## 6.4 Sediment Classification of Kolkata

Sediments are classified based on grain size percentage of four types of particle size categories *viz*. gravel, sand, silt and clay with the particle diameter described by Wentworth (1922) as:

(i) Gravel Size: particle diameter > 2 mm.

(ii) Sand Size: particle diameter varying from 2 mm-62.5 µm.

(iii) Silt Size: particle diameter varying from 62.5 µm-4 µm.

(iv) Clay Size: particle diameter < 4 µm.

Although several classifications have been proposed by numerous authors, Shepard's classification for fine grained sediments with gravel size percentage less than 10 is most commonly used. Shepard (1954) proposed a ternary diagram shown in Figure 6.11 to define the type of sediment based on the percentages of sand, silt & clay present in the sediment. Each sediment is plotted as a point within or along the sides of the diagram for example, a sample with 100% sand falls at the same named apex, a sample which completely lacks one of the components falls along the side of the triangle opposite to that apex, rest falls somewhere in between of the triangle. To classify sediment samples, he divided the ternary diagram into ten classes *viz*. Sand, Silt, Clay, Sandy Silt, Silty Sand, Silty Clay, Clayey Silt, Sandy Clay, Clayey Sand and Sand Silt Clay. Shepard's "Clays" contain at least 75% clay-sized particles. "Silty Sands" and "Sandy Silts" contain no more than 20% clay-sized particles, and "Sand-Silt-Clays" contain at least 20% of each of the three components (O'Malley, 2007). This classification is not applicable in case of

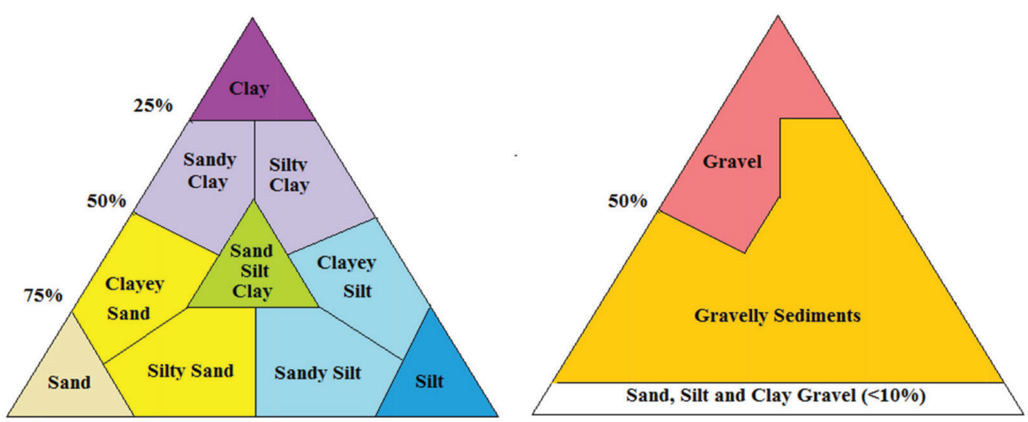



**Figure 6.11** **Ternary diagram of the Sediment Classification Scheme proposed by Shepard (1954) and Modified by Schlee (1973) based on the Grain Size Percentage (after Shepard, 1954; O'Malley, 2007).**

the sediments where gravels are present in significant amount. Schlee (1973), therefore, further modified this classification by considering gravel size percent in addition to the previously defined classes.

This classification requires the assessment of gravel size percentage, sand size percentage, silt size percentage and clay size percentage of the soil sample. Sediment classification of Kolkata has been performed based on this classification scheme by using the grain size percentage data obtained from particle size analysis of soil samples collected during drilling at various depth levels. Shallow sediment classification map of Kolkata for a depth of upto 5 m has been generated in GIS platform and presented in Figure 6.12 which depicts the dominance of sediments with nearly equal proportions of sand, silt and clay followed by coarse grained sediments *viz*. silty clay and clayey sand.

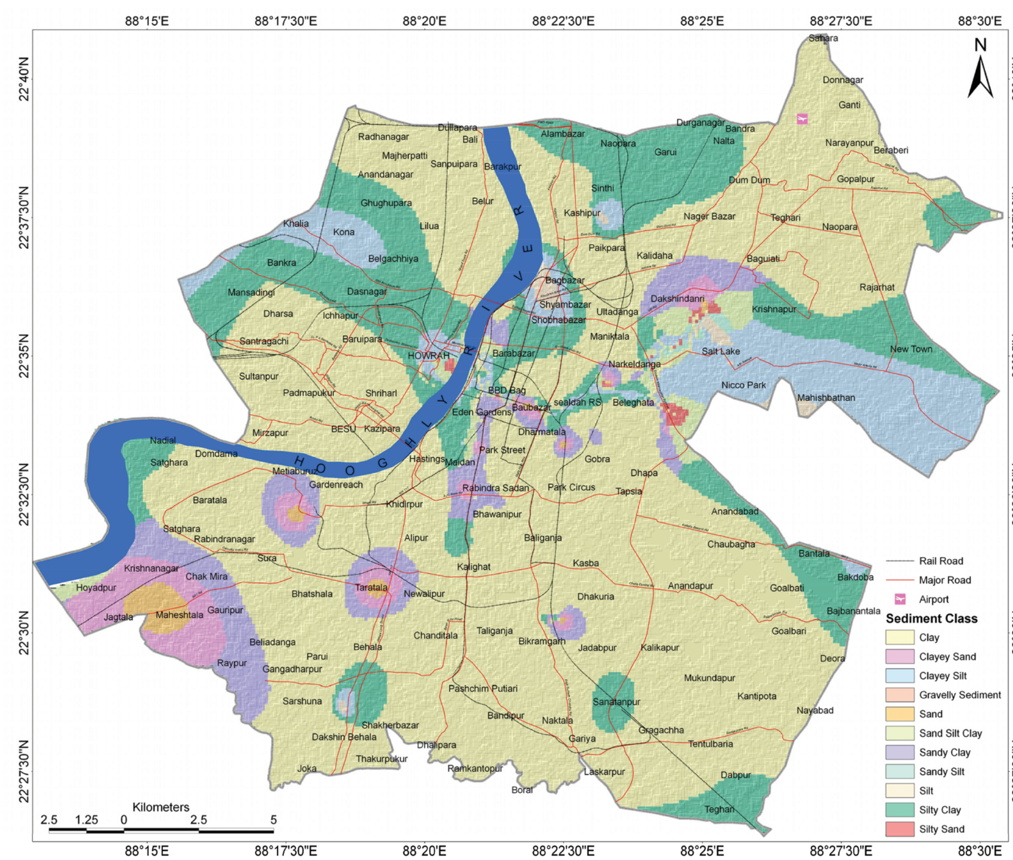



**Figure 6.12** **Sediment classification map of Kolkata based on Shepard (1954) and Schlee (1973) sediment classification system generated from a database of 654 boreholes.**

## 6.5 Generation of Site and Lithology specific, Depth Dependent Empirical Relations

The shear wave velocity estimation of shallow sediments is one among the main steps in site response modeling as well as site classification adhering to National Earthquake Hazard Reduction Program (NEHRP) and Federal Emergency Management Authority (FEMA) regulations. It is preferable to obtain shear wave velocity profiles by conducting insitu downhole test which however is often not feasible economically and due to lack of specialized personnel to perform these tests at all locations. Therefore, development of reliable correlation between lithology-specific $V_s$ and SPT-N values act as a good alternative for the prediction of shallow $V_s$ profiles. In addition to this $V_s$ profiles obtained from Multi-channel Analysis of Surface Wave (MASW) and those obtained by the inversion of Ambient noise signals can also be calibrated by establishing empirical regression relations between the two.

The geotechnical database of Kolkata reveals the presence of shallow high plastic silty clay with peat/decomposed wood in the region which are unconsolidated organic material accumulated as a result of incomplete decomposition of dead plant under the conditions of excessive moisture. They exhibit very high compressibility and low shear strength, which leads to slip failure, local sinking and massive primary and long term settlement even when load increases moderately (Al-Ani *et al.,* 2013). The acquired insitu downhole data of Kolkata suggests noticeable variation in shear wave velocity with the variation of lithology, for instance presence of peat/decomposed wood reduces the shear wave velocity of silty clay in comparison to silty clay associated with mica, sand and/or kankar. Hence, an attempt has been made to develop site specific and lithology dependent empirical correlations between SPT-N and Downhole $V_s$, Downhole $V_s$ and MASW $V_s$, and Calibrated MASW $V_s$ with those $V_s$ obtained from the inversion of HVSR data derived from Microtremor Survey of the city.

### 6.5.1 Correlation between Downhole $V_s$ and corrected SPT-N

Many attempts have been made in the past to generate correlation equations between shear wave velocity ($V_s$) and N value (Shibata,1970; Ohba and Toriuma, 1970; Ohta *et al*., 1972; Fujiwara, 1972; Ohasaki and Iwasaki, 1973; Imai and Yoshimura, 1975; Campbell and Duke, 1976; Imai, 1977; Ohta and Goto, 1978; Seed and Idriss, 1981; Imai and Tonouchi, 1982; Barrow and Stokoe, 1983; Jinan, 1987; Okamoto *et al.,* 1989; Lee, 1990; Athanasopoulos, 1995; Kanai, 1966; Jafari *et al.*, 1997; Pitilakis *et al*., 1999; Kiku *et al.,* 2001; Tamura and Yamazaki, 2002; Hasancebi and Ulusay, 2007; Hanumantharao and Ramanna, 2008; Dikmen, 2009; Maheswari *et al*., 2010). For instance, Ohta and Goto (1978) generated empirical correlation relations by combining four indices *viz*. SPT-N, depth from ground surface, geological age and soil type (Fabbrocino *et al.,* 2015). Imai and Tonouchi (1982) proposed a regression equation which correlated N-values to $V_s$ based on about 1650 dataset collected from all over Japan. Their equations have been commonly used for estimating S-wave velocities from N-values in Japan. On the other hand, their study also revealed that clayey soils are generally characterized by higher $V_s$ than sands (Fabbrocino *et al*., 2015).

An attempt has been made to develop lithology and site specific empirical correlations between SPT-N and $V_s$ for Kolkata in which lithological units have been classified into ten categories according to their grain size, plasticity index and presence or absence of decomposed wood as: (i) Top Soil, (ii) Silty Clay with Decomposed Wood, (iii) Silty Clay with Mica, Sand and/or Kankar, (iv) Clay with Decomposed Wood, (v) Silty Sand with Mica and/or Clay (vi) Silty Clay with rusty Silty Spots, (vii) Sand with Silt and Clay, (viii) Silty Sand with Mica and Kankar, (ix) Bluish/ Yellowish grey Silt, and (x) Fine Sand with Gravel. This lead to the generation of depth dependent, lithology based and site specific seventeen empirical correlation equations. All of the seventeen empirical regression equations are power relations of the type

$$V_S = a.N_{SPT}^{b} \tag{6.11}$$

where $V_s$ is the shear wave velocity measured at a specific depth 'Z' and $N_{SPT}$ is the corrected blow counts at the same depth whereas, constants 'a' and 'b' are determined by performing statistical, nonlinear regression of the dataset.

A comparison between the measured $V_s$ and the predicted $V_s$ has been performed for all the relations exhibiting the plotted data scattered between the lines of 1:0.5 and 1:2 slopes with maximum values falling close to the 1:1 correspondence line. This confirms that the regression equations show a reasonable fit of the compiled data for the investigated lithological unit. Further the proposed relations have been verified by performing Graphical Residual Analysis. The residual values have been found to be scattered along their mean value *i.e.* zero without following any particular trend, thus indicating that the regression has removed bias with respect to the input variables.

The seventeen regressed equations for ten lithological units are discussed below

(i) Top Soil

The entire Kolkata is blanketed with a layer of top soil with varying thickness from 0-1.95 m. The shear wave velocity and SPT-N values have been found to be low in this litho-layer with the maximum $V_s$ value of 124 m/s and the corrected SPT-N value not exceeding 6. The nonlinear correlation has been shown in Figure 6.13 along with the comparison and residual analysis plot.

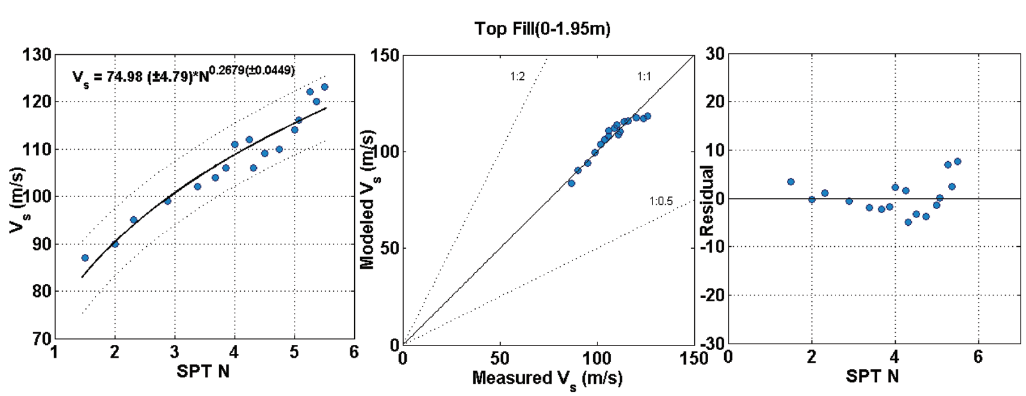



**Figure 6.13** **Correlation between Downhole $V_s$ and corrected SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for Top soil.**

(ii) Silty Clay with Mica, Sand and/or Kankar

The presence of low plastic silty clay in conjunction with either one, two or all three of mica, sand and kankar has been observed at three depth ranges of the region: (a) 1.5-4.95 m, (b) 4.95-10.95 m, and (c) 23.95-34.45 m. For each depth range three correlation equations have been generated and presented in Figure 6.14 with their comparison and residual analysis plots.

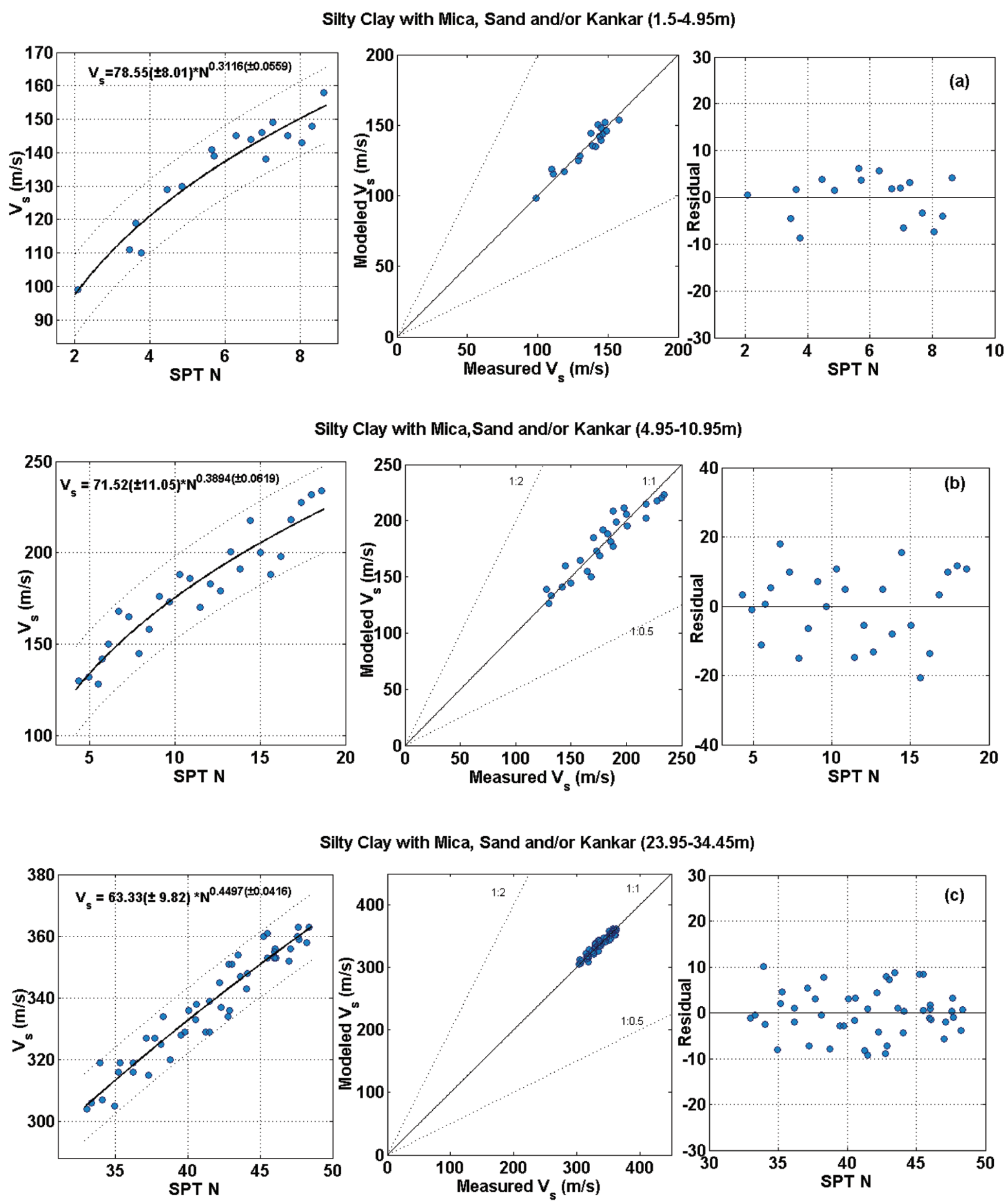



**Figure 6.14** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for low plastic Silty Clay with Mica, Sand and/or Kankar at (a) 1.5-4.95 m depth, (b) 4.95-10.95 m depth, and (c) 23.95-34.45 m depth.**

(iii) Silty Clay with Decomposed Wood/Peat

Very high plastic silty clay associated with decomposed wood or peat with comparatively low insitu shear wave velocity and low SPT-N values as compared to low plastic silty clay has been observed at two depth ranges: (a) 1.95-9.95 m and (b) 10.5-18.45 m. The correlation equations generated for the two depth ranges, comparison and residual analysis plot corresponding to this litho-unit are shown in Figure 6.15.

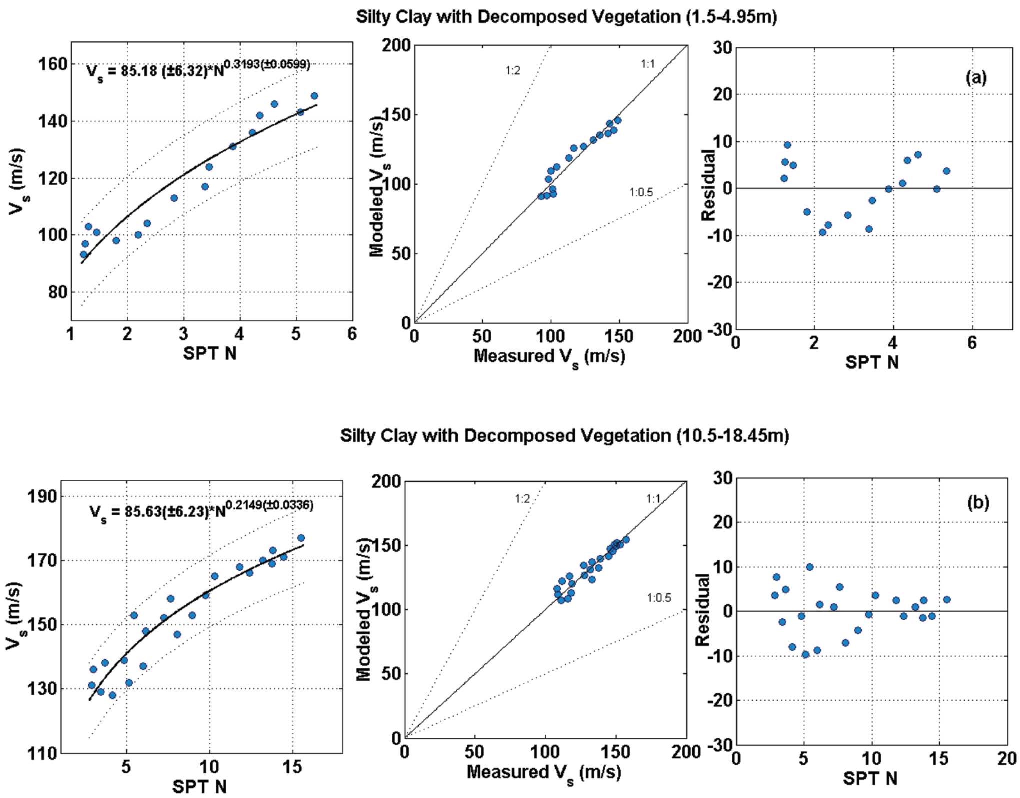



**Figure 6.15** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for high plastic Silty Clay with decomposed wood at (a) 1.5-4.95 m depth, and (b) 10.5-18.45 m depth.**

(iv) Sand with Silt and Clay

Non-plastic layer of sand associated with silt and/or clay with low SPT-N value with a variation of 1-5 and low insitu $V_s$ has been found at a depth range of 1.95-4.5 m. The regressed correlation along with the comparison plot and graphical residual analysis is shown in Figure 6.16.

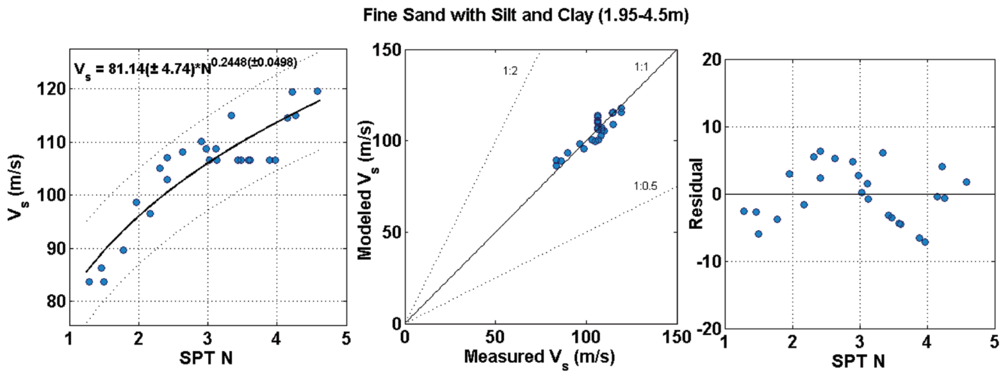



**Figure 6.16** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for non-plastic sand with silt and clay.**

(v) Clay with Decomposed Wood

High plastic clay associated with decomposed wood or peat lies at a depth range of 4.5-10.1 m. The regressed correlation equation between insitu $V_s$ and SPT-N has been displayed in Figure 6.17 in addition with the comparison and residual plot of the same.

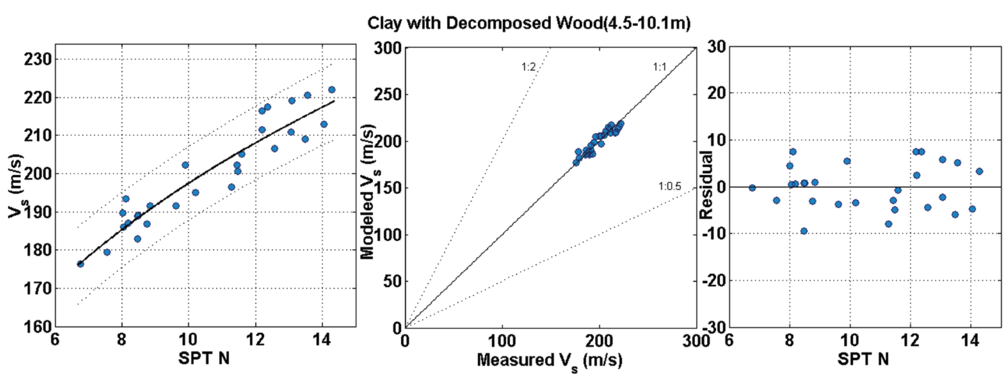



**Figure 6.17** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for high plastic clay with decomposed wood.**

(vi) Silty Sand with Mica, Clay and/or Kankar

This non-plastic layer lies at three different depth ranges in Kolkata: (a) 6-15.5 m, (b) 18.25-26.95 m, and (c) 39.45-50.45 m. The correlation for the three depth ranges along with their comparison and residual analysis plots are displayed in Figure 6.18.

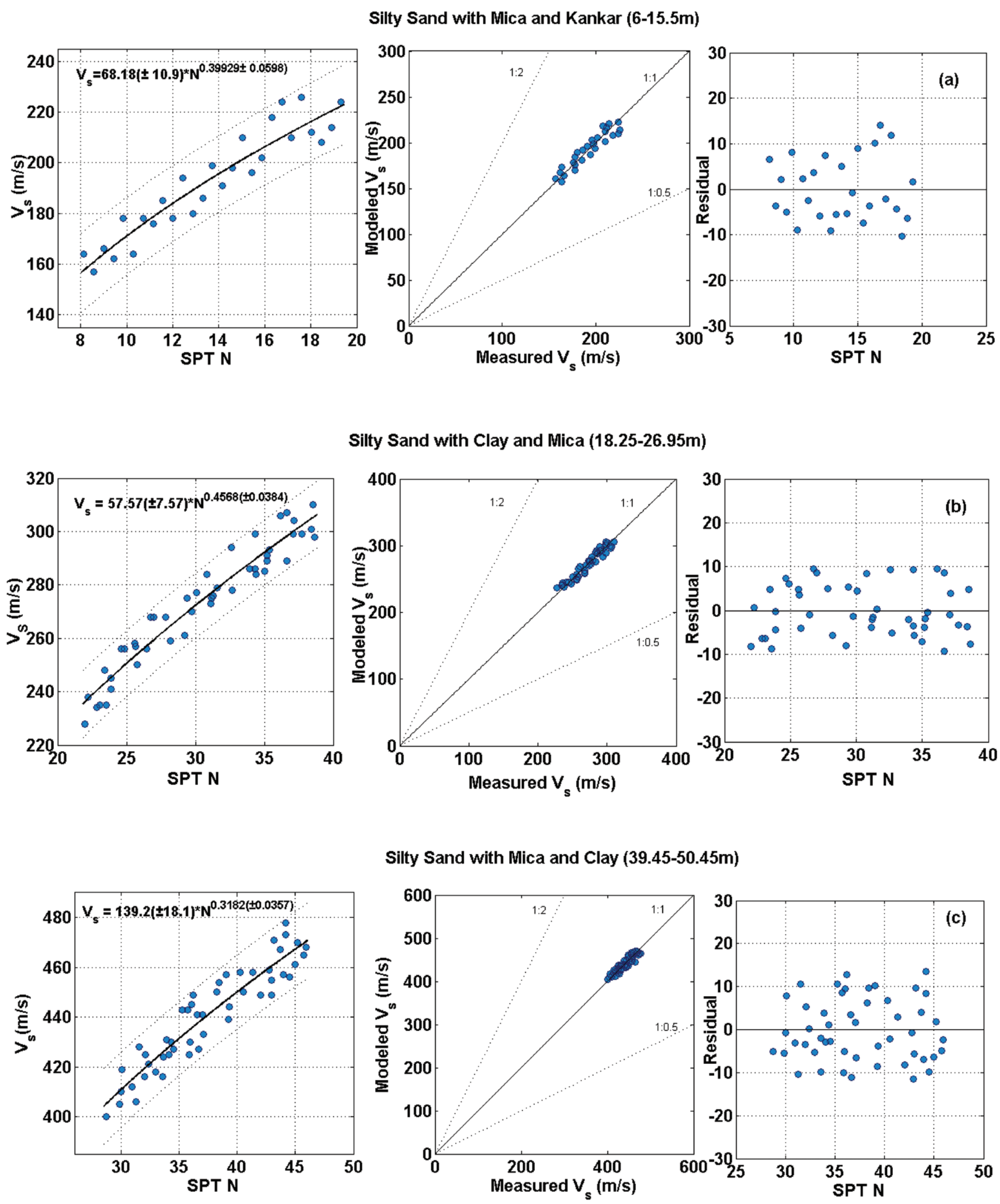



**Figure 6.18** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for non-plastic to low plastic Silty Sand with Mica, Clay and/or Kankar at (a) 6-15.5 m, (b) 18.25-26.95 m, and (c) 39.45-50.45 m depth.**

(vii) Silty Clay with Kankar and bluish grey Silty Spots

This lithologic unit has been observed at the depth range of 12-18.95 m and the corresponding correlation regressed equation along with its graphical residual analysis and comparison plot is shown in Figure 6.19.

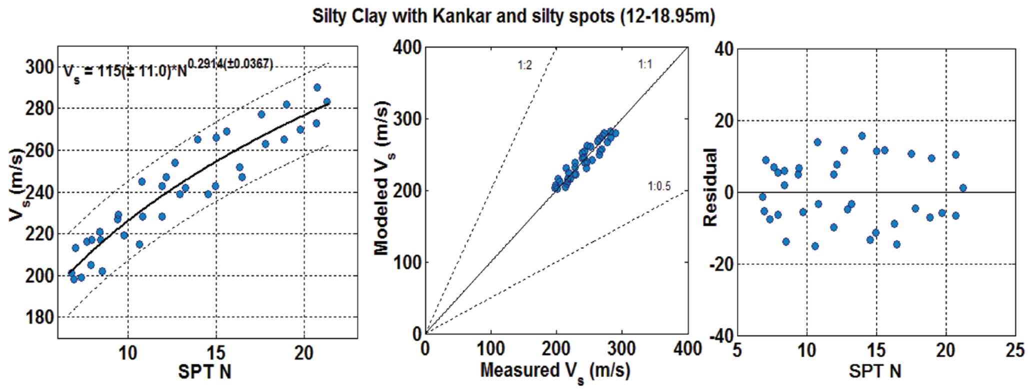



**Figure 6.19** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) Silty Clay with Kankar and bluish grey Silty Spots.**

(viii) Bluish Grey/ Light Yellowish Grey Silt

This low plastic silt layer with $V_s$ of range 215-275 m/s lies at a depth of 14.9-17.2 m. The correlation for this litho-unit along with its comparison plot and graphical residual analysis plot is shown in Figure 6.20.

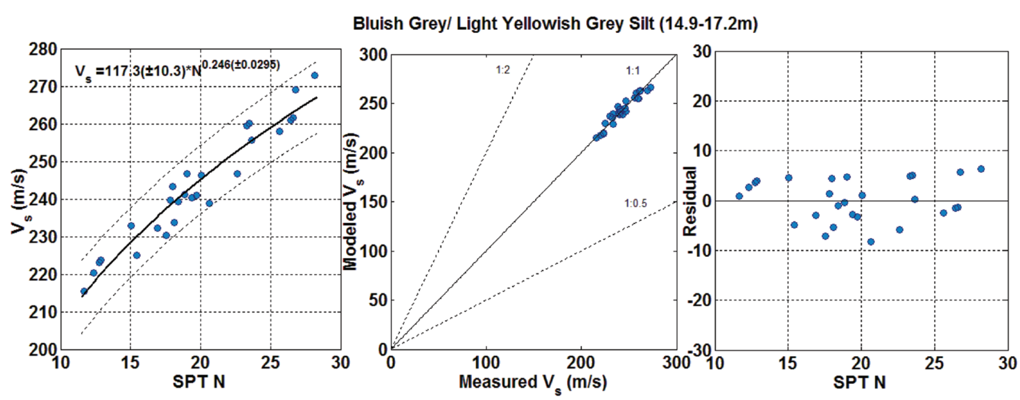



**Figure 6.20** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) Silty Clay with Kankar and bluish grey Silty Spots.**

(ix) Silty Clay/Clayey Silt with Micaceous Fine Sand

This non-plastic litho-unit lies at three different depth ranges: (a) 16.5-22.5 m, (b) 34.45-45.45 m, and (c) 45.5-54.5 m. Three correlation equations have, therefore, been generated for each depth range and are depicted in Figure 6.21 along with their comparison and residual analysis plot.

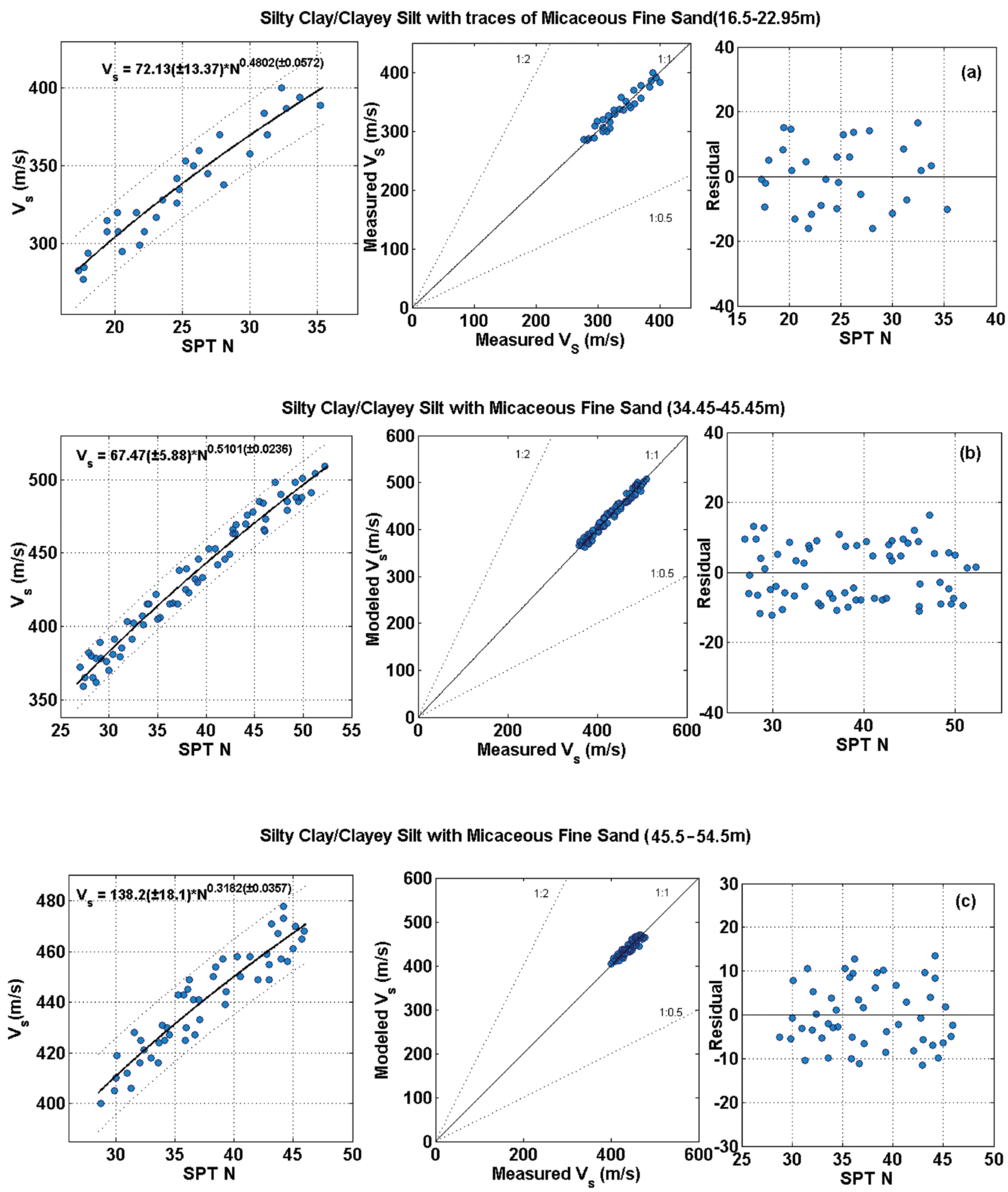



**Figure 6.21** Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for non-plastic to low plastic Silty Clay/ Clayey Silt with micaeceous fine sand at (a) 16.5-22.5 m depth, (b) 34.45-45.45 m depth, and (c) 45.5-54.5 m depth.

(x) Fine Sand with Gravel

This non-plastic layer of fine sand with gravel has been observed at a depth range of 24.6-34.6 m. The correlation equation is depicted in Figure 6.22 along with comparison plot and graphical residual analysis plot of the same.

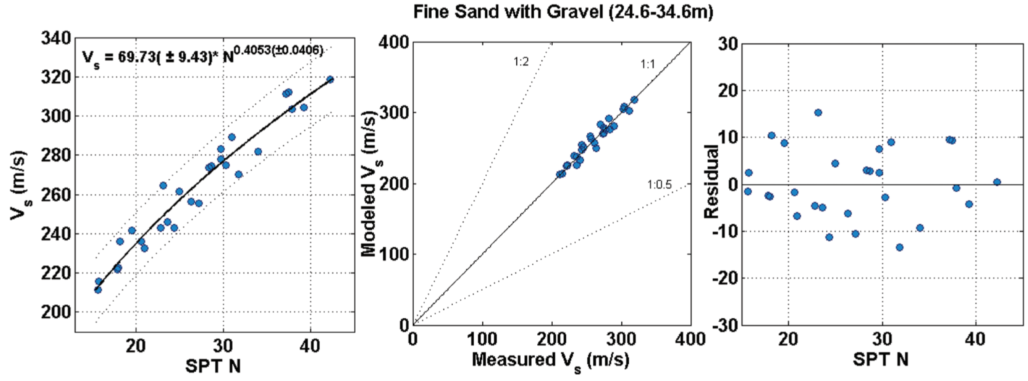



**Figure 6.22** **Correlation between Downhole $V_s$ and SPT-N (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) Fine sand with Gravel.**

These empirically derived lithology, site specific and depth dependent empirical nonlinear regression equations between the corrected SPT-N and insitu downhole $V_s$ generated for Kolkata are presented in Table 6.6. These equations have been used to assign shear wave velocity at each depth level at every borehole location.

**Table 6.6** **Empirically derived nonlinear regression equations between the corrected SPT-N and insitu downhole shear wave velocities for seventeen lithological units at various depths for the city of Kolkata**

| Depth Range (m) | Lithology | Relation |
|---|---|---|
| 0-1.95 | Top Fill | $V_S = 74.98(\pm4.79)*N^{0.2679(\pm0.0449)}$ |
| 1.5-4.95 | Silty Clay with Mica, Sand and Kankar | $V_S = 78.55(\pm8.01)*N^{0.3116(\pm0.0559)}$ |
| 1.5-9.96 | Silty Clay with Decomposed Wood | $V_S = 85.18(\pm6.32)*N^{0.3196(\pm0.0599)}$ |
| 1.5-4.97 | Fine Sand with Silt and Clay | $V_S = 81.14(\pm4.74)*N^{0.2448(\pm0.0498)}$ |
| 4.5-10.1 | Clay with Decomposed Wood | $V_S = 102.2(\pm10.13)*N^{0.286(\pm0.0417)}$ |
| 4.5-10.95 | Silty Clay with Mica, Sand and Kankar | $V_S = 71.52(\pm11.05)*N^{0.3894(\pm0.0619)}$ |
| 6-15.5 | Silty Sand with Mica and Kankar | $V_S = 68.18(\pm10.9)*N^{0.39929(\pm0.0598)}$ |
| 10.5-18.45 | Silty Clay with Decomposed Wood | $V_S = 85.63(\pm6.23)*N^{0.2149(\pm0.0336)}$ |
| 12-18.95 | Silty Clay with Kankar and Silty Spots | $V_S = 115.0(\pm11.0)*N^{0.2914(\pm0.0367)}$ |
| 14.9-17.2 | Bluish Grey/ Light Yellowish Grey Silt | $V_S = 117.3(\pm10.3)*N^{0.246(\pm0.0295)}$ |

| Depth Range (m) | Lithology | Relation |
|---|---|---|
| 18.25-26.95 | Silty Sand with Mica and Clay | $V_S = 57.57(\pm 7.57)*N^{0.4568(\pm 0.0384)}$ |
| 16.5-22.5 | Silty Clay/Clayey Silt with Micaceous Sand | $V_S = 72.13(\pm 13.37)*N^{0.4802(\pm 0.0572)}$ |
| 23.95-34.45 | Silty Clay with Mica, Sand and Kankar | $V_S = 63.33(\pm 9.82)*N^{0.4497(\pm 0.0416)}$ |
| 24.6-34.6 | Fine Sand with Gravel | $V_S = 69.73(\pm 9.43)*N^{0.4053(\pm 0.0406)}$ |
| 34.45-45.45 | Silty Clay/ Clayey Silt with Micaceous Fine Sand | $V_S = 67.47(\pm 5.88)*N^{0.5101(\pm 0.0236)}$ |
| 45.5-54.5 | Silty Clay/ Clayey Silt with Micaceous Fine Sand | $V_S = 138.2(\pm 18.1)*N^{0.3182(\pm 0.0357)}$ |
| 40.5-54.5 | Silty Clay/Clayey Silt with Mica | $V_S = 87.68(\pm 11.02)*N^{0.4772(\pm 0.0339)}$ |

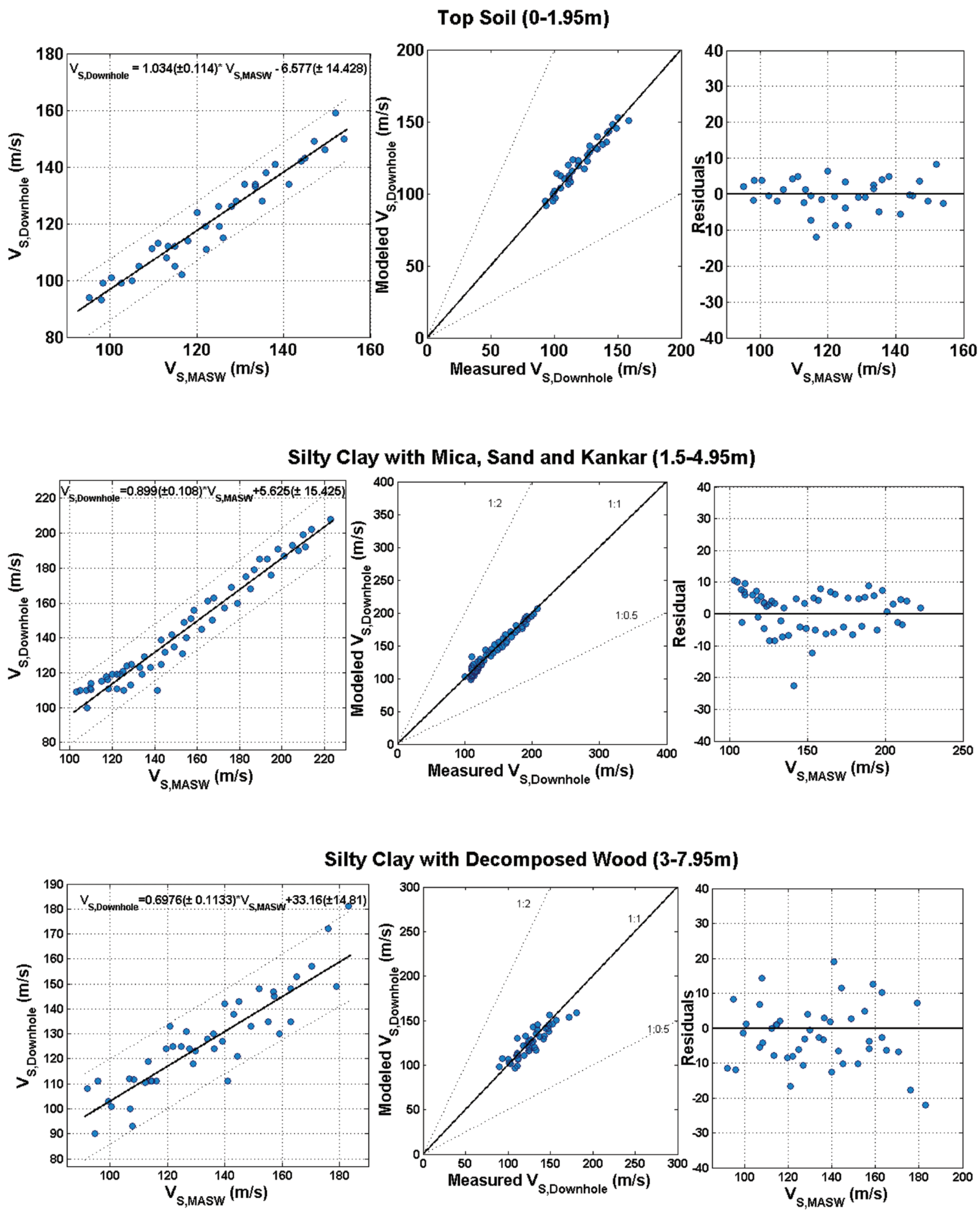
## 6.5.2 Correlation between Downhole $V_s$ and MASW $V_s$

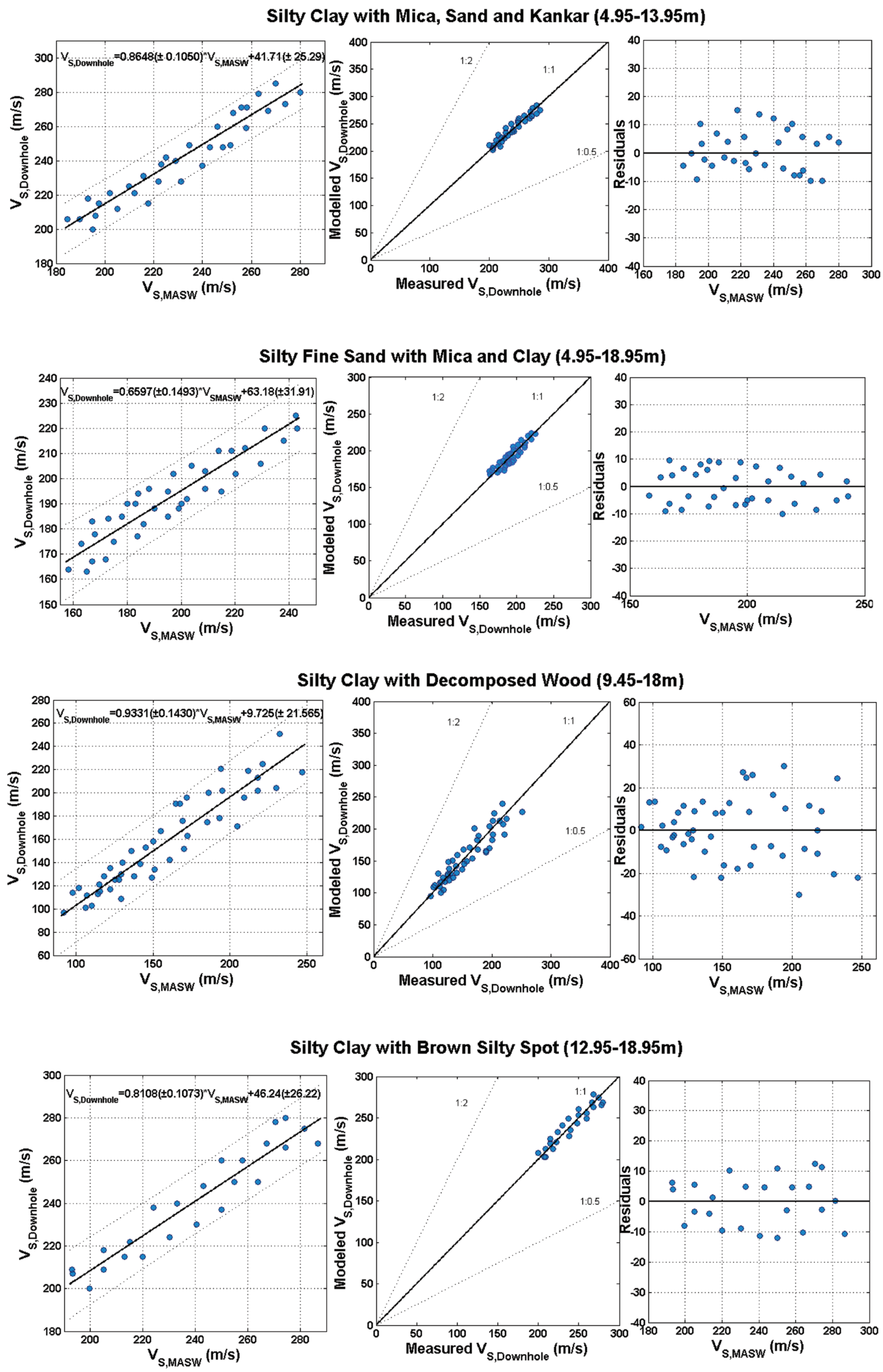
Insitu downhole survey derived shear wave velocity is considered most accurate amongst all the available invasive and non-invasive methods (Chang *et al*., 1999). Therefore, downhole $V_s$ is used to benchmark $V_s$ derived from MASW geophysical survey. This led to the generation of 10 site specific lithology based linear regression equations between the downhole $V_S$ and MASW derived $V_S$ as presented in Table 6.7.

**Table 6.7** **Empirically derived linear regression equations between the Downhole $V_s$ and MASW derived shear wave velocities of ten lithological units at various depths for the city of Kolkata**

| Depth Range (m) | Lithology | Relation |
|---|---|---|
| 0-1.95 m | Top Fill | $V_{S,Downhole} = 1.034(\pm 0.114)*V_{S,MASW}$ -6.577 (±14.428) |
| 1.5-4.95 m | Silty Clay with mica, sand and kankar | $V_{S,Downhole} = 0.899(\pm 0.108)*V_{S,MASW}$ +5.625 (±15.425) |
| 3-7.95 m | Silty Clay with Decomposed Wood | $V_{S,Downhole} = 0.6976(\pm 0.1133)*V_{S,MASW}$ +33.16 (±14.81) |
| 9.95-18 m | Silty Clay with Decomposed Wood | $V_{S,Downhole} = 0.9331(\pm 0.1430)*V_{S,MASW}$ +9.725 (±21.565) |
| 4.95-13.95 m | Silty Clay with Mica sand and Kankar | $V_{S,Downhole} = 0.8648(\pm 0.1050)*V_{S,MASW}$ +41.71 (±25.29) |
| 13.95-22.5 m | Silty Clay with Mica sand and Kankar | $V_{S,Downhole} = 0.7601(\pm 0.1235)*V_{S,MASW}$ + 79.5 (±29.86) |
| 22.5-30.5 m | Silty Clay with Mica sand and Kankar | $V_{S,Downhole} = 0.8857(\pm 0.1063)*V_{S,MASW}$ + 53.32 (±30.3) |
| 4.95-18.5 m | Silty Fine Sand with Mica and Clay | $V_{S,Downhole} = 0.6597(\pm 0.1493)*V_{S,MASW}$ + 63.18 (±31.91) |
| 18.5-30.5 m | Silty Fine Sand with Mica and Clay | $V_{S,Downhole} = 1.036(\pm 0.1238)*V_{S,MASW}$ +37.59 (±32.53) |
| 12.95-18.95 m | Silty Clay with Silty Brown Spots | $V_{S,Downhole} = 0.8108(\pm 0.1073)*V_{S,MASW}$ +46.24 (±26.22) |

The proposed relations have been verified which was previously done through a comparison plot of the measured downhole $V_s$ & the predicted $V_s$ and by performing the graphical residual analysis test. The linearly regressed 10 empirical relations with their associated comparison and residual plots are shown in Figure 6.23.




Silty Clay with Mica, Sand and Kankar (4.95-13.95m)
V S,Downhole =0.8648(± 0.1050)*V S,MASW +41.71(± 25.29)
V S,Downhole (m/s)
V S,MASW (m/s)
Modelled V S,Downhole (m/s)
Measured V S,Downhole (m/s)
1:2
1:1
1:0.5
Residuals
Silty Fine Sand with Mica and Clay (4.95-18.95m)
V S,Downhole =0.6597(±0.1493)*V SMASW +63.18(±31.91)
V S,Downhole (m/s)
V S,MASW (m/s)
Modeled V S,Downhole (m/s)
Measured V S,Downhole (m/s)
1:2
1:1
1:0.5
Residuals
Silty Clay with Decomposed Wood (9.45-18m)
V S,Downhole =0.9331(±0.1430)*V S,MASW +9.725(± 21.565)
V S,Downhole (m/s)
V S,MASW (m/s)
Modeled V S,Downhole (m/s)
Measured V S,Downhole (m/s)
1:2
1:1
1:0.5
Residuals
Silty Clay with Brown Silty Spot (12.95-18.95m)
V S,Downhole =0.8108(±0.1073)*V S,MASW +46.24(±26.22)
V S,Downhole (m/s)
V S,MASW (m/s)
Modeled V S,Downhole (m/s)
Measured V S,Downhole (m/s)
1:2
1:1
1:0.5
Residuals

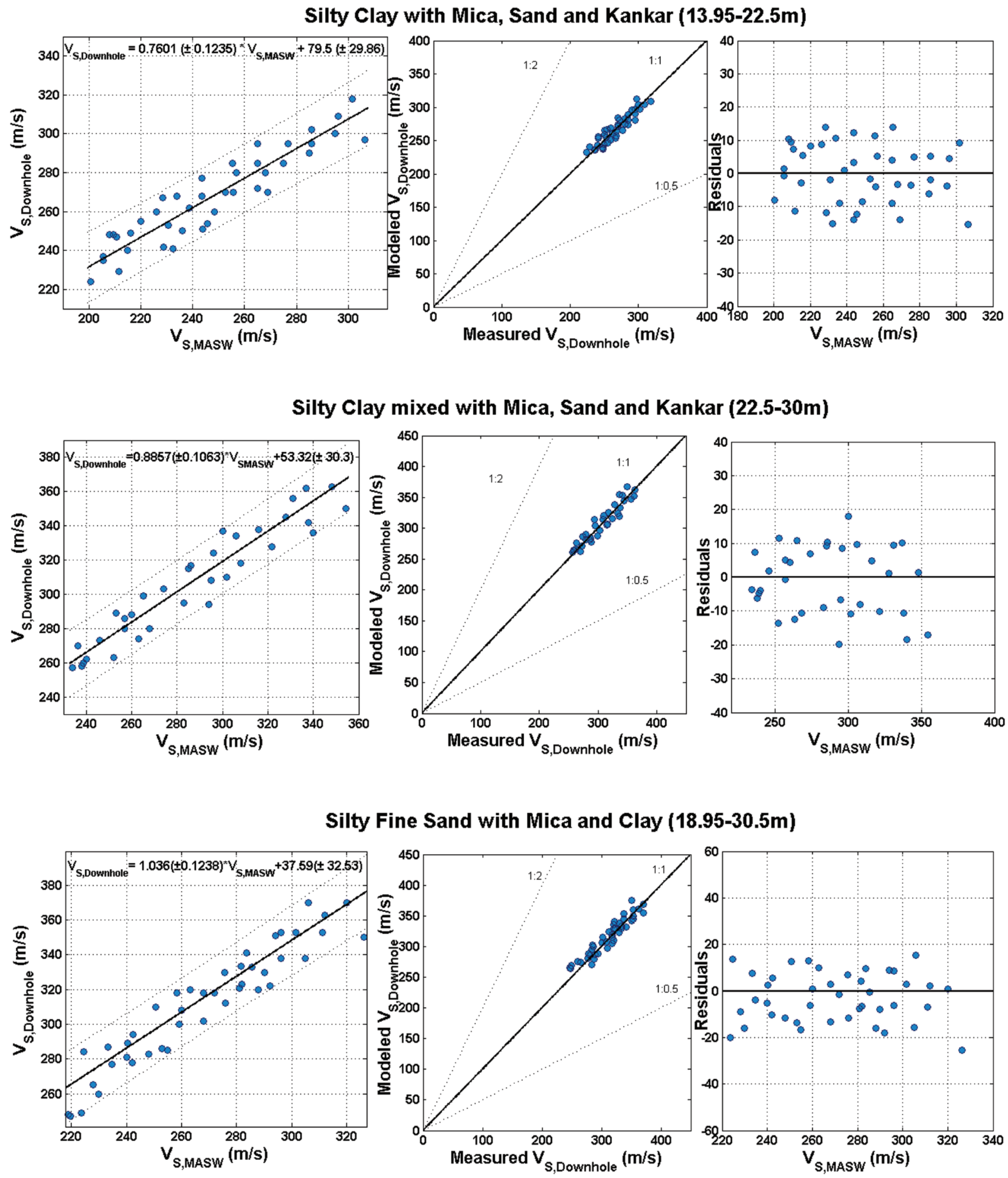



**Figure 6.23** **Correlations between Downhole $V_s$ and MASW derived $V_s$ (left-most panel), Measured (downhole) versus predicted shear wave velocities (middle-most panel) and residual plots (right-most panel) for ten lithological units identified in Kolkata.**

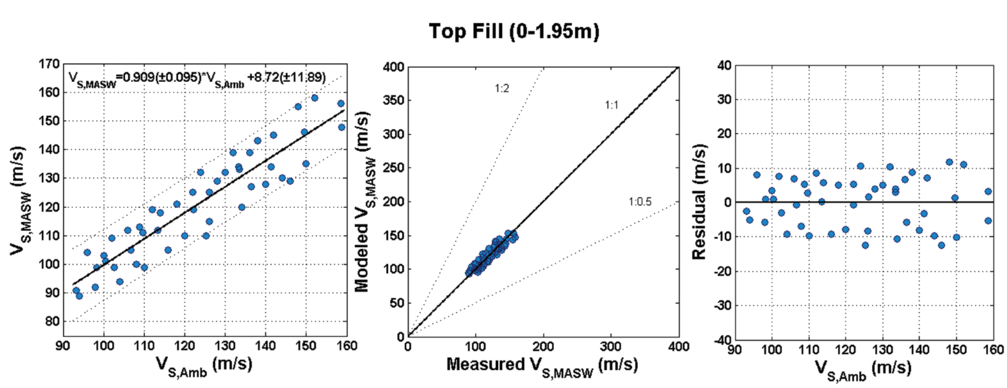
These relations have been used to calibrate MASW derived $V_s$ thus providing pseudo 1-D insitu shear wave velocity profiles at all the 85 MASW survey locations.

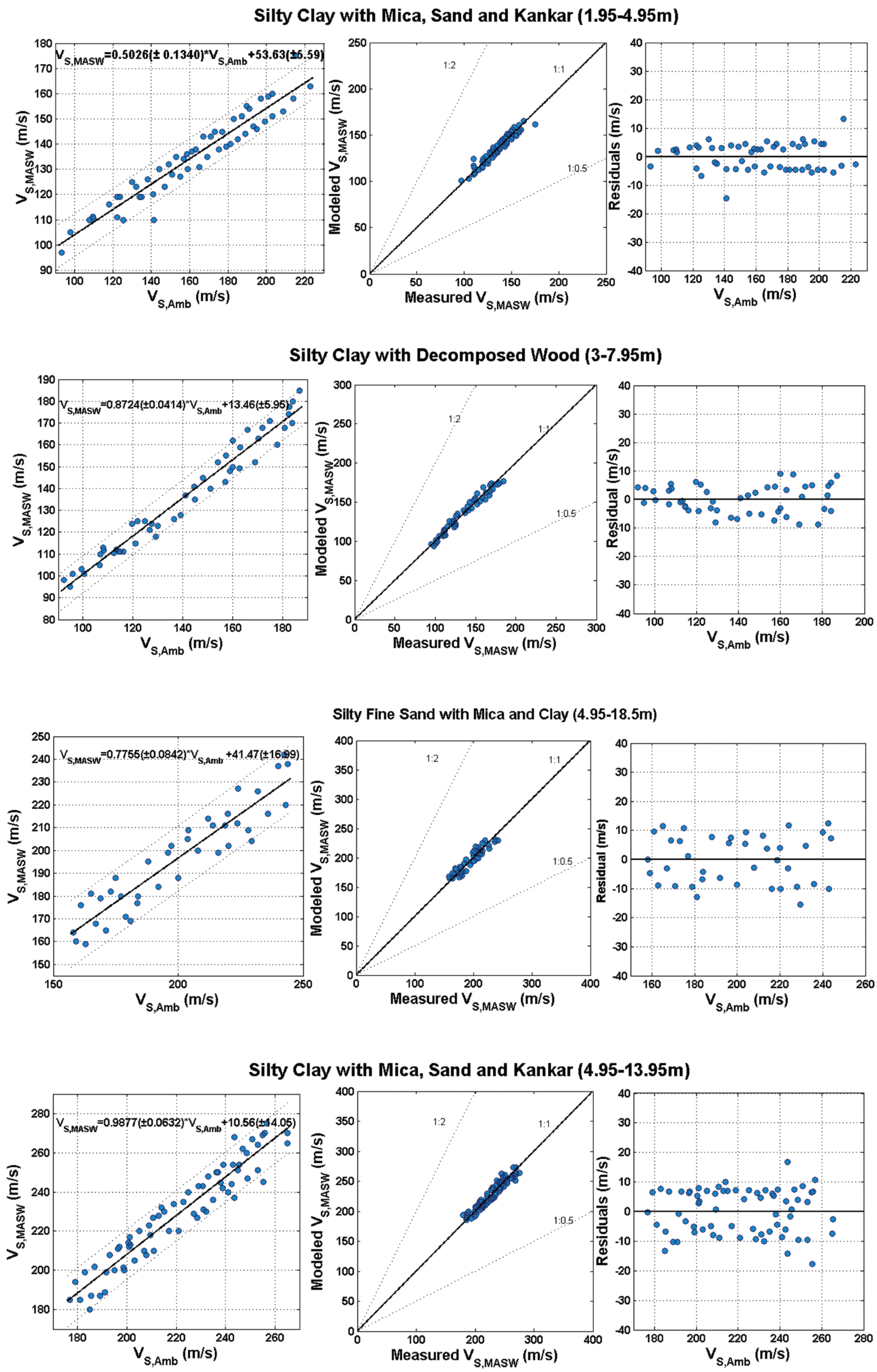
### 6.5.3 Correlation between Calibrated MASW $V_s$ with the $V_s$ obtained from Microtremor Survey

The calibrated MASW derived $V_s$ profiles have further been used to calibrate $V_s$ obtained from microtremor survey by performing regression analysis, thus generating another set of ten site specific lithology based linear regression equations between MASW derived $V_s$ and microtremor survey derived $V_s$ as presented in Table 6.8 and Figure 6.24.

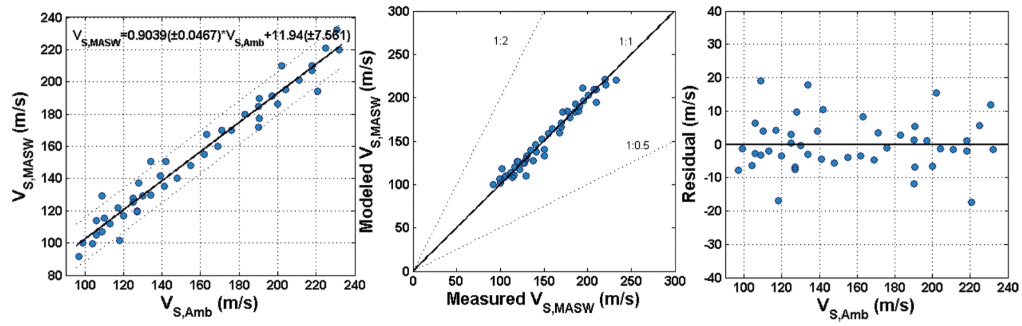
**Table 6.8** **Empirically derived linear regression equations between the MASW derived $V_s$ and Microtremor survey derived shear wave velocities of ten lithological units at various depths for the city of Kolkata**

| Depth Range (m) | Lithology | Relation |
|---|---|---|
| 0-1.95 m | Top Fill | $V_{S,MASW} = 0.909(\pm0.095)*V_{S,Amb}+8.72$ $(\pm11.89)$ |
| 1.5-4.95 m | Silty Clay with mica, sand and kankar | $V_{S,MASW} = 0.5026(\pm0.1340)*V_{S,Amb}+53.63$ $(\pm5.59)$ |
| 3-7.95 m | Silty Clay with Decomposed Wood | $V_{S,MASW} = 0.8724(\pm0.0414)*V_{S,Amb}+13.46$ $(\pm5.94)$ |
| 9.95-18 m | Silty Clay with Decomposed Wood | $V_{S,MASW} = 0.9039(\pm0.0467)*V_{S,Amb}+11.94$ $(\pm7.561)$ |
| 4.95-13.95 m | Silty Clay with Mica sand and Kankar | $V_{S,MASW} = 0.9877(\pm0.0632)*V_{S,Amb}+10.56$ $(\pm14.05)$ |
| 13.95-22.5 m | Silty Clay with Mica sand and Kankar | $V_{S,MASW} = 0.8114(\pm0.0797)*V_{S,Amb}+39.88$ $(\pm19.48)$ |
| 22.5-30.5 m | Silty Clay with Mica sand and Kankar | $V_{S,MASW} = 0.9387(\pm0.0616)*V_{S,Amb}+36.68$ $(\pm19.23)$ |
| 4.95-18.5 m | Silty Fine Sand with Mica and Clay | $V_{S,MASW} = 0.7755(\pm0.0842)*V_{S,Amb}+41.47$ $(\pm16.99)$ |
| 18.5-30.5 m | Silty Fine Sand with Mica and Clay | $V_{S,MASW} = 0.6830(\pm0.0487)*V_{S,Amb}+136.4$ $(\pm13.1)$ |
| 12.95-18.95 m | Silty Clay with Silty Brown Spots | $V_{S,MASW} = 0.9594(\pm0.0785)*V_{S,Amb}+9.192$ $(\pm18.462)$ |

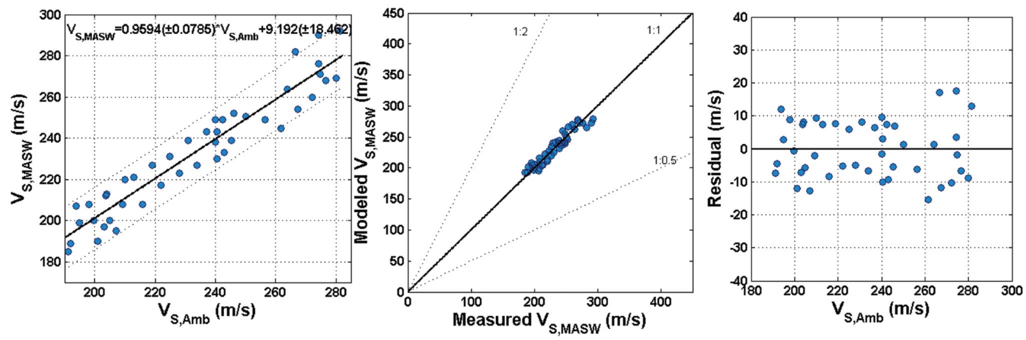



Silty Clay with Mica, Sand and Kankar (1.95-4.95m)
VS,MASW=0.5026(± 0.1340)*VS,Amb+53.63(±5.59)
Silty Clay with Decomposed Wood (3-7.95m)
VS,MASW=0.8724(±0.0414)*VS,Amb+13.46(±5.95)
Silty Fine Sand with Mica and Clay (4.95-18.5m)
VS,MASW=0.7755(±0.0842)*VS,Amb+41.47(±16.89)
Silty Clay with Mica, Sand and Kankar (4.95-13.95m)
VS,MASW=0.9877(±0.0632)*VS,Amb+10.56(±14.05)
VS,Amb (m/s)
VS,MASW (m/s)
Measured VS,MASW (m/s)
Modeled VS,MASW (m/s)
Residuals (m/s)
1:2
1:1
1:0.5

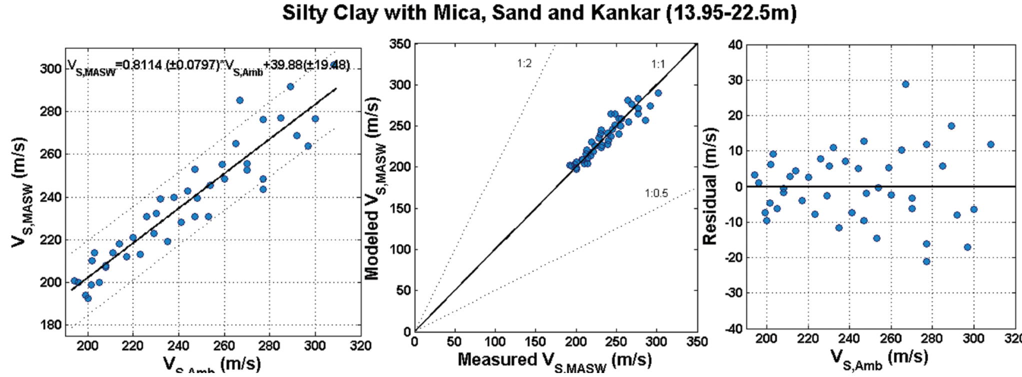
Silty Clay with Decomposed Wood (9.95-18m)



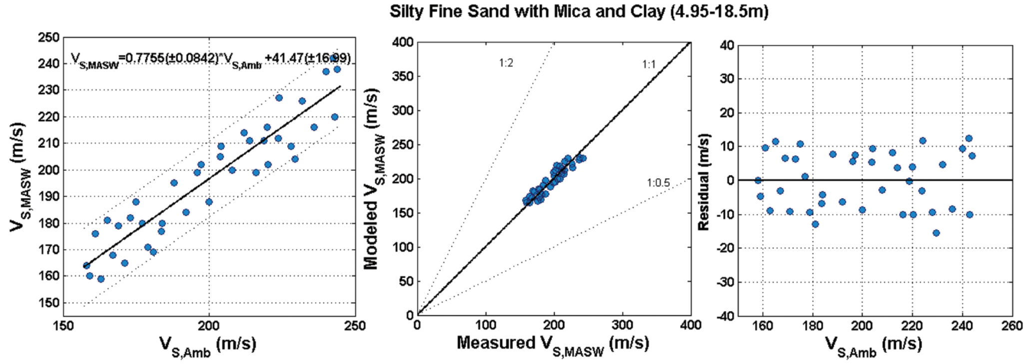

Silty Clay with Brown Silty Spots (12.5-18.95m)




Silty Clay with Mica, Sand and Kankar (13.95-22.5m)




Silty Fine Sand with Mica and Clay (4.95-18.5m)



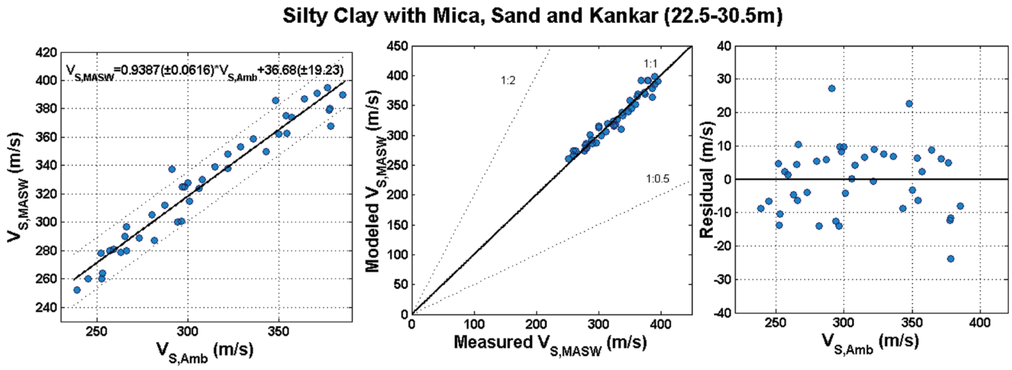



**Figure 6.24** **Correlations between MASW derived $V_s$ and Microtremor survey derived $V_s$ (left panel), Measured (downhole) versus predicted shear wave velocities (middle panel) and residual plots (right panel) for ten lithological units identified in Kolkata.**

These relations have been used to rectify Microtremor survey derived $V_s$ profiles of 1200 locations, thus providing another 1200 pseudo downhole $V_s$ profiles. The framework followed for the calibration of all the $V_s$ profiles is displayed in Figure 6.25.

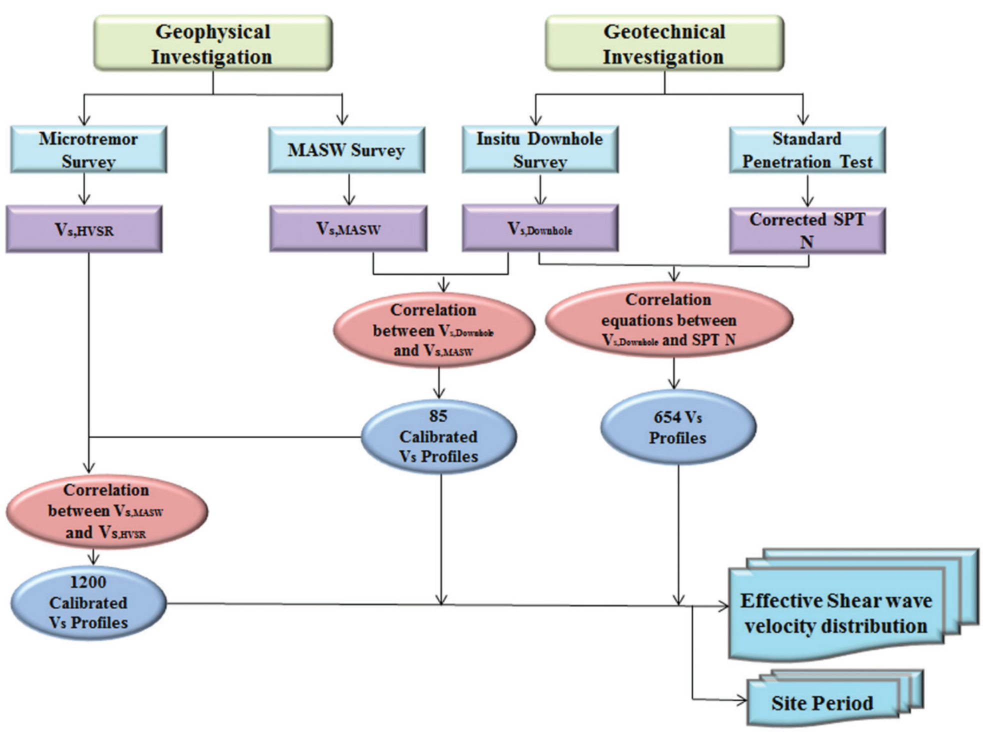



**Figure 6.25** **The framework used for the calibration of $V_s$ obtained from MASW and Nakamura technique. The idea is to calibrate $V_s$ derived through non-invasive MASW and HVSR survey at all the locations with reference to insitu $V_s$ from downhole measurements in order to implicate rationality in the shear wave velocity data base thus created considering all sorts of measurements.**

Shear wave velocity profiles obtained from all the four methods *viz*. insitu downhole survey, $V_s$ & SPT-N relation, MASW Survey and microtremor survey have been compared and found to be in good agreement with each other. Figure 6.26 depicts the borehole lithology along with the corresponding 1-D shear wave velocity profiles obtained from SPT-N value, MASW derived $V_s$, Microtremor HVSR inverted $V_s$ and insitu $V_s$ at four representative sites of Kolkata *viz*. Dum Dum, Shibpur, Alipore and Thakurpukur.

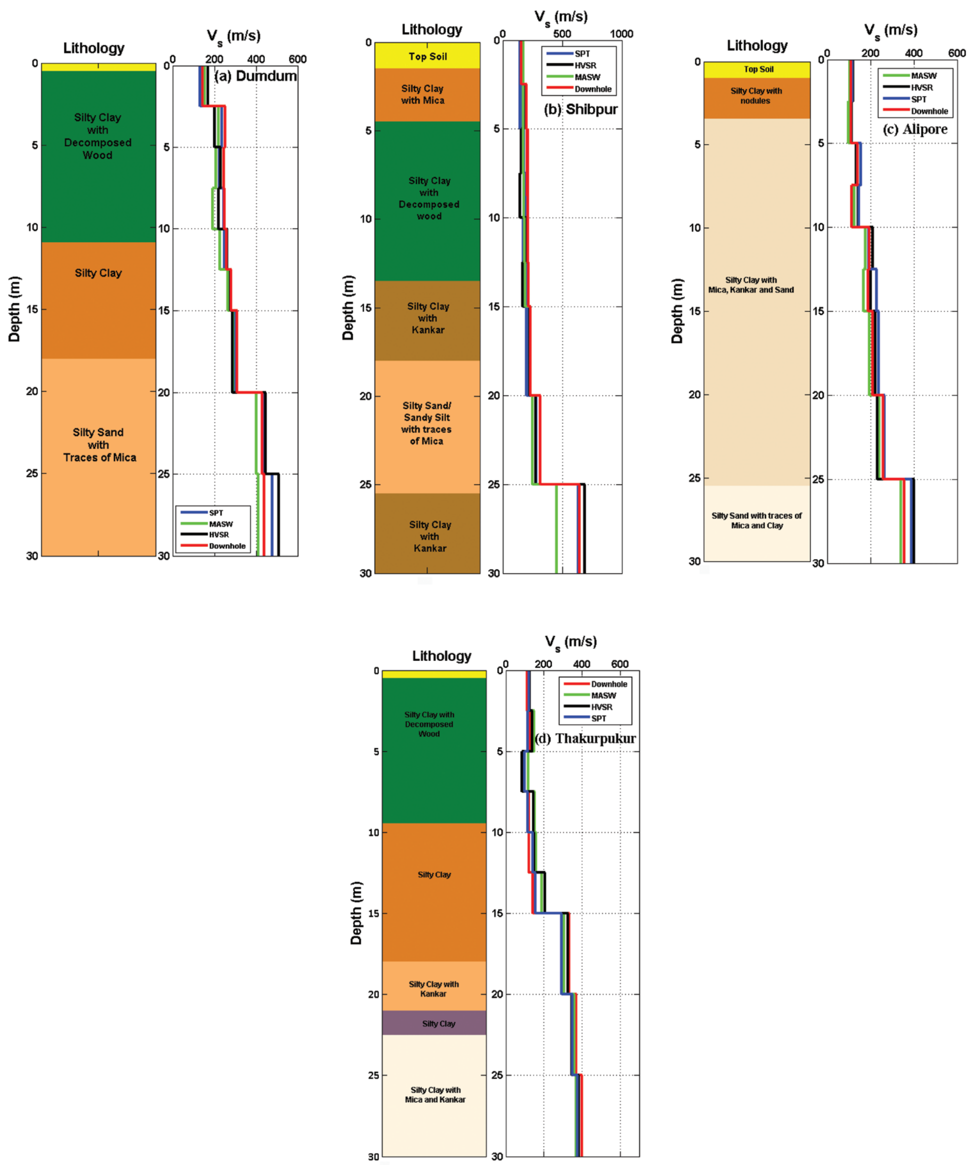


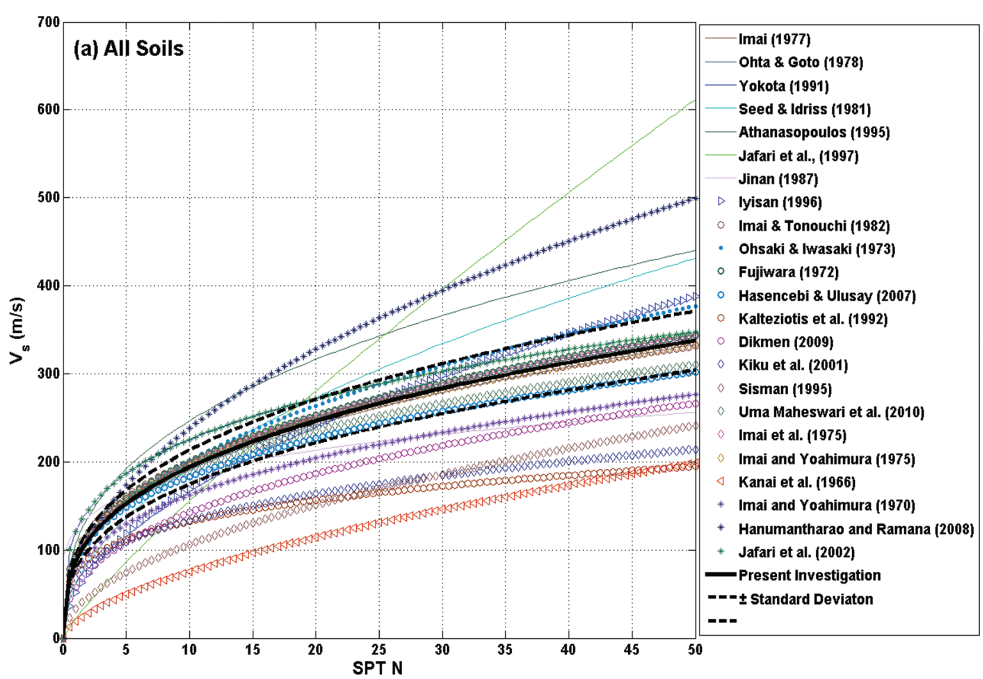

**Figure 6.26** **Lithostratigraphy and comparative 1-D Shear wave velocity ($V_s$) profiles derived from empirical SPT formulations, HVSR inversion, MASW survey and insitu downhole survey of four representative sites of Kolkata *viz.* (a) Dum Dum, (b) Shibpur, (c) Alipore, and (d) Thakurpukur.**

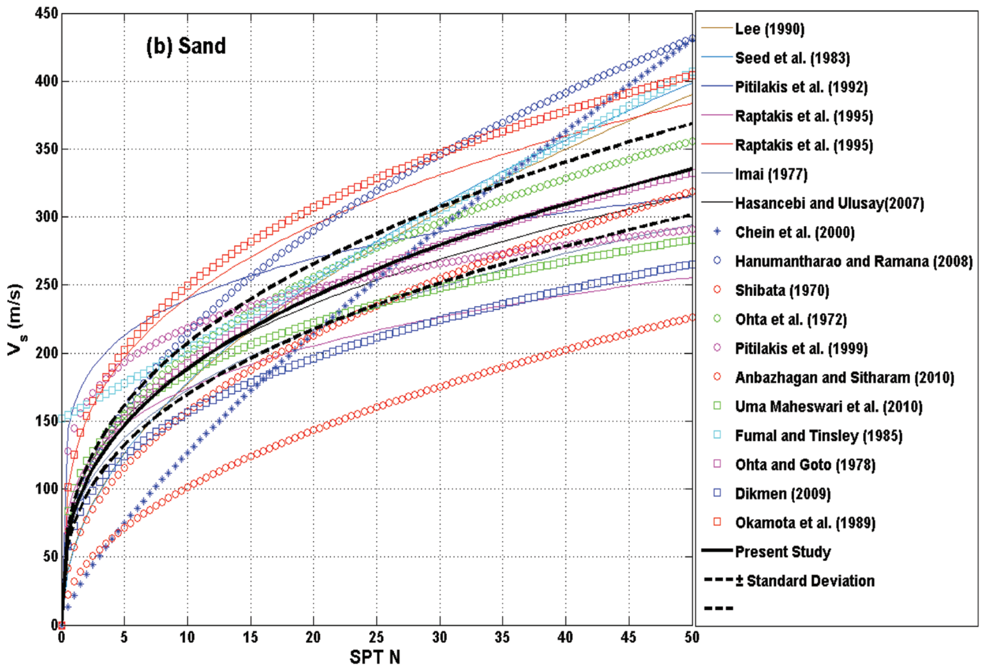
The generated relations for the present study between SPT-N and insitu $V_s$ are site and depth specific and can't be compared with the available generalized, globally accepted relations between the same unless the data pair of the corrected SPT-N values and insitu shear wave velocities at same depths have been reclassified into four generalized soil classes *viz*. Sand, Silt, Clay and All Soils to generate four empirical, nonlinear regression equations as presented in Table 6.9.

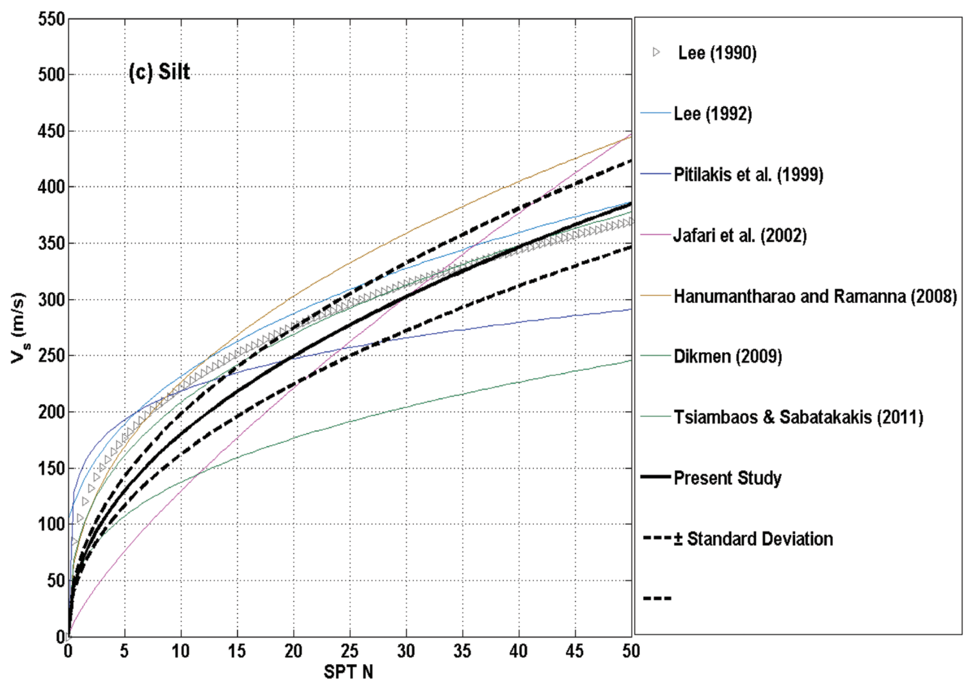
**Table 6.9** **Empirical correlation relations between $V_s$ and $N$ for the generalized soil classes recommended for Kolkata region**

| Soil Class | Shear Wave Velocity Equations |
|---|---|
| All Soils | $V_s = 87.54N^{0.345}$ |
| Sand | $V_s = 82.59N^{0.358}$ |
| Silt | $V_s = 60.47N^{0.473}$ |
| Clay | $V_s = 97.86N^{0.308}$ |

These correlation equations between $V_s$ and SPT-N values have further been compared with those equations obtained from the available empirical correlations published in various literatures presented in Table 6.10, as shown in Figure 6.27. A careful analysis of the available empirical correlations shows that although the proposed relations for Kolkata lies in between and reasonably close to the global relations, a variation in $V_s$ has been observed for same type of lithology, which is likely to be caused by differences in depositional environment and geology of the region where the analysis has been performed, thus implicating the necessity of site, depth and lithology-specific relations derived for the region and illustrated in the earlier sections.




(b) Sand
Vs (m/s)
SPT N
Lee (1990)
Seed et al. (1983)
Pitilakis et al. (1992)
Raptakis et al. (1995)
Raptakis et al. (1995)
Imai (1977)
Hasancebi and Ulusay(2007)
Chein et al. (2000)
Hanumantharao and Ramana (2008)
Shibata (1970)
Ohta et al. (1972)
Pitilakis et al. (1999)
Anbazhagan and Sitharam (2010)
Uma Maheswari et al. (2010)
Fumal and Tinsley (1985)
Ohta and Goto (1978)
Dikmen (2009)
Okamota et al. (1989)
Present Study
± Standard Deviation


(c) Silt
Vs (m/s)
SPT N
Lee (1990)
Lee (1992)
Pitilakis et al. (1999)
Jafari et al. (2002)
Hanumantharao and Ramanna (2008)
Dikmen (2009)
Tsiambaos & Sabatakakis (2011)
Present Study
± Standard Deviation

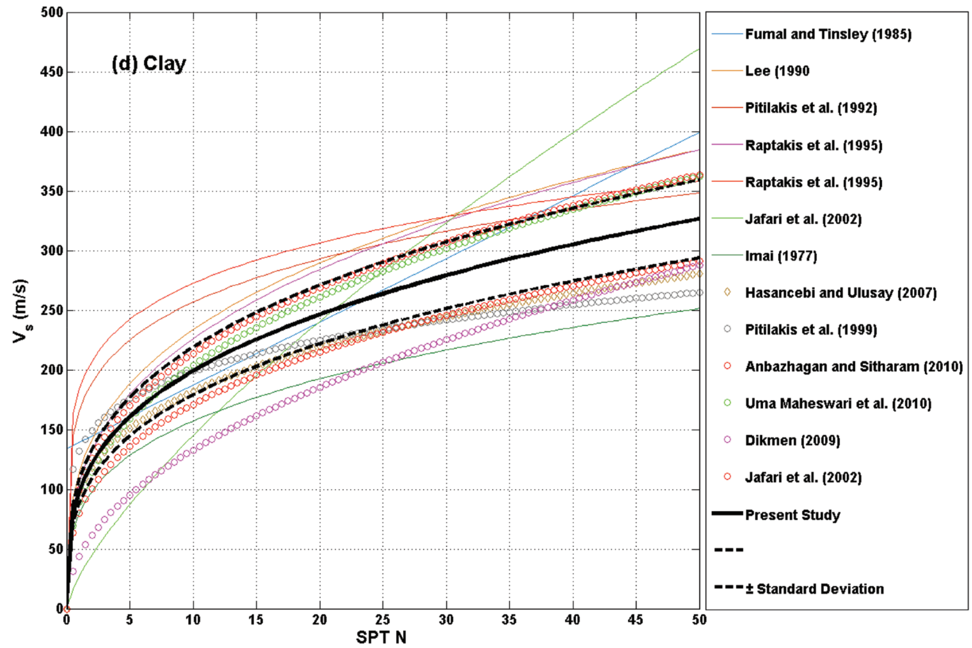



**Figure 6.27** Comparison of the generated nonlinear empirical power equations for Kolkata with the available empirical correlations published in various literatures for (a) All Soils, (b) Sand, (c) Silt, and (d) Clay. The proposed correlation relations lie in between the previously suggested relations.

**Table 6.10** Relations between SPT-N value and Shear Wave Velocity of different soil types published in various regions of the world which has been used to compare the proposed empirical relation of Kolkata

| Lithology | Reference | Relation | Region |
|---|---|---|---|
| Sand | Lee (1990) | $V_s$=57.4 $N^{0.49}$ | USA |
| | Seed *et al.* (1983) | $V_s$=56.4 $N^{0.50}$ | USA |
| | Pitilakis *et al.* (1992) | $V_s$=162.0 $N^{0.17}$ | Greece |
| | Raptakis *et al.* (1995) | $V_s$=100.0 $N^{0.24}$ | Greece |
| | Raptakis *et al.* (1995) | $V_s$=123.4 $N^{0.29}$ | Greece |
| | Imai (1977) | $V_s$=80.6 $N^{0.331}$ | Japan |
| | Hasancebi and Ulusay (2007) | $V_s$=90.8 $N^{0.319}$ | Turkey |
| | Chien *et al.* (2000) | $V_s$=22.0 $N^{0.76}$ | Western Taiwan |
| | Hanumantharao and Ramana (2008) | Vs = 79.0 $N^{0.434}$ | Delhi |
| | Shibata (1970) | Vs = 32 $N^{0.5}$ | Japan |
| | Ohta *et al.* (1972) | Vs = 87 $N^{0.36}$ | Japan |
| | Pitilakis *et al.* (1999) | $V_s$=145 $(N_{60})^{0.178}$ | Greece |
| | Anbazhagan and Sitharam (2010) | $V_s$=57 $((N_1)_{60,cs})^{0.44}$ | Bangalore, India |
| | Maheswari *et al.* (2010) | $V_s$=100.53$N^{0.265}$ | Chennai, India |

| Lithology | Reference | Relation | Region |
|---|---|---|---|
| Sand | Fumal and Tinsley (1985) | $V_s$=5.1N + 152 | USA |
| | Ohta and Goto (1978) | Vs = 88.0 $N^{0.34}$ | Japan |
| | Dikmen (2009) | Vs = 73 $N^{0.33}$ | Western Taiwan |
| | Okamoto *et al.* (1989) | Vs = 125 $N^{0.3}$ | - |
| | Jafari *et al.* (2002) | Vs = 80.0 $N^{0.33}$ | Japan |
| Clay | Fumal and Tinsley (1985) | $V_s$=5.3 N+134 | USA |
| | Lee (1990) | $V_s$=114.4 $N^{0.31}$ | USA |
| | Pitilakis *et al.* (1992) | $V_s$=165.7 $N^{0.19}$ | Greece |
| | Raptakis *et al.* (1995) | $V_s$=105.7 $N^{0.33}$ | Greece |
| | Raptakis *et al.* (1995) | $V_s$=184.2 $N^{0.17}$ | Greece |
| | Jafari *et al.* (2002) | $V_s$=27.0 $N^{0.73}$ | South of Tehran |
| | Imai (1977) | $V_s$=80.2 $N^{0.292}$ | Japan |
| | Hasancebi and Ulusay (2007) | $V_s$=97.9 $N^{0.269}$ | Turkey |
| | Pitilakis *et al.* (1999) | $V_s$=132 $(N_{60})^{0.178}$ | Greece |
| | Anbazhagan and Sitharam (2010) | $V_s$=80$(N)^{0.33}$ | Bangalore ,India |
| | Maheswari *et al.* (2010) | $V_s$=89.31$N^{0.358}$ | Chennai, India |
| | Dikmen (2009) | Vs = 44 $N^{0.48}$ | Western Taiwan |
| | Jafari *et al.* (2002) | Vs = 100.0 $N^{0.33}$ | Japan |
| Silt | Lee (1990) | Vs = 105.6 $N^{0.32}$ | Taiwan |
| | Lee (1992) | Vs = 104$( N+1)^{0.334}$ | Taiwan |
| | Pitilakis *et al.* (1999) | Vs = 145.6 $N^{0.178}$ | Greece |
| | Jafari *et al.* (2002) | Vs = 22 $N^{0.770}$ | Tehran |
| | Hanumantharao and Ramana (2008) | Vs = 86 $N^{0.420}$ | Delhi |
| | Dikmen (2009) | Vs = 60 $N^{0.360}$ | Turkey |
| | Tsiambaos and Sabatakakis (2011) | Vs = 88.8$(N_{60})^{0.370}$ | Greece |
| All Soils | Imai (1977) | $V_s$=91.0 $N^{0.34}$ | Japan |
| | Ohta and Goto (1978) | $V_s$=85.35 $N^{0.348}$ | Japan |
| | Jafari *et al.* (2002) | $V_s$=121.0 $N^{0.27}$ | Japan |
| | Seed and Idriss (1981) | $V_s$=61.0 $N^{0.50}$ | USA |
| | Athanasopoulos (1995) | $V_s$=107.6 $N^{0.36}$ | Greece |
| | Jafari *et al.* (1997) | $V_s$=22.0 $N^{0.85}$ | Iran |
| | Jinan (1987) | $V_s$=116.1 $(N + .3185)^{0.202}$ | China |
| | Iyisan (1996) | $V_s$=51.5 $N^{0.516}$ | Turkey |
| | Imai and Tonouchi (1982) | $V_s$=97.0 $N^{0.314}$ | Japan |
| | Ohsaki and Iwasaki (1973) | $V_s$=82.0 $N^{0.39}$ | Japan |
| | Fujiwara (1972) | $V_s$=92.1 $N^{0.337}$ | Japan |

| Lithology | Reference | Relation | Region |
|---|---|---|---|
| All Soils | Hasancebi and Ulusay (2007) | $V_s$=90.0 $N^{0.309}$ | Turkey |
| | Hanumantharao and Ramana (2008) | Vs = 82.6 $N^{0.43}$ | Delhi |
| | Imai and Yoshimura (1970) | Vs = 76 $N^{0.33}$ | Japan |
| | Kanai *et al.* (1966) | Vs = 19 $N^{0.6}$ | - |
| | Imai and Yoshimura (1975) | Vs = 92 $N^{0.329}$ | Japan |
| | Imai *et al.* (1975) | Vs = 90 $N^{0.341}$ | Japan |
| | Maheswari *et al.* (2010) | $V_s$=95.64$N^{0.301}$ | Chennai, India |
| | Sisman (1995) | $V_s$=32.8$N^{0.51}$ | Turkey |
| | Kiku *et al.* (2001) | $V_s$=68.3$N^{0.292}$ | Turkey |
| | Dikmen (2009) | Vs = 58 $N^{0.39}$ | Western Taiwan |
| | Kalteziotis *et al.* (1992) | Vs = 76.2$N^{0.24}$ | Greece |

## 6.6 Effective Shear Wave Velocity distribution in Kolkata

Effective Shear Wave Velocity ($V_s^{30}$) for the top 30 m soil column is an integral component of many seismic analyses *viz*. seismic site classification, site response analysis, seismic hazard analysis *etc*. which provides an understanding of the shallow subsurface condition of the region and is directly related to the stiffness of sediments. The amplification of the ground motion in a region is associated with the acoustic impedance contrast due to the presence of soft sediments, which according to Aki and Richards (2002) is proportional to

$$\frac{1}{\sqrt{(V_S.\rho)}} \qquad (6.12)$$

where $V_s$ is the shear wave velocity and $\rho$ is the density of the soil. The variation of density with depth upto 30 m is not as significant as that of the variation of shear wave velocity, hence $V_s^{30}$ proves to be an effective tool for site characterization. The effective shear wave velocity of the top 30 m soil column is computed as

$$V_S^{30} = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{v_i}} \qquad (6.13)$$

where '$h_i$' is the thickness in meters and '$v_i$' is the shear wave velocity in m/s for the $i^{th}$ layer from the '$n$' layers in top 30 m of the soil column. The effective shear wave velocity obtained from the 1-D $V_s$ profiles at 1957 locations obtained from 654 geotechnical borehole sites, 85 MASW sites, 1200 microtremor survey locations and 18 insitu downhole seismic survey sites are used to generate the effective shear wave velocity distribution map of Kolkata in GIS platform as shown in Figure 6.28(a) along with the standard error associated with it. The estimated effective shear wave velocity range for Kolkata Megacity has been found to be varying from 144 m/s to 357 m/s with the dominance of the velocity range of 174-210 m/s, thus indicating the soft soil conditions in the terrain. Areas like Central Kolkata, Saltlake, Thakurpukur, Shibpur and New Town clearly indicate the presence of low shear wave velocity zone of a range of 160-195 m/s thus affirmating the presence of soft sediments in these urban clusters.

In order to account for the uncertainty associated with the shear wave velocity distribution a standard error map has been generated and plotted in Figure 6.28(b).

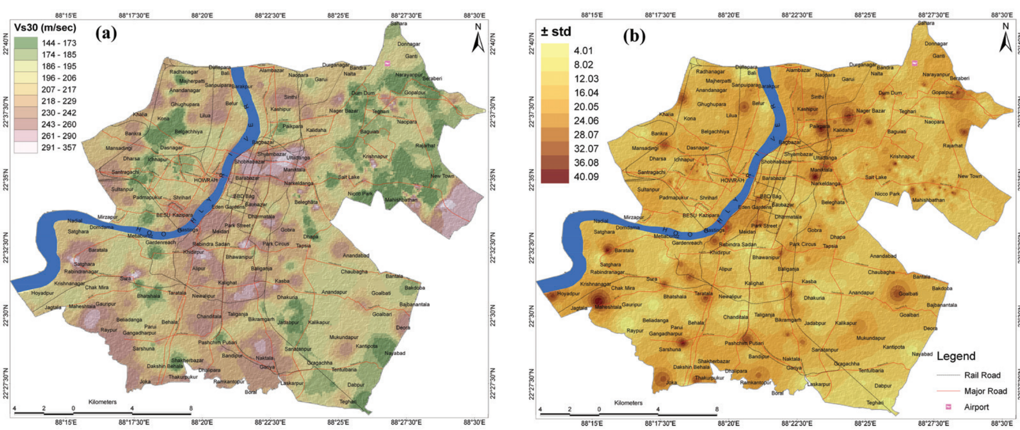



**Figure 6.28** **(a) Effective Shear wave velocity ($V_s^{30}$) distribution map of Kolkata generated from 1957 Shear wave velocity profiles derived from empirical SPT formulations, HVSR inversion, MASW survey and insitu downhole survey, (b) the associated standard error distribution map.**

## 6.7 Site Period

The local site condition directly influences the dominant site period depending on its physical properties and sediment thickness. Site period ($T_G$) indicates the period of vibration at which maximum ground motion amplification is expected (Sun *et al.,* 2009). Therefore, closer the fundamental site period to the natural period of the building, more will be the damage (Maheswari *et al.,* 2010). It is governed by the shear wave velocity of each soil layer at a site and its thickness and is calculated for multi-layered soil horizon by using the expression (Sun *et al.,* 2008; Kramer, 1996)

$$T_G = 4\sum_{i=1}^{n} \frac{D_i}{V_{Si}} \tag{6.14}$$

where $D_i$ is the thickness of each soil layer above the bedrock, $V_{Si}$ is the shear wave velocity of each soil layer, and *n* is the total number of soil layers. The 1957 Shear wave velocity profiles derived from empirical SPT formulations, HVSR inversion, MASW survey and insitu downhole survey have been clubbed together to assess the predominant period of vibration or site period, $T_G$ of a location using the formulation (6.14). The site periods thus estimated have been represented in a boxplot as shown in Figure 6.29 in which the fundamental statistical elements, *i.e.* minimum value, maximum value, median value, first quartile (25$^{th}$ percentile) and third quartile (75$^{th}$ percentile) of the site periods are displayed. The boxplot exhibits a minimum, maximum and median value as 0.32, 0.98 and 0.57 sec respectively. The first quartile and third quartile values are 0.46 and 0.68 sec respectively thus providing an inter quartile range of 0.46-0.68 sec.

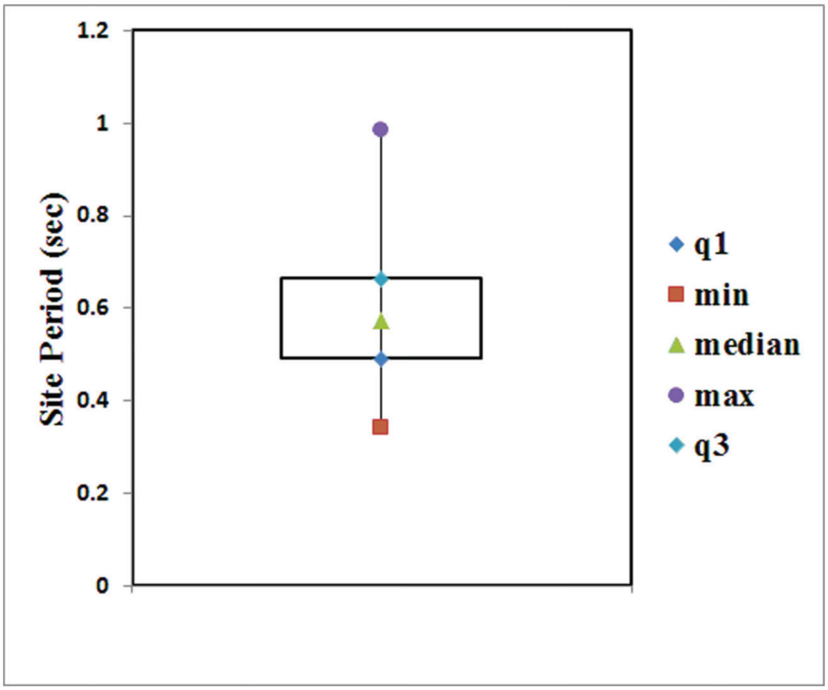
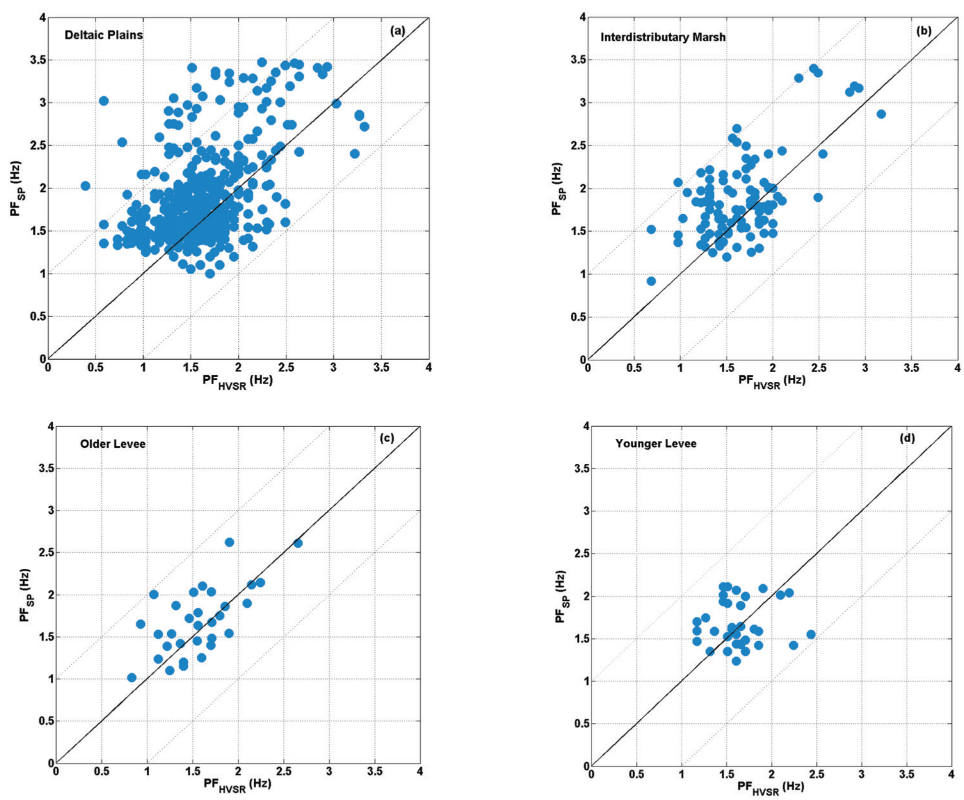



**Figure 6.29** **Box Plot of the estimated site periods displaying their fundamental statistical elements *viz.* First Quartile 'q1' (25$^{th}$ percentile), minimum value 'min', median value, maximum value 'max' and Third Quartile 'q3' (75$^{th}$ percentile).**

These site periods have further been inverted ($1/T_G$) to estimate the predominant frequency of each site and then compared with those obtained from HVSR analysis of Nakamura method extracting the same from the recorded Ambient Noise data set for each geomorphologic unit in the region.

## 6.8 Geomorphology specific comparison between Predominant Frequencies obtained from Site Period with those obtained from HVSR Analysis

There are seven geomorphologic units that encompass Kolkata including the water body which is considered the seventh geomorphologic unit. For each geomorphologic unit predominant frequencies obtained from the inversion of site periods are compared with those extracted from HVSR curves and shown in Figure 6.30 for all the six geomorphologic units except the water bodies.



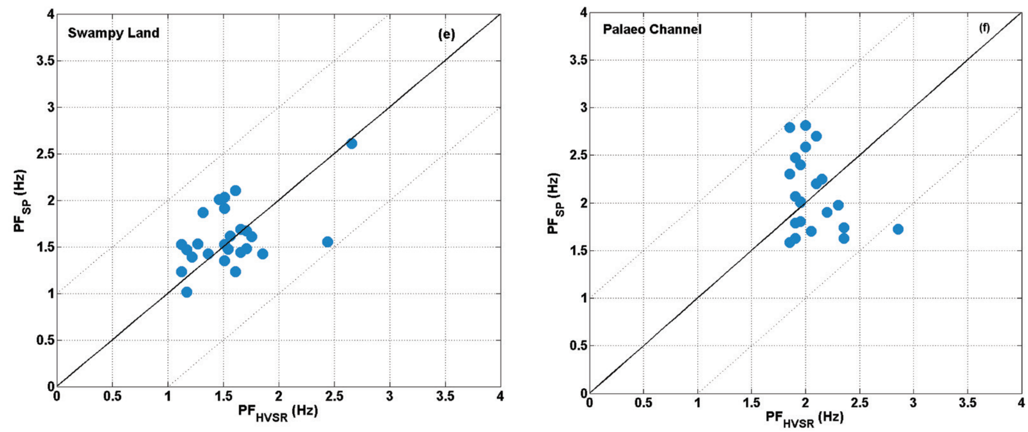



**Figure 6.30** **A comparison between the predominant frequencies obtained from site period ($PF_{SP}$) with those obtained from HVSR curves ($PF_{HVSR}$) for (a) Deltaic Plains, (b) Interdistributary Marsh, (c) Older levee, (d) Younger levee, (e) Swampy Land, and (f) Palaeo channel.**

Figure 6.30 exhibits a clustering of data in the proximity of 1:1 correspondence line and seen to remain within ±1 standard deviation, thus suggesting a good match between the two estimates. Deltaic plain and interdistributary marsh is the most dominant geomorphologic units in Kolkata. For these geo-units the predominant frequency ranges from 0.7-2 Hz and 1.25-2 Hz respectively. The older levee and the younger levee have majority of the predominant frequencies within the range of 1.2-1.9 Hz and 1.2-2 Hz respectively. Swampy land has majority of predominant frequencies in the range of 1.25-1.8 Hz while that for the palaeo channel mostly lie in the range of 1.5-2.3 Hz.

## 6.9 Site Classification of Kolkata

Site classification of a region is performed based on the effective shear wave velocity distribution in the region considering top 30 m soil column (Boore, 2004). Table 6.11 depicts the site classification protocol as proposed by National Earthquake Hazard Reduction Program (NEHRP) based on effective shear wave velocity $V_s^{30}$ distribution.

**Table 6.11** **NEHRP site classification scheme (BSSC, 2001), $V_s^{30}$ denotes effective shear wave velocity for 30 m upper soil column**

| Site class | $V_s^{30}$ | Description |
|---|---|---|
| A | > 1500 m/s | Hard rock |
| B | 760 – 1500 m/s | Rock site |
| C | 360 – 760 m/s | Soft rock, hard or very stiff soils or gravels |

| Site class | $V_s^{30}$ | Description |
|---|---|---|
| D | 180 – 360 m/s | Stiff soils |
| E | <180 m/s | More than 3 m of soft clay defined as soil with plasticity index (PI)>20, moisture content (w)≥40 percent, and average undrained shear strength (Su)<25 kPa |
| F | Site-specific evaluation of the soil | Either of the following our categories of soil are considered:<br>(i) soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, and collapsible weakly cemented soils,<br>(ii) peats and/or highly organic clays (soil thickness >3 m) of peat and/or highly organic clay,<br>(iii) very high plasticity clays (soil thickness >8 m with PI >75, and<br>(iv) very thick soft/medium stiff clays (soil thickness >36 m). |

This site classification protocol is further revised by FEMA (1994) & Wald and Allen (2007) as given in Table 6.12 to incorporate subcategories within the NEHRP mega site classes.

**Table 6.12** **Revised Site Classification protocol based on FEMA (1994) & Wald and Allen (2007). $V_S^{30}$ denotes effective shear wave velocity for 30 m upper soil column**

| Site Class | $V_S^{30}$ (m/s) |
|---|---|
| D3 | 300-360 |
| D2 | 240-300 |
| D1 | 180-240 |
| E | <180 |

However, Sun (2004) has also proposed sub-classes which not only considers effective shear wave velocity $V_S^{30}$ distribution but also the corresponding site periods, thus subdividing Site Class C and Site Class D into four sub-classes: C1 ($V_S^{30}$: 760-620 m/s; $T_G$: 0.06-0.10 sec), C2 ($V_S^{30}$: 620-520 m/s; $T_G$: 0.10-0.14 sec), C3 ($V_S^{30}$: 520-440 m/s; $T_G$: 0.14-0.19 sec), C4 ($V_S^{30}$: 440-360 m/s; $T_G$: 0.19-0.27 sec), D1 ($V_S^{30}$: 360-320 m/s; $T_G$: 0.27-0.34 sec), D2 ($V_S^{30}$: 320-280 m/s; $T_G$: 0.34-0.43 sec), D3 ($V_S^{30}$: 280-240 m/s; $T_G$: 0.43-0.55 sec), and D4 ($V_S^{30}$: 240-180 m/s; $T_G$: 0.55-0.68 sec). In the present study we adopted this sub-classification protocol of Sun (2004) as presented in Table 6.13. Thus considering both the NEHRP and Sun (2004), Site Classification nomenclature the final site classification map of Kolkata is generated on GIS platform as presented in Figure 6.31.

**Table 6.13** **Seismic Site Classification based on Effective Shear Wave Velocity of 30 m soil column, $V_s^{30}$ and the corresponding Site Period, $T_G$ followed for Kolkata (after NEHRP; Sun, 2004; Sun and Shin, 2009; Sun *et al.*, 2009)**

| Generic Description | Site Class | | Criteria | |
|---|---|---|---|---|
| | | | $V_s^{30}$ (m/s) | Site Period , $T_G$ (sec) |
| Rock | B | | <760 | <0.06 |
| Weathered Rock and Very Stiff Soil | C | C1 | <620 | <0.10 |
| | | C2 | <520 | <0.14 |
| Intermediate Stiff Soil | | C3 | <440 | <0.19 |
| | | C4 | <360 | <0.27 |
| Deep Stiff Soil | D | D1 | <320 | <0.34 |
| | | D2 | <280 | <0.43 |
| | | D3 | <240 | <0.55 |
| | | D4 | >180 | <0.68 |
| Soft Soil | E | | <180 | ≥0.68 |

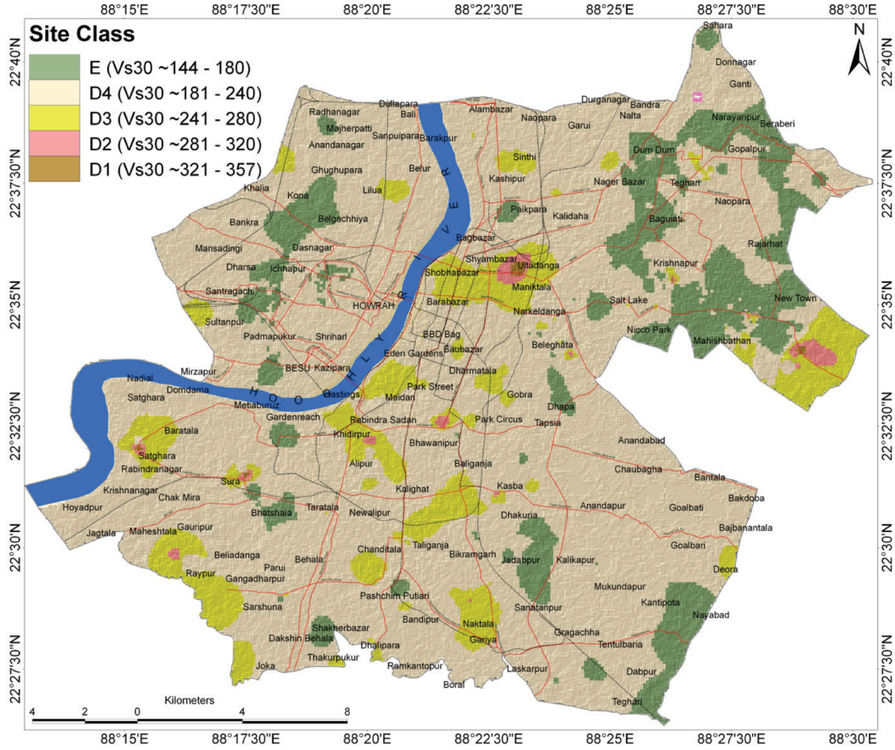



**Figure 6.31** **Site Classification map of Kolkata adhering Sun (2004), Sun and Shin (2009) & Sun *et al.* (2009) and displaying the presence of Site Class E, D4, D3, D2 & D1 in the terrain with the dominance of Site Class D4 followed by Site Class D3 and Site Class E in the region.**

The Site Classification map of Kolkata exhibits the presence of Site Class E, D4, D3, D2 & D1 with the dominance of Site Classes corresponding to low shear wave velocity *viz*. D4 followed by Site Class D3 and Site Class E in the region which may be attributed to the presence of a low velocity layer of high plastic silty clay associated with decomposed wood/peat. Site Class E marks its presence in parts of the city at Howrah, Shibpur, Saltlake, Nicco Park, Dhapa, Jadabpur and so on. Site Class D4 is covering mostly the southeastern region of the city and also partly in Mukundapur, Saltlake, Narkeldanga, Sealdah, Alipur, Metiabruz, Howrah and so on. These areas are predominantly underlain by silty clay/clayey silt and silty sandy clay. The areas classified as Site Class D3 found in Rabindra Sadan, Maidan, Garia, Maniktala, Shobhabazar are composed of stiff soil with varied sediment deposits of clay associated mostly with silt followed by sand. In contrast, Site Class D2 & D1 have been identified in small patches in Ultadanga, Khidirpur, and outskirts of Rajarhat which comprise of very stiff to very dense soil and soft rock, such as boulders, cobbles or near-surface fractured rocks.

## 6.10 Concluding Remarks

Site classification is the basic component of site characterization achieved through the estimation of $V_s^{30}$ by both insitu measurements and surface geophysical investigations correlating each other through linear/nonlinear regression analysis and spatially distributing the same on GIS platform there by segregating the vector layer for the city into five clusters *viz*. site classes D1 ($360 \geq V_S^{30} > 320$ m/s), D2 ($320 \geq V_S^{30} > 280$ m/s), D3 ($280 \geq V_S^{30} > 240$ m/s), D4 ($240 \geq V_S^{30} > 180$ m/s) and E ($180 \geq V_S^{30}$) following the USGS, FEMA and Sun (2004) nomenclature. The associated predominant site periods ($T_G$) of the five site classes are: 0.27-0.34 sec; 0.34-0.43 sec; 0.43-0.55 sec; 0.55-0.68 sec & $T_G > 0.68$ sec respectively that delimits the vulnerability of urbanization in the city on the top 30 m alluvium envisaging amplification of ground motion and triggering liquefaction due to earthquake shaking in the top 5-10 m alluvium dominated by sand and silty sand thus increasing the severity of seismic hazard of the terrain.