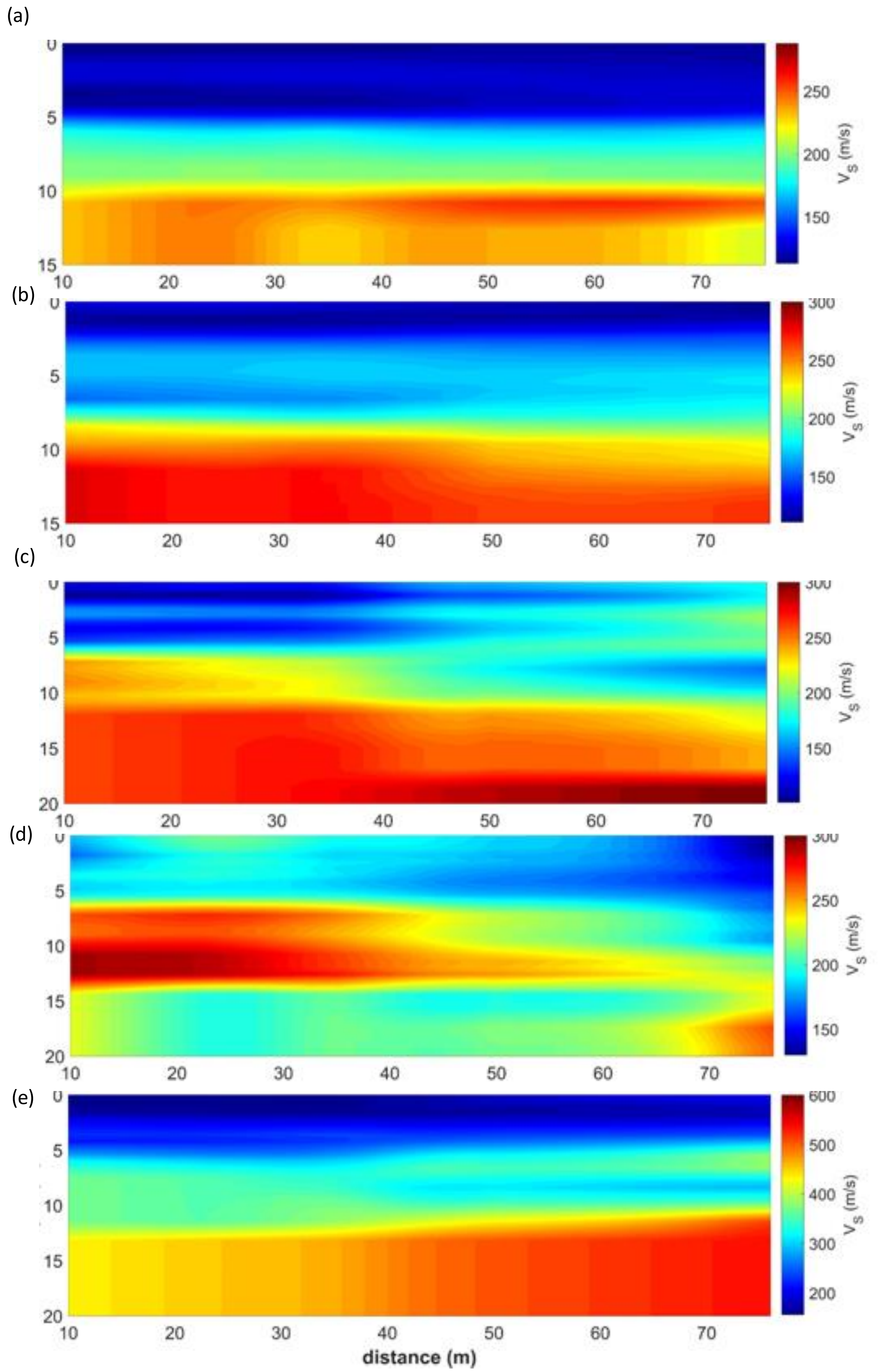

Figure 6. *2D Vs profile for right bank boreholes (a) LBBH1; (b) LBBH4; (c) LBBH5; LBBH6; and (d) LBBH7*

4 PROPOSED EMPIRICAL RELATION

The present study focuses on the correlation of *Vs* with uncorrected and corrected SPT-N values. Figure 7a shows the correlation of *Vs* and uncorrected SPT-N for all soils utilized in this research work. The correlation coefficient for this relationship is $R^2 = 0.874$, which is a respectable number. The *Vs* and corrected SPT-N for all soils were correlated in Figure 7b. This has a correlation coefficient R^2 of 0.8752, which is a good number. In between these correlations, the *Vs* and corrected SPT-N show a more significant correlation coefficient compared to that of uncorrected SPT-N. As a result, it is observed that the suggested *Vs* with corrected SPT-N value produced good correlations for the Bharuch region. The sites corresponding to borehole RBBH1(*Vs_avg* 260 m/s), RBBH4 (*Vs_avg* 320 m/s), RBBH5 (*Vs_avg* 300 m/s), LBBH1 (*Vs_avg* 180 m/s), LBBH4 (*Vs_avg* 200 m/s), LBBH5 (*Vs_avg* 190 m/s), LBBH6 (*Vs_avg* 190 m/s) and LBBH7 (*Vs_avg* 310 m/s) exhibits the site class *D* (stiff soil) based on the *Vs30*, whereas site RBBH6 (*Vs_avg* 420 m/s) comes under site class *C* (Very dense soil). These site classifications are referred from Parhi et al. (2019), as recommended by National Earthquake Hazard Reduction Program (NEHRP).

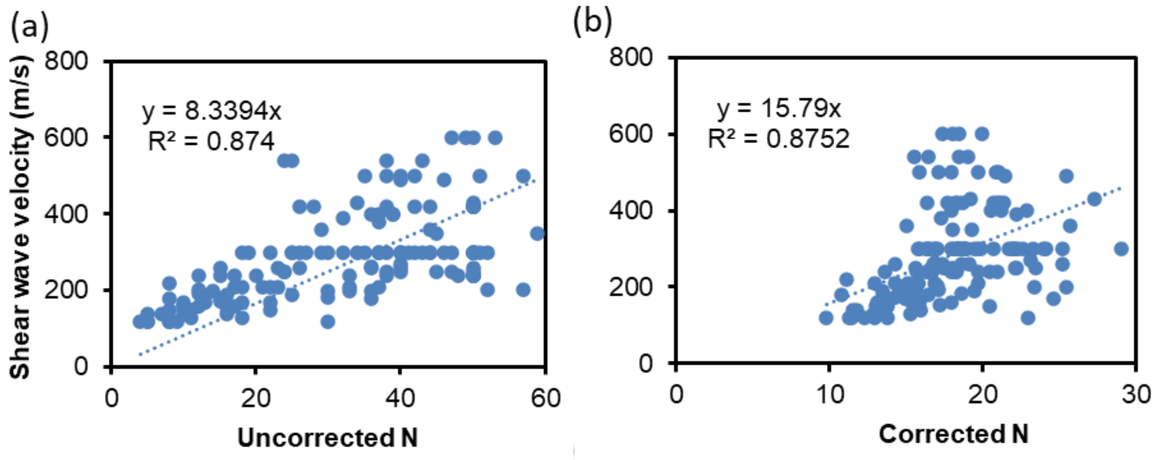

Figure 7. *(a) Correlation between Vs and uncorrected SPT-N; and (b) correlation between Vs and corrected SPT-N*

5 CONCLUSIONS

The MASW testing was completed at nine different borehole locations along the Narmada River bank in Bharuch, Gujarat, India. At the left bank, the average shear wave velocity at the RBBH1 was computed to be 260 m/s. The maximum value of *Vs* was recorded to be 300 m/s at 20 m depth. From the *Vs* profile and soil classification, the top 4 m consists of predominantly clayey-silt followed by sand silty-clay and silty-sand up to 30 m. At the right bank, the average *Vs* at the three boreholes, LBBH1, LBBH5, and LBBH6, was observed in the range of 180-200 m/s. The maximum value of *Vs* was recorded to be 400-600 m/s at 20 m depth. The top 8 m consists of predominantly clayey-silt followed by silty-clay and sand up to 20 m depth. From 11 m to 20 m, the strata are predominantly stiff silty-clay followed by silty-sand. These correlations are helpful in seismic site characterization, liquefaction potential evaluation, and seismic hazard analysis of nearby locations.

6 ACKNOWLEDGEMENTS

The experiment described in this paper is a part of MASW testing carried out along the Narmada River in Gujarat's Bharuch district. The IIT Gandhinagar Geotechnical Lab facility assisted the author in carrying out the MASW tests, for which they are grateful.

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The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 3, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.