5 Geophysical Investigations in Kolkata

5.1 Introduction

The damage patterns in an earthquake prone territory at the onslaught of large earthquakes exhibit that the soil condition at a site may have significant effects on the level of ground shaking. The estimation of seismic hazard and mapping the same at local scale necessitates incorporation of the effect of soil conditions which is imperative in the calculation of the probability of exceeding different levels of ground motion parameters in seismic microzonation of any urban center. The nonlinear behavior of the soil causes amplification to the ground motion thereby making it a pivotal cause on which the intensity of shaking depends significantly. The soil condition is governed by a site classification scheme based on shear wave velocity of the top 30 m soil cover (V_s^{30}) as proposed by Borcherdt (1994) and a similar scheme adopted by the National Earthquake Hazard Reduction Program (NEHRP). The subsurface shear wave velocity can be ascertained using either the invasive techniques like downhole, uphole, crosshole geophysical surveys or non-invasive techniques such as Spectral Analysis of Surface Waves (SASW) and Multi-channel Analysis of Surface Waves (MASW) (Park *et al.,* 1999; Xia *et al.,* 1999). In the present investigation intended for seismic microzonation of the city of Kolkata both the invasive and non-invasive geophysical surveys have been conducted for the estimation of shear wave velocity and hence to ascertain its spatial distribution for the purpose of site classification considering the top 30 m sediment covers. In this chapter we concentrate exclusively on non-invasive techniques like the microtremor/ambient noise survey and the MASW survey wherein H/V in the former is inverted to obtain a 1-D shear wave velocity structure at the site under investigation while in the later the dispersive properties of Rayleigh waves are used to generate both the 1-D and 2-D subsurface shear wave velocity structures at the site of interest. Recording and analyzing ambient noises rather simple which provide a good estimate of the fundamental frequency of the soil structure. The multi-channel approach has been extensively used to investigate surface waves by obtaining fundamental mode in dispersion curves (Ivanov *et al*., 2000; Park *et al*., 2002). Xia *et al*. (2000) have demonstrated MASW technique to extract the fundamental mode in surface wave spectrum from shot records using phase velocity.

5.2 Ambient Noise Survey

The predominant frequency of ground vibration is one of the dynamic properties of soil which is often considered an important parameter for seismic hazard estimation and the designing of earthquake resistant structures. If the natural frequency of vibration of a structure matches the ground predominant frequency of the site on which it is resting, the structure might undergo severe damage including total collapse due to quasi-resonance effect. Therefore, the use of microtremors can be extended to identifying the main frequencies of the buildings, their vulnerability and soil-structure resonance effect (Mucciarelli *et al.*, 2001; Gallipoli *et al*., 2004). In the present investigation the horizontal-to-vertical (H/V) spectral ratios (HVSRs) of microtremors popularly known as the Nakamura method (Nakamura, 2000) is used, to compute the predominant frequency of site vibration. Recent advancements in theoretical modeling of horizontal-vertical spectral ratio (HVSR) have led to the feasibility in its inversion to achieve sub-surface profile information. Although the HVSR technique is widely considered as a surface wave method, it uses a three component (two horizontal and one vertical) sensor to measure the ambient vibrations at the observation point in the ground surface. The horizontal to vertical spectral ratio of the surface displacements are used rather than the phase velocity dispersion curves of the surface waves as the theoretical basis to infer the layered soil profile of the compacted ground. The method was initiated in the late 1950s when ambient vibration measurements were pioneered but it was not a recognizable practice until the studies of Nogoshi and Igarashi (1971) and, in particular, Nakamura (1989) that the possibility of employing this technique to establish the resonance frequencies of the ground was seriously contemplated. Recent developments in the methodologies and algorithms to invert the measured HVSR curves to infer the V_s profile and the associated soil stratigraphy of the site made the technique easily adaptable in shallow subsurface shear wave tomographic studies.

The Ambient noise microtremor survey have been conducted in the Kolkata city at 1200 locations and the field measurements were taken using velocity sensors for one hour duration at each location. The data have been analyzed using VIEW2002 and GEOPSY software for the estimation of fundamental frequency at each site of investigation. Several scientists illustrated that the H/V peak is due to the horizontal-vertical polarization of the Rayleigh waves (Nogoshi and Igarashi, 1971; Shiono *et al.,* 1979; Kobayashi, 1980). Lachetl and Bard (1994), Kudo (1995), and Bonnefoy-Claudet *et al.* (2006) confirmed the correlation between the H/V peak frequency and the site resonance frequency. The H/V spectral ratios obtained by analyzing microtremor data can also be used to retrieve the S-wave velocity structure from a single station ambient vibration record, by using its relation to the ellipticity of the fundamental mode Rayleigh wave and the amplitude of the observed H/V ratio. The average H/V spectral ratios are presumed to be implicit measures of ellipticity of fundamental mode Rayleigh waves. The ellipticity at each frequency is defined as the ratio between the horizontal and vertical displacement eigen-functions in the P-SV case, at the free surface. Hence, the shape of H/V ratio can be used to estimate the shear wave velocity profile. Yamanaka *et al.* (1994) and Satoh *et al.* (2001) applied this concept for deep sedimentary basins while Fäh *et al.* (2001) used it for shallow site conditions. Array methods were established by Horike (1985) after the pioneering work done by Aki (1957). Herak (2008) proposed an inversion scheme in order to retrieve the S-wave velocity structure from a single ambient vibration record. The primary aim of the present study is to estimate resonance frequency using Nakamura method and the inversion of H/V using ModelHVSR for obtaining shear wave velocity of upper sedimentary strata.

5.2.1 Microtremor Data Acquisition

The microtremor survey has been conducted in Kolkata at 1200 locations as shown in the survey map in Figure 5.1 using MR2002-CE vibration monitoring system manufactured by SYSCOM, Switzerland, which ensures accurate, reliable vibration measurements and long term monitoring. The MR2002-CE is easy to handle and convenient to use. The instrument has two main units *viz*. the vibration sensor (MR2003+) with three sensitive geophones which pick up the ground vibrations and the other unit is the recorder (MR2002) in which the acquired data get stored. The MR2003+ velocity sensor is highly sensitive with three orthogonal components *viz*. two horizontal (H) and one vertical (V). Figure 5.1 depicts the field set up of the microtremor equipment. Initially the sensor is placed on the ground and the mounting plate of the sensor is leveled using the adjusting screws. The sensor cable and the recorder are connected to the field laptop using communication cable. After initial setup, the recorder is switched on and WINCOM 2002 communication software is used to access the MR2002. A baseline correction has been performed which assures that the recorded signal is centered around zero even if the sensor is not 100% leveled. The correction has to be performed before starting recording at each and every site. The data is recorded continuously for one hour with pre- and post-event time of 1 sec at each site creating 60 data files with the sample length of one minute each. The recorded events can be viewed using VIEW2002 software and then transferred for further analysis. The data recorded using this compact triaxial vibration monitoring equipment is analyzed using VIEW2002 and GEOPSY software. A differential GPS system provides the geographic position of each measurement point. The mean distance between successive recording sites is ~500 m. The sample ambient noise microtremor raw data recorded at various locations in Kolkata are displayed in Figure 5.2.

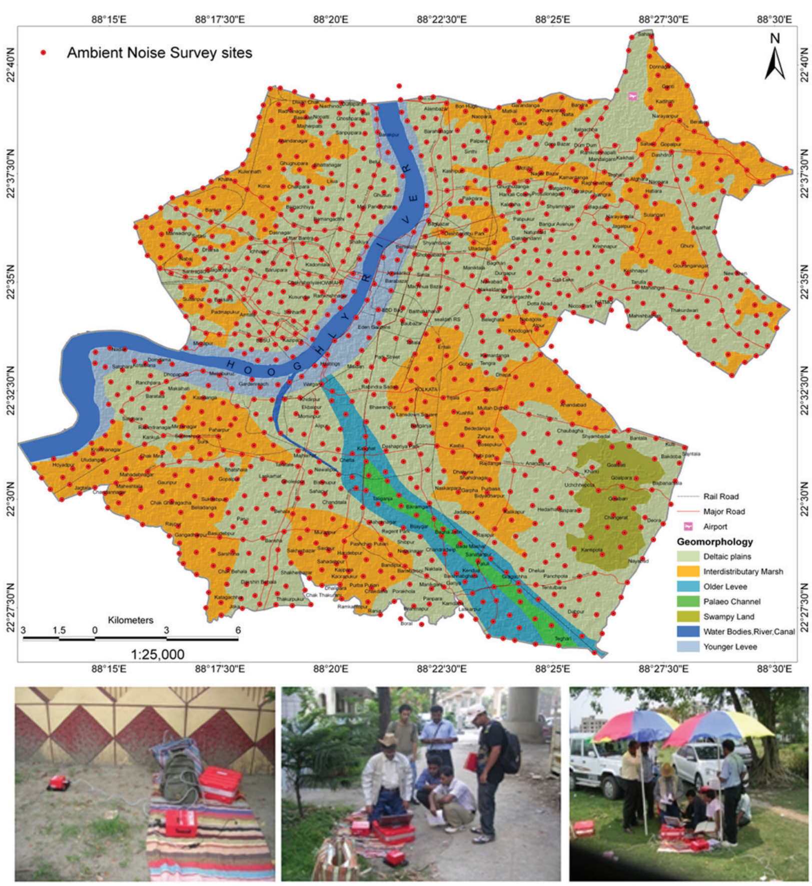
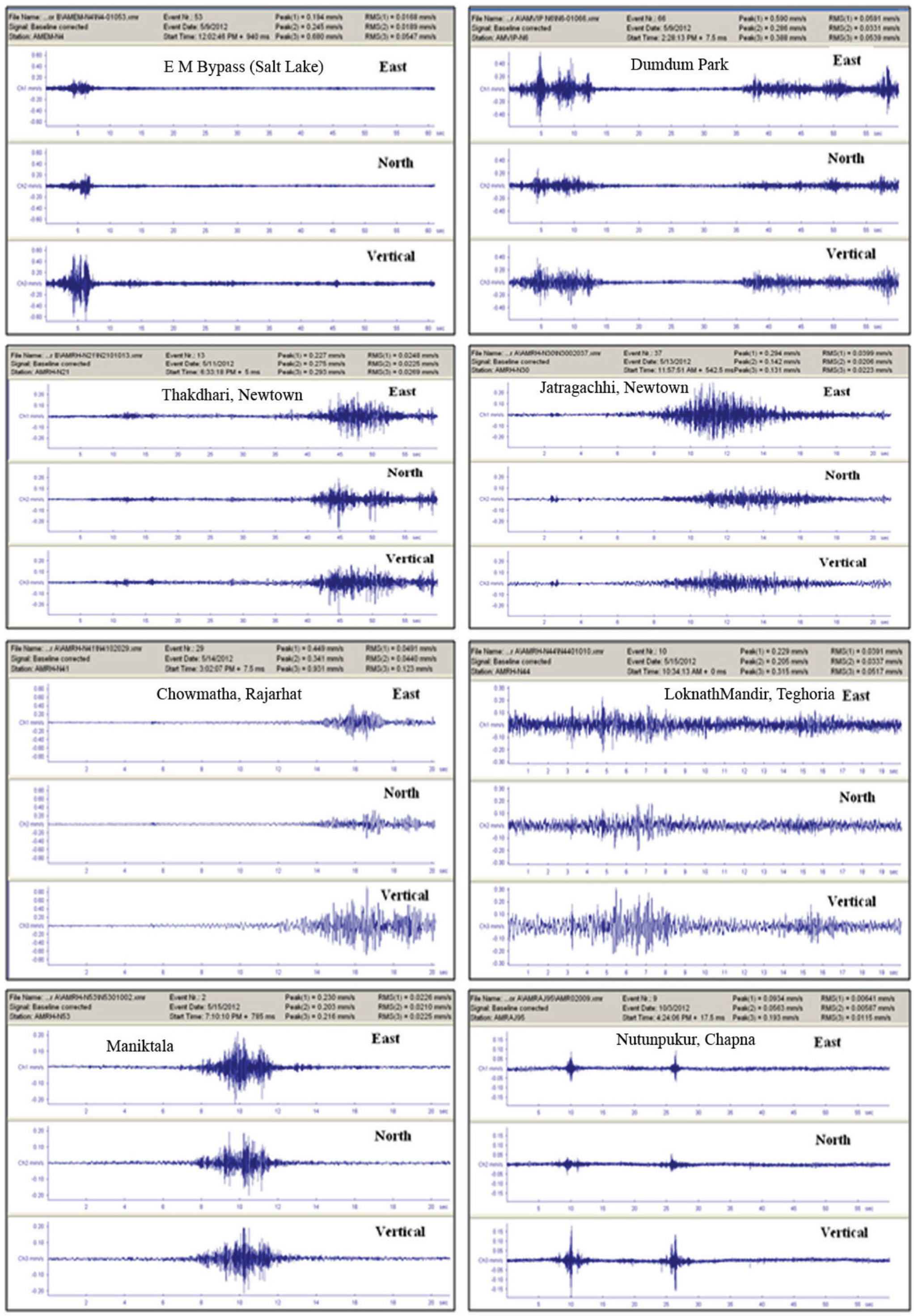
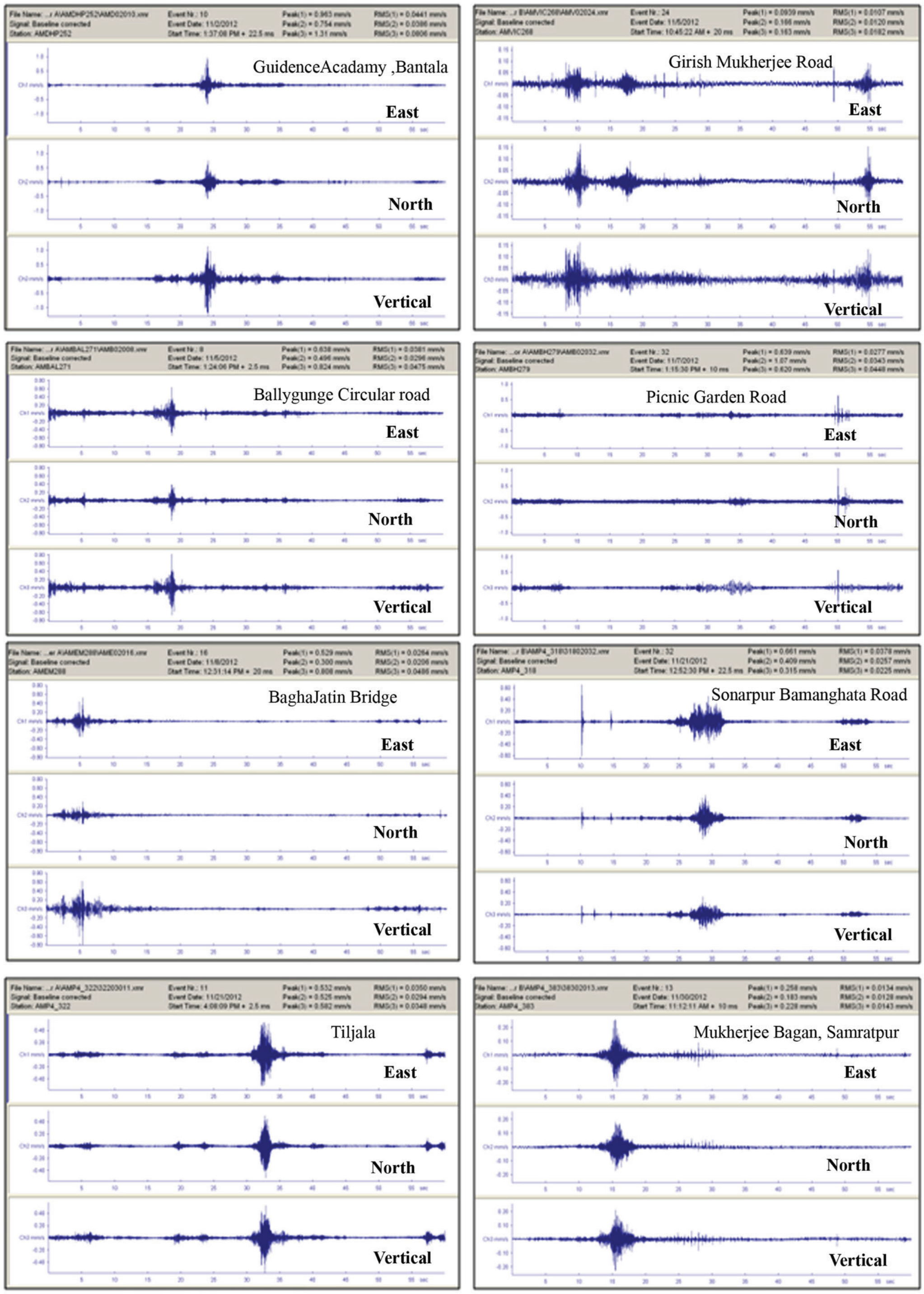


Figure 5.1 **Ambient noise survey sites in Kolkata together with the field setup.**


E M Bypass (Salt Lake)
East
North
Vertical
Dumdum Park
East
North
Vertical
Thakdhari, Newtown
East
North
Vertical
Jatragachhi, Newtown
East
North
Vertical
Chowmatha, Rajarhat
East
North
Vertical
LoknathMandir, Teghoria
East
North
Vertical
Maniktala
East
North
Vertical
Nutunpukur, Chapna
East
North
Vertical


GuidenceAcadamy ,Bantala
East
North
Vertical
Girish Mukherjee Road
East
North
Vertical
Ballygunge Circular road
East
North
Vertical
Picnic Garden Road
East
North
Vertical
BaghaJatin Bridge
East
North
Vertical
Sonarpur Bamanghata Road
East
North
Vertical
Tiljala
East
North
Vertical
Mukherjee Bagan, Samratpur
East
North
Vertical

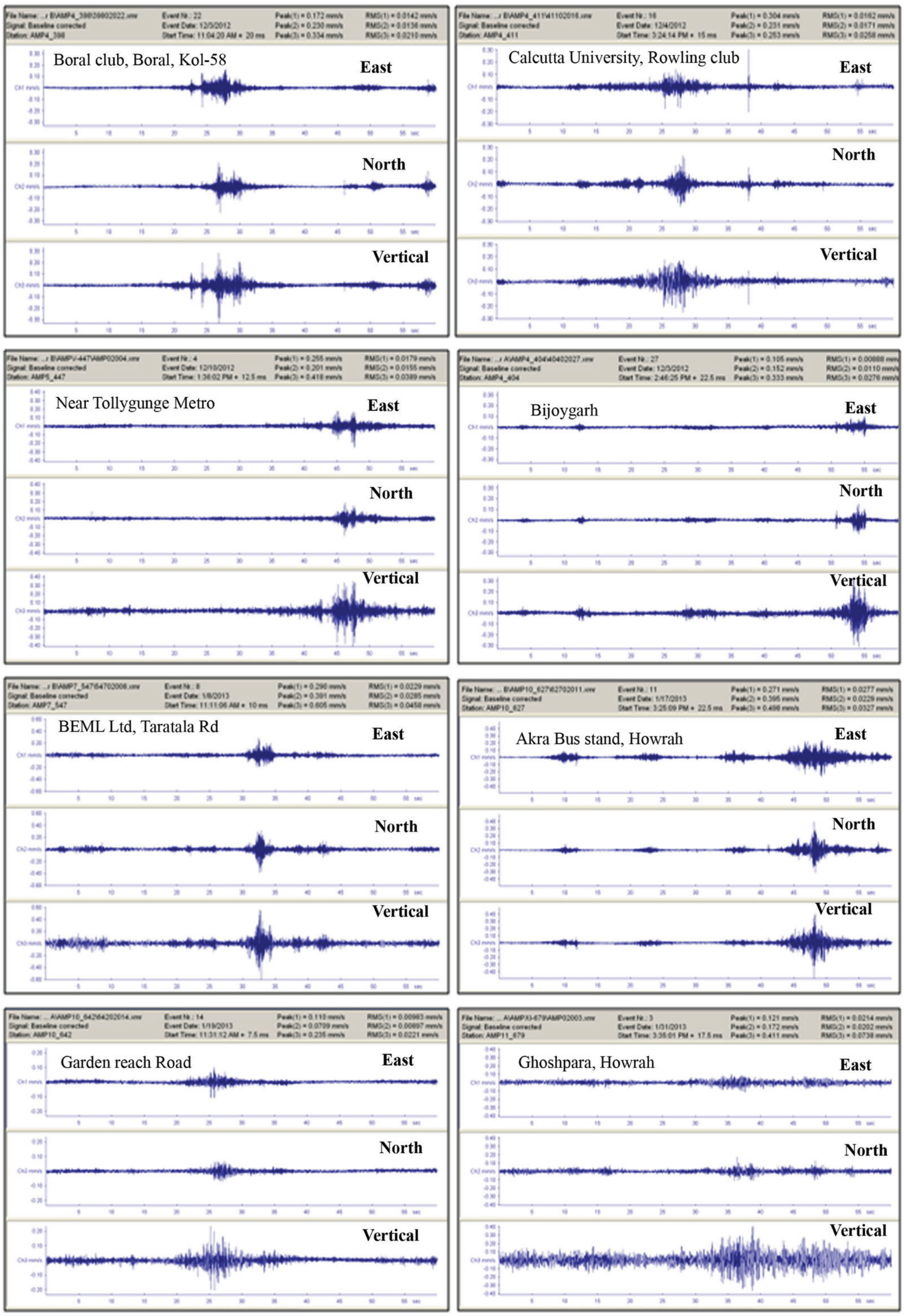


Figure 5.2 **Representative Ambient noise recorded data at various locations in Kolkata.**

5.2.2 Microtremor Data Processing

A sharp peak at the fundamental frequency of the sediments is observed in HVSR curves if a high impedance contrast between the sediments and the bedrock is present. It is widely accepted that the frequency at the peak of the HVSR curve represents the fundamental frequency of the sediments. Its amplitude depends mainly on the impedance contrast with the bedrock and therefore, cannot be used to ascertain site amplification. Udwadia and Trifunac (1973) investigated the use of microtremor method in the determination of site amplification for earthquake shaking by comparing the site response results from strong motion seismic records with those from microtremor measurements in California. They found little correlation between the ground motion due to earthquake shaking and the microtremor excitation. Several studies by various researchers (Ohmachi *et al.,* 1991) conclude that the peak H/V amplitude is not well correlated with the S-wave amplification at the site's resonant frequency. It is highly sensitive to the elastic parameters like Poisson's ratio near the surface. Comparisons with the results of standard spectral ratio method have also shown that the HVSR peak amplitude underestimates the actual site amplification (Bard, 1999; Gosar and Martinec, 2009). The HVSR method on the contrary directly estimates the sediments' resonance frequency without a priori knowledge about the subsurface geology and S-wave velocity structure. Nakamura (1989) found that site characteristics are related to a site transfer function derived from the ratio of Fourier spectra of the horizontal and vertical components of the ambient noise recordings. Mucciarelli and Gallipoli (2001) observed that HVSR is a stable quantity and is a function of site only with no periodicity in time, and slight or no dependence on other factors.

5.2.2.1 HVSR Analyses

The Nakamura method directly estimates the predominant frequency factors without any reference site and many researchers have validated the theory (Horike *et al*., 2001; Lermo and Chavez-Garcia, 1994). Initially the trigger levels were checked before the actual recording commences at every test site and the signals erroneously recorded below the trigger level are removed before the analysis is carried out on the recorded data. The recorded data at a particular test site are processed using the file group option in VIEW2002 and GEOPSY Software. Fourier analysis based on H/V spectral ratio is applied for each location where the microtremor recordings are transformed into frequency domain using the Fast Fourier transform method. The Fourier spectra of the filtered data are generated by the vectorial summation of two horizontal component spectra (*i.e.* EW and NS) to obtain the resultant horizontal spectrum (H). Finally the H/V spectrum is obtained by dividing the horizontal spectral amplitude by the vertical component spectral amplitude at each frequency as

$$H/V_{spectralratio} = \sqrt{\frac{\sum P_{NS}(\omega) + \sum P_{EW}(\omega)}{\sum P_V(\omega)}} \tag{5.1}$$

Where $P_{NS}(\omega)$, $P_{EW}(\omega)$ and $P_V(\omega)$ are the power spectra of NS, EW and the vertical component respectively, the summation is taken over all the data blocks. The average H/V spectrum is obtained by arithmetically averaging individually smoothed H/V spectra over all time windows. For clear identification of peak frequency, spectra are smoothened. In the present study smoothing is performed using a moving average technique. The basic assumption of the HVSR method is that the vertical component of the ground motion is supposed to be free of any kind of influence related to the soil conditions at the recording site (Roser and Gosar, 2010) in the cases where the soil stratigraphy is parallel to the recording plane.

5.2.2.2 HVSR Inversion

Microtremor HVSR method does not provide the shear wave velocity structure directly, but this can be derived by the modeling of the spectral ratio curve. It is usually based on the search for the model whose theoretical HVSR response matches well with the observed HVSR by random perturbation of model parameters within the preselected limits (Herak, 2008). One-dimensional modeling of the average HVSR curve is performed using the ModelHVSR code (Herak, 2008) which computes the theoretical P and S wave transfer functions (amplification) of a layered, visco-elastic model for the vertical incidence of P and S waves and use it for the calculation of a theoretical HVSR curve. The ModelHVSR algorithm inverts the observed HVSR curves by Monte Carlo perturbation in order to obtain the best fitting geotechnical model. The routine randomly perturbs an initial visco-elastic model within the user defined vector length, visco-elastic parameters and number of iterations. The inversion model consist of a homogeneous and isotropic horizontal visco-elastic multi layered soil column over a half space. According to Tsai (1970), the response at the surface for a horizontally stratified N-layered linear elastic system can be derived as

$$u_1(\text{-}H,\ t) = \frac{2a_{N+1}}{\sqrt{\mathrm{Re}^2_{\ N+1} + \mathrm{Im}^2_{\ N+1}}} e^{\iota(\omega t - \phi_{N+1})} \tag{5.2}$$

where the phase is formulated as

$$\Phi_{N+1}(\omega) = \tan^{-1}\frac{\mathrm{Im}_{N+1}}{\mathrm{Re}_{N+1}} \tag{5.3}$$

and, therefore, the amplification ratio is given by

$$AMP(\omega) = \frac{u_1(-H_1,t)}{|2y(t)|} = \frac{u_1(-H_1,t)}{2a_{N+1}} = \frac{1}{\sqrt{\mathrm{Re}^2_{\ N+1} + \mathrm{Im}^2_{\ N+1}}} \tag{5.4}$$

where, y(t) is the incident wave form and a_{N+1} is the amplitude of the incident wave that generates the response. Following the principle of mathematical induction, the recursive formulae for Re_j and Im_j are given by

$$\mathrm{Re}_j \ = \ \mathrm{Re}_{j-1}\cos\delta_{j-1} - \mathrm{I}m_{j-1}\sin\delta_{j-1} \tag{5.5}$$

$$\mathrm{I}m_j = \alpha_{j-1}\left(\mathrm{Re}_{j-1}\sin\delta_{j-1} + \mathrm{I}m_{j-1}\cos\delta_{j-1}\right) \tag{5.6}$$

and with the condition that $\mathrm{Re}_1 = 1$, $\mathrm{Im}_1 = 0$ at the initial layer

Both δ_j and α_j are real and hence Re_j and Im_j are also real, only if the layers are non-viscous. However, Re_j and Im_j will be complex for visco-elastic systems. The approach adopted by Herak (2008) for the modeling employs modified version of the recursive algorithm developed by Tsai (1970) to take care of the frequency dependent attenuation and body wave dispersion. The transfer functions or amplification spectra (*AMP*) for S-waves and P-waves are as follows

$$AMP_S(f) = \frac{d_{Ss}(f)}{d_{S_b}(f)}, \qquad AMP_P(f) = \frac{d_{P_S}(f)}{d_{P_b}(f)} \tag{5.7}$$

where, d(*f*) is the amplitude of the steady-state body wave at frequency *f*, the first index denote the wave type (P or S), while the second index denote the level where the amplitude is measured (s - surface, b – bedrock, the top of the half-space). Considering that the horizontal and vertical motions are almost equal at the bedrock level, the HVSR is given by

$$HVSR\ (f) = \frac{d_{Ss}(f)}{d_{Ps}(f)} = \frac{AMP_S(f)}{AMP_P(f)} \tag{5.8}$$

Inversion of horizontal to vertical spectral ratio (INV_HVSR) module in ModelHVSR code is a Matlab based tool that inverts the observed HVSR to find the soil models as described in Herak (2008). The inversion algorithm is achieved by a combination of simple and guided Monte Carlo search in the model space, where the misfit function m defined below is minimized

$$m = \sum_i \left\{ \left[HVSR_{OBS}(f_i) - HVSR_{THE}(f_i) \right] W_i \right\}^2 \tag{5.9}$$

where, *OBS* and *THE* stand for the observed and the theoretical HVSR and W_i are the weights defined as

$$w_i = \left[HVSR_{OBS}(f_i) \right]^E \qquad E \geq 0 \tag{5.10}$$

For E ≥0, larger weights are assigned to the data around the frequencies where the observed HVSR is large.

The model space consists of six parameters for each layer (excluding the half-space). Since there are only three independent parameters in each layer for each wave type (P and S), and the density is common in both the cases, the number of independent parameters get reduced to five parameters. In practice, the thickness for each stratum is kept fixed as it is generally measured in the field very easily other than velocities or densities, which are then constrained during the inversion process. Also, scope has been provided by the user to choose any number of additional parameters to be kept fixed (*e.g.* P-wave velocity or density in some layers in case they are sufficiently well defined from geotechnical explorations), which inherently helps to reduce uncertainties and the bias of inverted values. The Monte Carlo search initiated with a starting model whose parameters are then randomly perturbed within the bounds defined by the user. The random numbers are chosen either from uniform or normal distributions, whose parameters are set by the user. The user also sets the desired number of random trials, the smallest and the largest allowed values, and the minimal and maximal ratios of V_p/V_s and Q_p/Q_s within the layers. The search may be of simple or guided. In the simple search all perturbations are done around the initial parameter values, within the prescribed bounds. In the guided search, the perturbations are done around the best set of parameters found so far. The guided search converges more quickly, but there is always a possibility that it will miss the global minimum and end up in a local one. Therefore, there is also an option to choose what proportion of perturbations will be given around the best solution so far, with the rest of them being centered on the initial model parameters. The amplification spectrum of S-waves is significant in seismic hazard studies or microzonation studies because S-waves cause severe shaking and they also describe seismic forces at the position. It is obvious that $HVSR(\mathrm{f}) \approx AMP_S(f)$ if $AMP_P(f) \approx 1$ for all frequencies, but this is valid when P-waves propagate through the topmost layers much faster than the S-waves in which case they have much higher resonant frequencies than those of S-waves (Nakamura, 1989). Thus the empirical HVSR soil amplification estimation leads to overall underestimation of S-wave amplification, due to higher mode resonance being masked in $HVSR(f)$ by vertical response, and by non-negligible vertical amplification at lower frequencies (Diagourtas *et al.,* 2001).

The intrinsic attenuations Q_s and Q_p used in the present analysis for inversion can be estimated using the relation given by Brocher (2008)

$$Q_s = 13 \quad \text{for } V_s < 0.3 \text{ km/sec} \tag{5.11}$$

$$= -16 + 104.13 V_s - 25.255 V_s^2 + 8.218 V_s^3, \quad \text{otherwise}$$

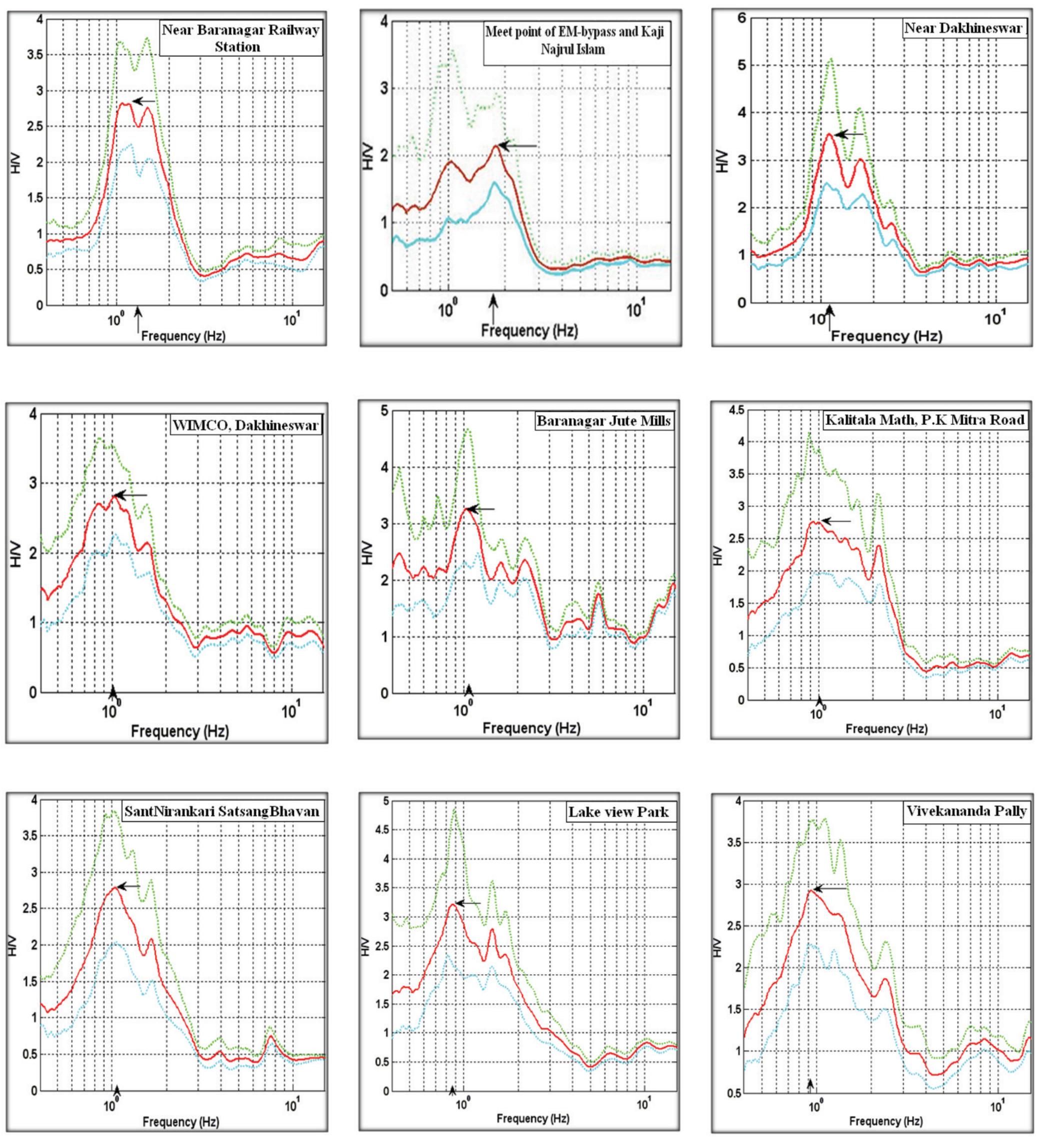
and

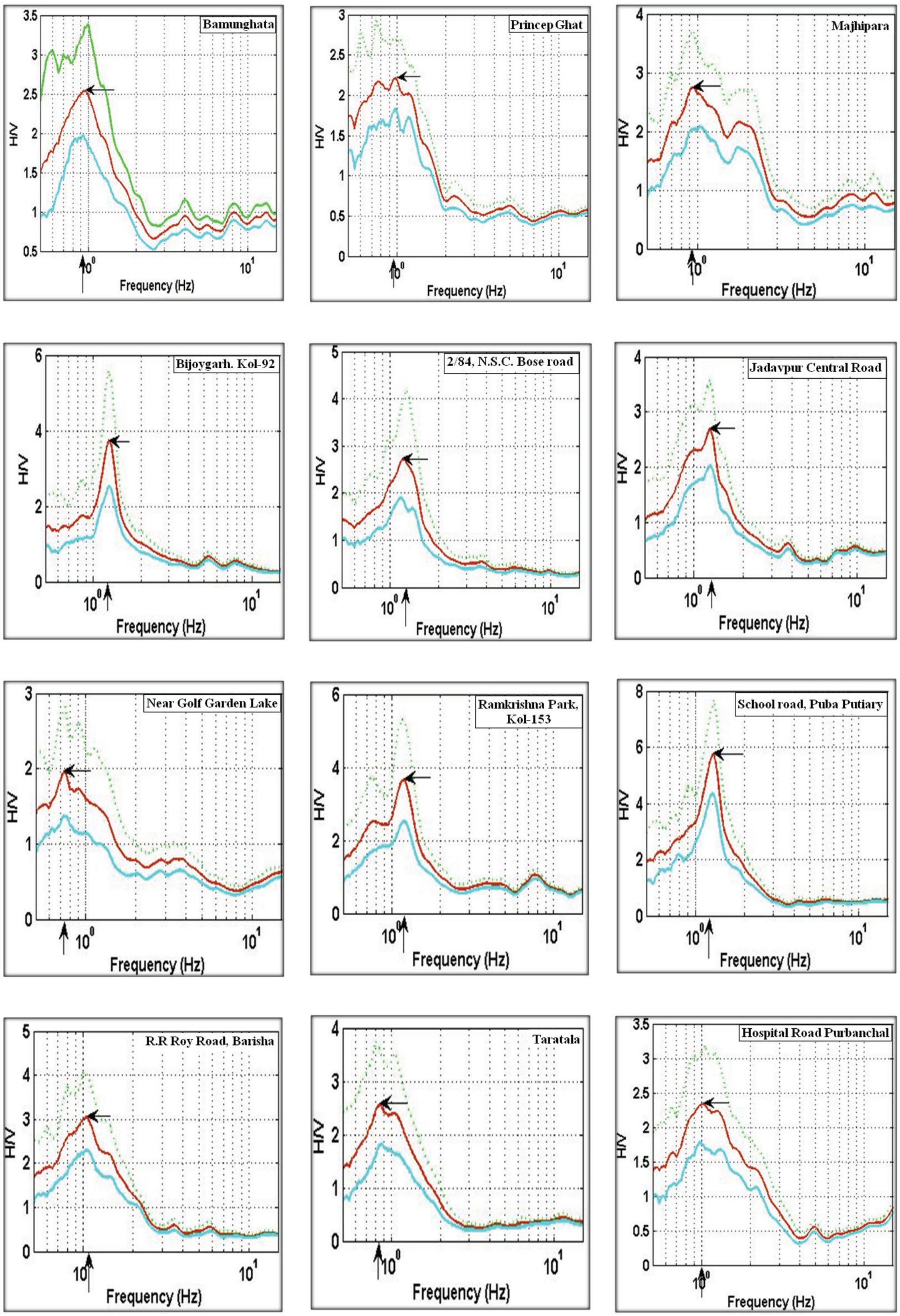
$$Q_p = 2Q_s \tag{5.12}$$

Initially 10,000 perturbations are applied to the initial model with model parameters being drawn from the uniform distribution centered at the particular model parameter for every layer. Also at the beginning 25% of window width is applied to every model parameter with simple to guided search ratio of 1/3. The best fit model is retained and is used as an initial model for the next successive iteration with 2-5% of increased window width, where parameters are drawn from normal distribution with 100% guided search. In the third iteration window width is increased beyond 30% (even up-to 100% for badly constrained data). When perturbations are over, the best model and the starting model will be displayed in a diagram which is finally accepted as the estimated 1-D shear wave velocity structure at a particular site. The good agreement between the experimental HVSR curve and the HVSR curve obtained from the final model of the soil validates that the final model represents the best geophysical structure of the subsurface profile. The ModelHVSR code is based on the theoretical assumptions regarding the body wave composition of the noise, horizontal layering, vertical incidence and hence the obtained results should be critically evaluated for further analysis purpose.

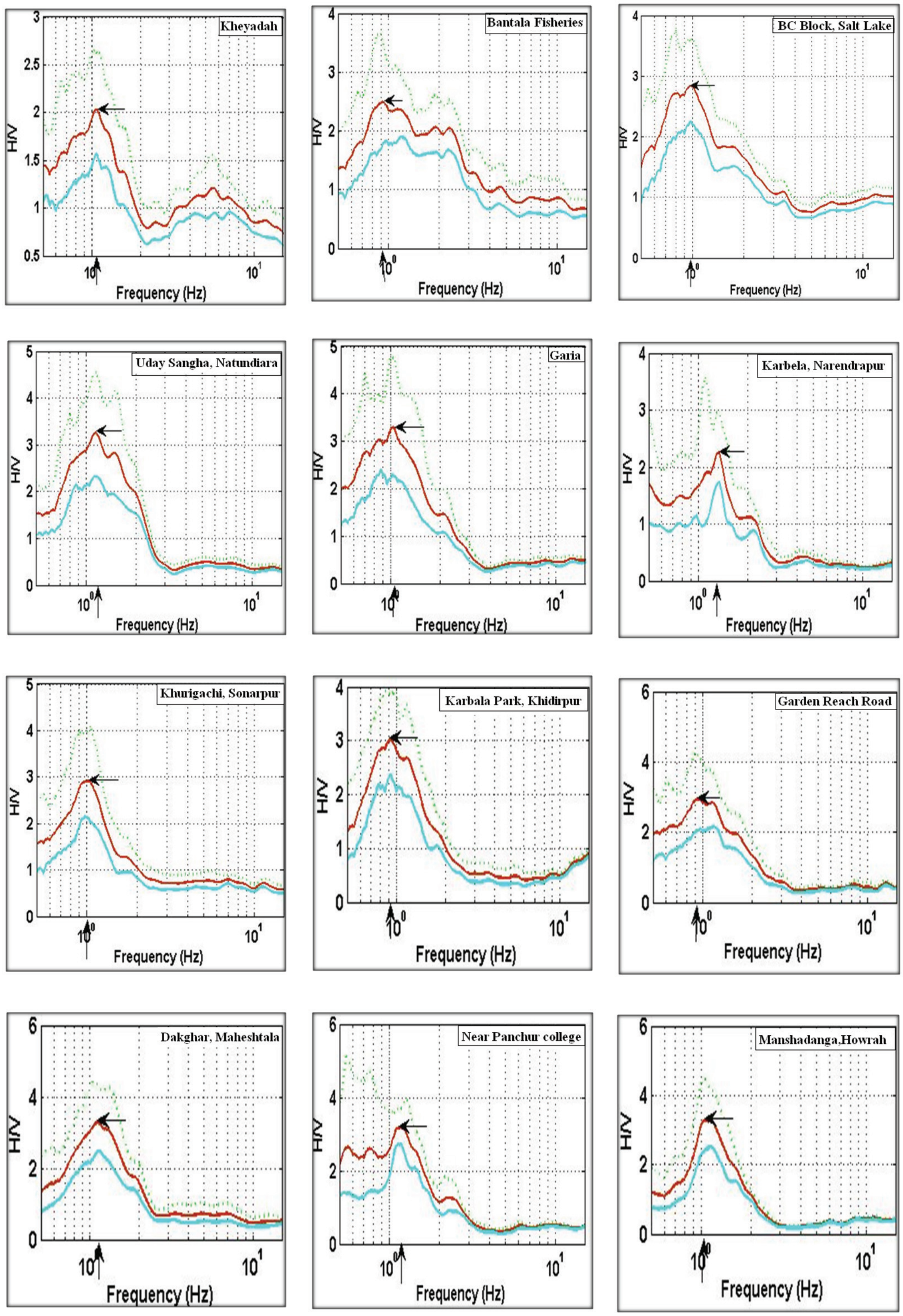
5.2.3 HVSR Results and Interpretation

The H/V response curves obtained from the microtremor survey reflects the geology and soil properties of the test location. Ambient noise measurements have been conducted in the Kolkata city covering an area of ~435 km^2 (approximately) that included 1200 sites with spacing interval of 500 m. The records have been processed using VIEW2002 and GEOPSY software (www.geopsy.org). GEOPSY was developed as integrated tools for processing of ambient vibrations with the following processing steps: (a) baseline correction, (b) 5% cosine tapering, (c) Fast Fourier TTransform (FFT) for the three components, (d) smoothing the FFT spectra using the Konno and Ohmachi (1998) algorithm. Horizontal-to-vertical spectral ratios (HVSR) have been computed as the ratio of geometrical average of horizontal and vertical Fourier amplitude spectra and smoothened by Konno–Ohmachi window (Konno and Ohmachi, 1998) with a 'b'-parameter equal to 40. The spectra are finally stacked to obtain the representative HVSR for each measurement point. The analyzed data shows three types of HVSR curves *i.e.* curves with clear, broad and low amplitude HVSR peaks as depicted in Figure 5.3. According to Bonnefoy-Claudet *et al.* (2009), the shape of HVSR curve is related to the impedance contrast where a sharp peak indicates high impedance contrast between the overlying soft sediments and the underlying bedrock.





Bamunghata
Princep Ghat
Majhipara
Bijoygarh. Kol-92
2/84, N.S.C. Bose road
Jadavpur Central Road
Near Golf Garden Lake
Ramkrishna Park, Kol-153
School road, Puba Putiary
R.R Roy Road, Barisha
Taratala
Hospital Road Purbanchal
H/V
Frequency (Hz)


Kheyadah
Bantala Fisheries
BC Block, Salt Lake
Uday Sangha, Natundiara
Garia
Karbela, Narendrapur
Khurigachi, Sonarpur
Karbala Park, Khidirpur
Garden Reach Road
Dakghar, Maheshtala
Near Panchur college
Manshadanga,Howrah
H/V
Frequency (Hz)

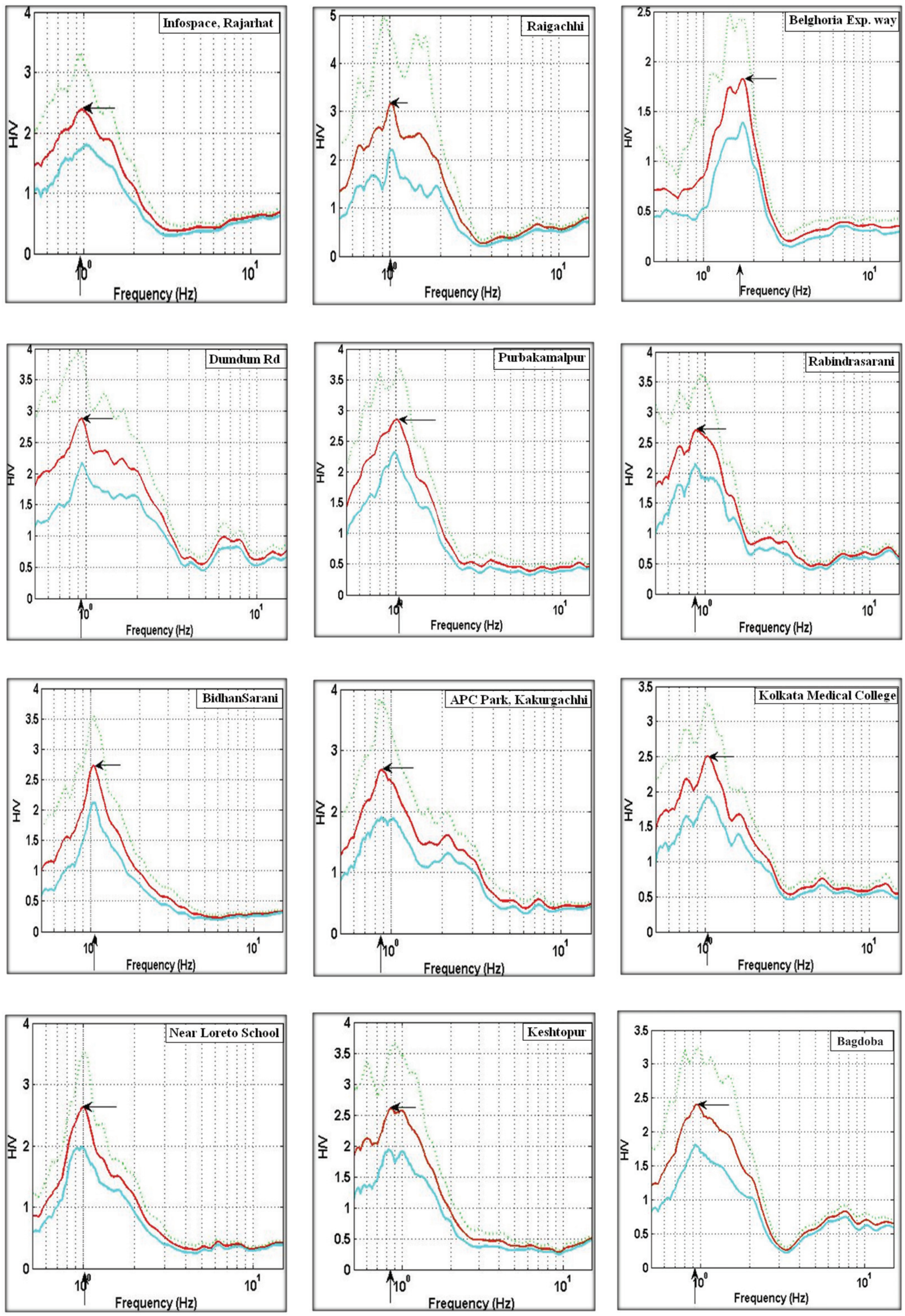


Figure 5.3 **H/V curves obtained from Nakamura technique at various sites in Kolkata.**

The Predominant Frequency distribution map obtained by HVSR analysis is prepared on GIS platform as shown in Figure 5.4 exhibiting a variation between 0.67 Hz to 3.64 Hz. Most sites display clear resonant peaks, with variable HVSR amplitudes, while only few of them feature flat response spectra. The predominant frequency exhibits lower value in parts of Rajarhat, Saltlake, Dum Dum, Beliaghata, Dhapa, Mukundapur, Garia regions of Kolkata whereas low frequency patches are also observed in Belgachia and Liluah in Howrah district which are considered to be more prone to hazard during the occurrence of seismic shaking. Figure 5.4 also reveals that higher predominant frequency is observed in regions of Baguiati, Shyambazar, Park Circus, Maidan, Maniktala *etc*. The proximity of Predominant Frequency of the soil column and the natural frequency of life line facilities indicates higher vulnerability of the built-up environment owing to resonance effects (Navarro and Oliveira, 2006). Usually care is taken that the natural period of vibration of any structure should not coincide with the predominant period of earthquake excitations in order to avoid resonance that may occur, causing damage to even strongest structures which may eventually collapse (BIS, 2002).

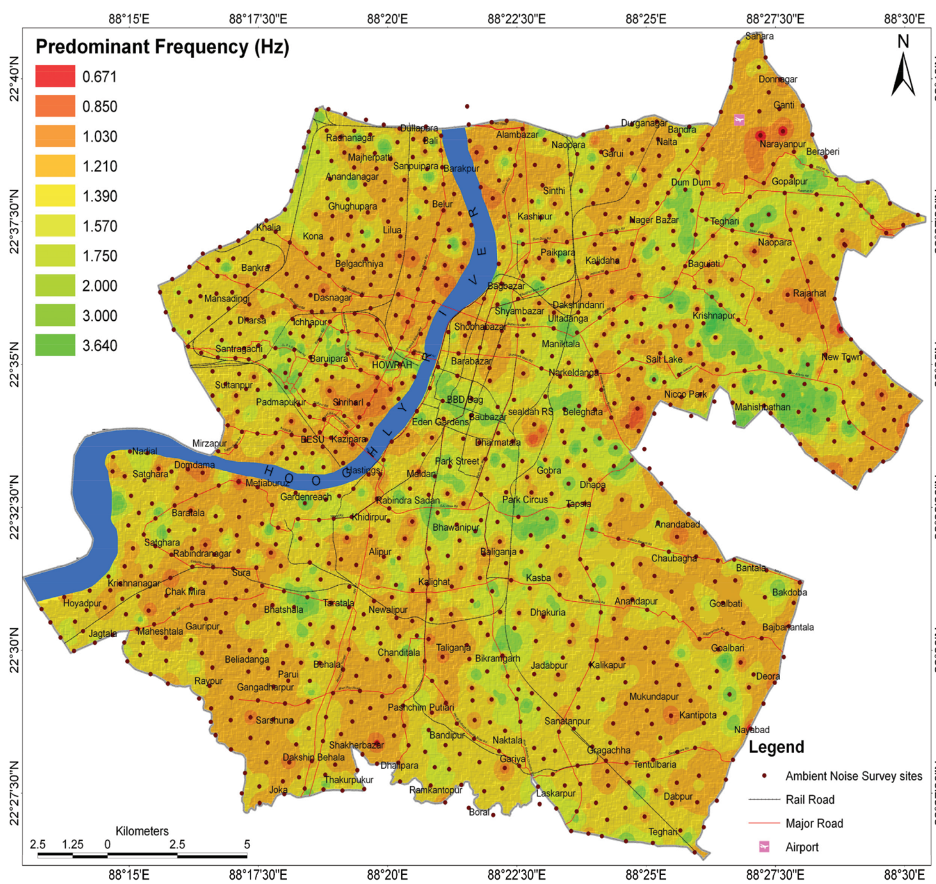


Figure 5.4 **Spatial distribution of Predominant Frequency in Kolkata as obtained from Ambient Noise Survey at 1200 locations in Kolkata and on processing those by Nakamura Ratio.**

In the present study, the statistical error associated with predominant frequency has also been estimated. The error has been calculated during the H/V analysis of Microtremor data as depicted in Figure 5.3 (*i.e.* green and cyan line indicates the ±standard deviation). Thereafter, the error map has been prepared that exhibits the spatial distribution of statistical error in terms of ±standard deviation associated with Predominant Frequency in Kolkata as shown in Figure 5.5.

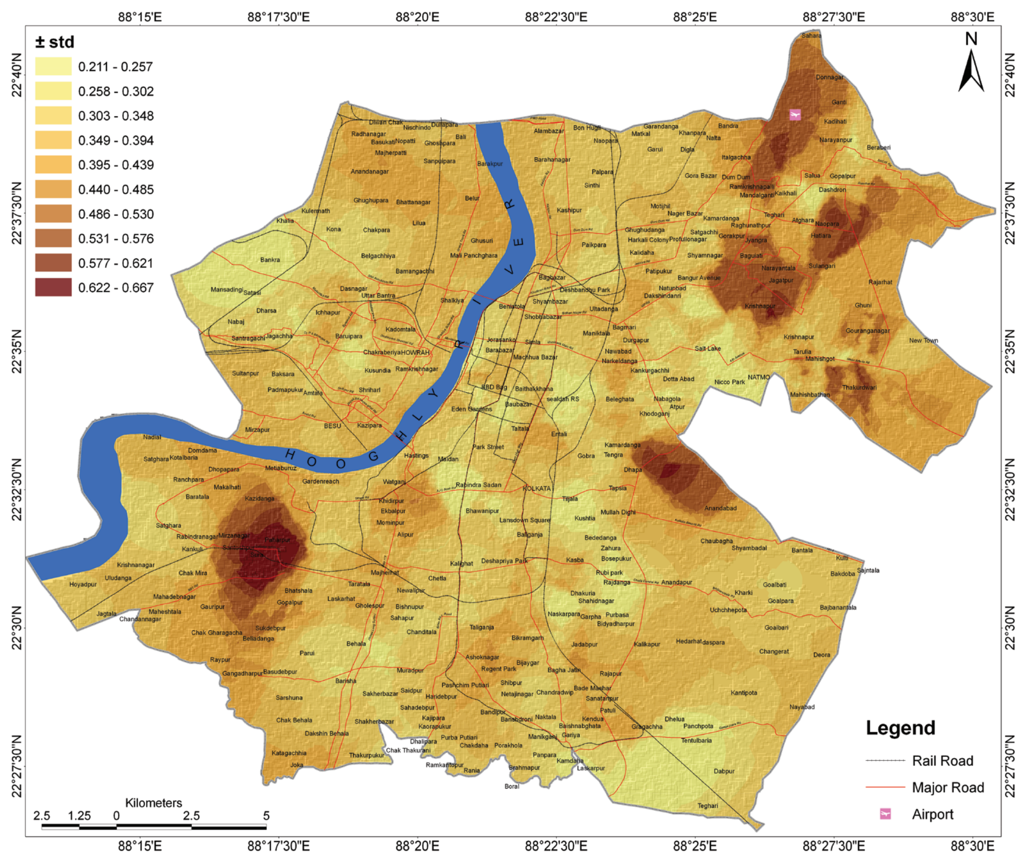


Figure 5.5 **The standard deviation (±σ) associated with predominant frequency.**

From selective HVSR measurements theoretical HVSR has been obtained for a given soil model and compared with the observed ones to derive V_s model from ambient noise using ModelHVSR Matlab code (Herak, 2008). The idea is to finally compare the soil models derived from the geotechnical standard penetration test (SPT) and downhole seismic survey with the ones generated from the ModelHVSR Matlab tool. The soil model consists of n-number of visco-elastic layers stacked over a half space each of which is defined by thickness (h), propagation velocity of the body waves (V_p or V_s), density (ρ) and the frequency dependant Q-factor which controls the inelastic properties (Aki and Richards, 2002). The Monte Carlo search is initiated with a model whose parameters are randomly perturbed within the bounds defined by the user. The program computes theoretical S-wave amplification and P-wave amplification spectra of a layered visco-elastic model for vertically incident S-wave and P-wave respectively (Figure 5.6).

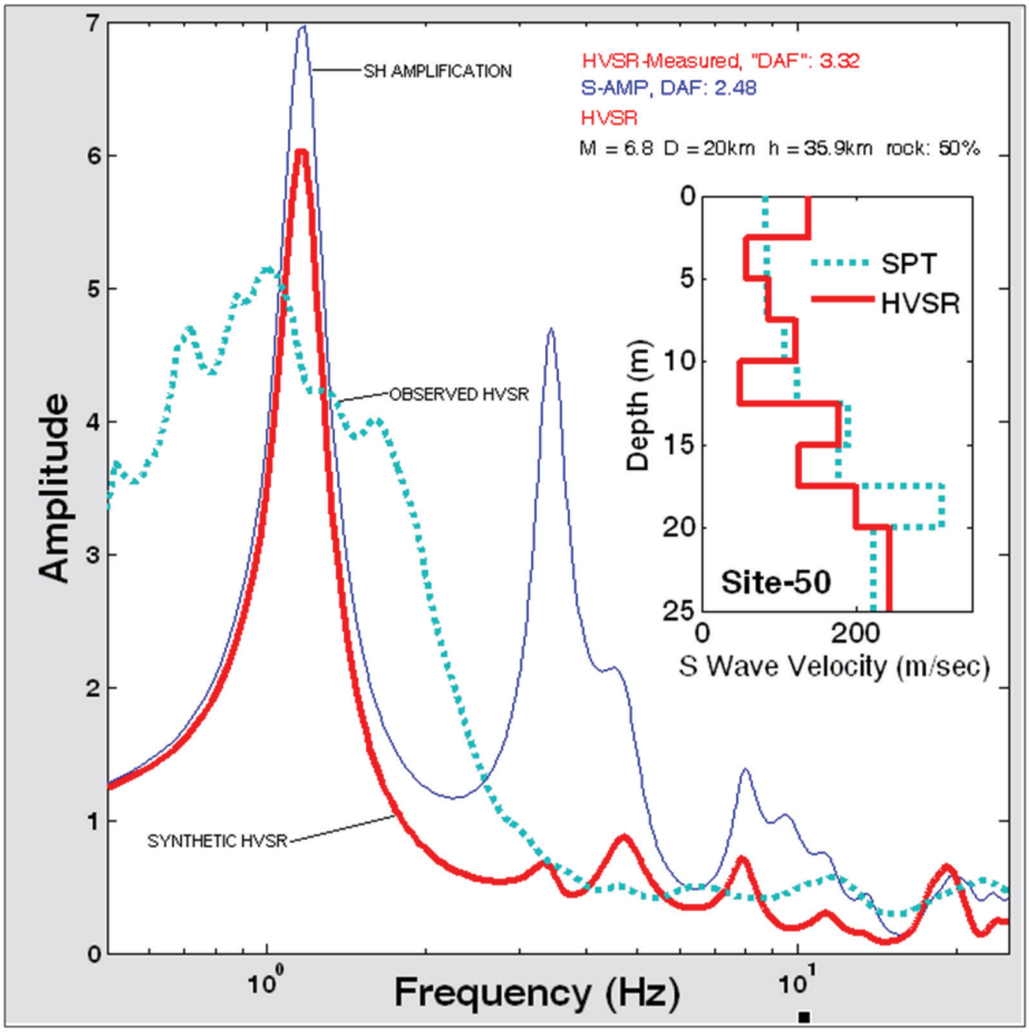


Figure 5.6 **Modeling of HVSR: Observed HVSR (cyan dotted line), Theoretical (synthetic) HVSR (red solid line). The theoretical spectra are for the final model which provides a best fit with the observed HVSR.**

The initial soil model has been obtained from SPT while the theoretical V_s model has been derived from ModelHVSR as shown in Figure 5.7. The values obtained from HVSR modeling of the microtremor inversion are almost 10% less than the values obtained by SPT; however, the difference is not too large to have a significant influence on the determination of ground type in seismic microzonation.

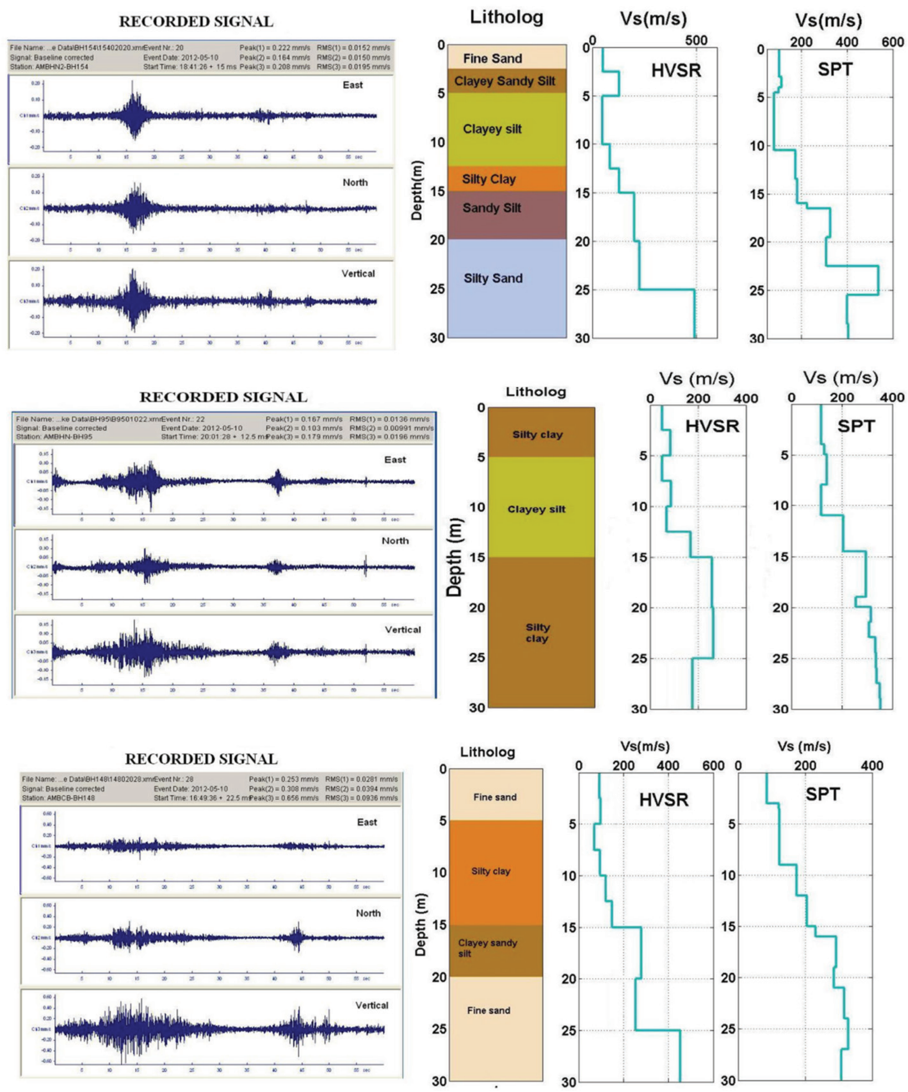


Figure 5.7 **Recording signal of microtremor, lithology, SPT based shear wave velocity and HVSR inverted shear wave velocity with depth at three representative sites in Kolkata.**

5.3 Multi-channel Analysis of Surface Wave (MASW)

A number of geophysical methods have been proposed for near-surface characterization and measurement of shear wave velocity by using a great variety of testing configurations, processing techniques, and inversion algorithms. The most widely used techniques are Spectral Analysis of Surface Waves (SASW) and Multi-channel Analysis of Surface Waves (MASW). Multi-channel analysis of surface wave method is a non-invasive method developed to estimate shear wave velocity profile from surface wave energy. Measurements of phase velocity of Rayleigh waves of different frequencies can be used to determine a velocity depth profile. In the SASW method, the dispersion curve is obtained by using a two-receiver test configuration. Evaluating and distinguishing signal from noise with only a pair of receivers by SASW method is difficult. Thus to improve the inherent difficulties a new technique of multi-channel analysis of surface waves (MASW) using active sources have been developed which has been found to be a more efficient method for unraveling the shallow subsurface properties. Multi-channel analysis of surface waves overcomes the drawbacks associated with SASW method. Multi-station technique increases the reliability of results and shortens the execution time both in the field and during interpretation for surface wave tests. In the recent years, MASW method is widely used by the researchers all over the world since the method is powerful, rapid and cost effective because the entire range of investigation is performed by the generation of ground roll without changing receiver configuration for constraining shallow wave velocity structures. The advantage of this technique over drilling boreholes, cone penetration or any other geophysical technique is that it is less intensive, non-invasive, more cost effective, and more robust. In addition, data processing and analysis is fairly straightforward, and the MASW method allows for analysis of a large area of interest as compared to drilling boreholes.

The MASW technique was introduced in the late 1990's by the Kansas Geological Survey (Park *et al.,* 1999). It extracts the fundamental mode dispersion curve from the shot record which is inverted to obtain the shear wave velocity model. Multi-channel data displays in a time variable frequency format also allows the identification and elimination of non-fundamental mode Rayleigh waves and other coherent noise during the analysis process. The method has improved in the field due to the utilization of multiple transducers, and enhanced relation of dispersive characteristic by sampling spatial wave field with multiple receivers. The entire process involves three major steps *viz.* acquisition of data, construction of dispersion curves (phase velocity versus frequency) and inversion process to compute the velocity model. This method provides reliable estimation of S-wave velocity profiles within upper 30 m below the ground surface. The method can also be used for solving various geophysical problems like seismic characterization of pavements (Park *et al.,* 2001; Ryden *et al.,* 2001), to study Poisson's ratio (Ivanov *et al.*, 2000), seismic investigation of sea bottom sediments (Park *et al.,* 2000; Ivanov *et al.,* 2000), mapping bedrock surface (Miller *et al.,* 1999), detecting dissolution features (Miller *et al.*, 1999) and most importantly to generate shear wave velocity profiles (Xia *et al*., 1999).

One of the unique features of surface waves is that they are dispersive, that is, the phase velocity of surface waves in a vertically heterogeneous medium is dependent on frequency. This is the key issue in the surface waves allowing them to be used to determine the variation of material properties with depth. Extraction of accurate dispersion curve is a critical step in MASW method, because, error in dispersion curve would cause inversion to produce inaccurate V_s value. The dispersion curve is achieved by converting the data from the time-space domain to frequency-phase velocity domain by using a suitable mathematical transformation process like the pi-omega transform (McMechan and Yedlin, 1981) or the phase shift method (Park *et al.,* 1998). The final step of MASW data processing involves inverting the surface wave dispersion data in order to obtain a 1-D shear wave velocity profile. The inversion process involves back calculating shear wave velocity variation with depth that yields the best fit between the theoretical and the measured dispersion curves (*e.g.* Xia *et al.,* 2003). The method is useful for geotechnical engineers/seismologists who need a quick site characterization or a reliable velocity structure, which is used in earthquake ground motion synthesis.

5.3.1 MASW Data Acquisition

In this study a 48 channel engineering seismograph McSEIS-SX 48 from OYO Corporation, Japan is used for the MASW survey. The instrument is preferred for its portable nature, light weight and low power consumption and ease in transportation. Tests have been performed in Kolkata at 85 profiles by spreading multiple geophones. A 2-D V_s profile is constructed from the acquisition of multichannel seismic data along each profile. 2 meters to 1.5 meters of survey spacing between the geophones and the sources have been used at different locations depending on the availability of free space for each profile. Geophones with 4.5 Hz specification are used in the MASW survey which is connected to a geophone cable that is finally connected to the seismograph either directly or through a multiplexer switch. A vibrator hammer PEG 40 of 40 kg weight is used as a source for inducing energy into the ground. A rectangular metal plate is used as the strike plate to maximize energy transfer between the hammer and the ground. A fixed receiver configuration is used and the source is placed between two receivers and at both the ends of the survey profile. The source

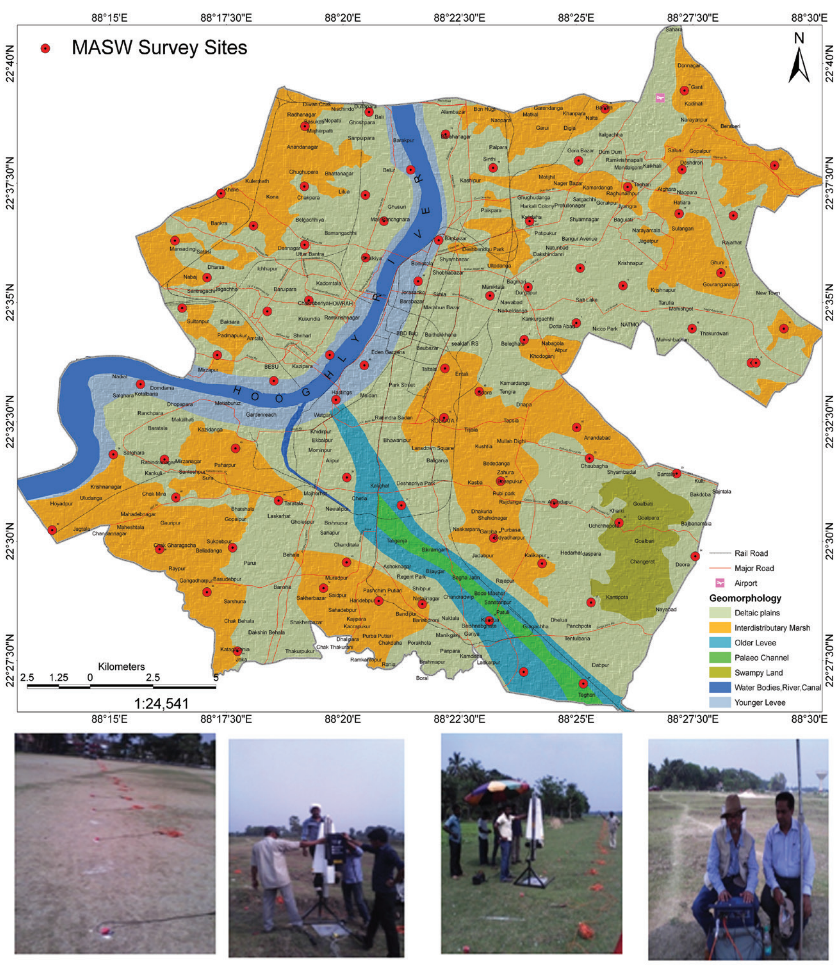


Figure 5.8 **MASW test sites in Kolkata and the field setup of one such survey.**

is shifted every time by 2 m interval and a total of 49 shots are fired at each test location. For each measurement, several shots are stacked for the enhancement of signal to noise ratio. Also, a trigger geophone is used at each shot point to synchronize the shooting with the commencement of recording. The Rayleigh wave data generated due to each shot is digitally recorded and stored in SEG-2 format. The acquired data are transferred from the seismograph to a laptop for advanced processing and analysis using SeisImager/SW software. 2-D subsurface shear wave velocity models are generated along each MASW profile. Figure 5.8 depicts the spatial distribution of survey sites and the field set up of a MASW survey.

5.3.2 Analysis of MASW Data: Processing and Interpretation

The acquired surface wave data in SEG-2 format for each MASW profile has been processed using SeisImager/SW software wherein spectral inversion is performed to obtain both 1-D and 2-D subsurface shear wave velocity profiles. The data processing and interpretation have been carried out as shown in the flowchart of Figure 5.9. The SeisImager/SW software has three modules *viz*. PickWin95, WaveEq and GeoPlot.

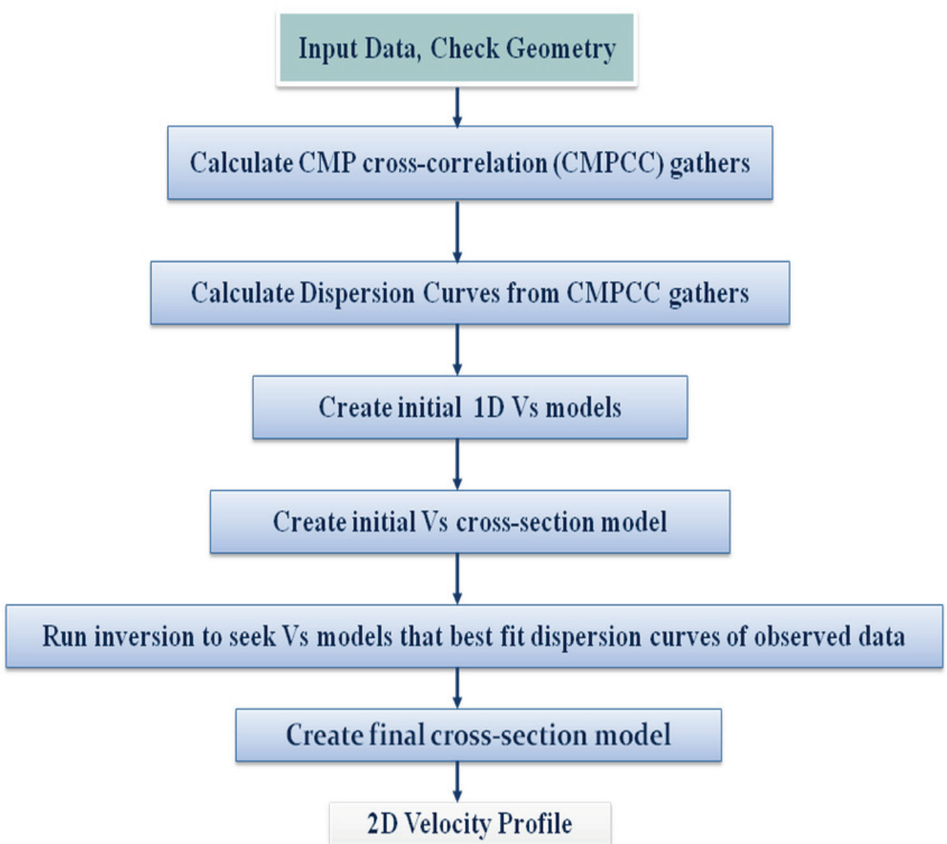


Figure 5.9 **Flowchart for 2-D Imaging and processing of MASW data.**

The initial step is to group (stack) the file list in which all the waveform files are given as input alongwith the detailed information about the source receiver geometry. The next step is to generate cross correlation CMP gathers (Oppenheim *et al.,* 1996) where data from all traces are extracted as per common midpoints (CMPs). The Cross correlation CMP gather (CMPCC) files are then saved as pseudo shot gather files for each CMP. Figure 5.10 depicts the Geometry and CMPCC of one representative MASW profile.

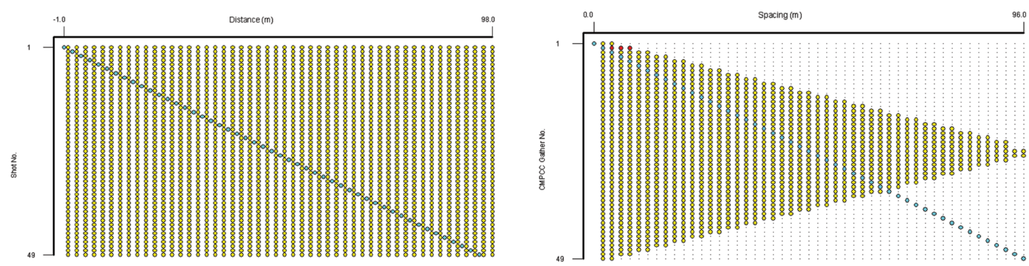


Figure 5.10 **Representative Geometry and CMPCC of one recorded MASW profile data.**

Subsequently the phase velocity is estimated for each cross-correlation CMP gather and a dispersion curve is generated. The dispersion curves are nothing but are presentation of phase velocities versus frequency. A multi-channel coherency measure can be applied to a ground roll seismogram with the isolation potential of each frequency component (Yilmaz, 1987). Park *et al.* (1998) proposed frequency-domain approach for the calculation of dispersion curve. The phase velocity-frequency wave field transformation is applied to the CMPCC gathers and the dispersion image (overtone) thus deduced from the surface wave data at one location is depicted in Figure 5.11. The dispersion curves generated at different sites of Kolkata are shown in Figure 5.12.

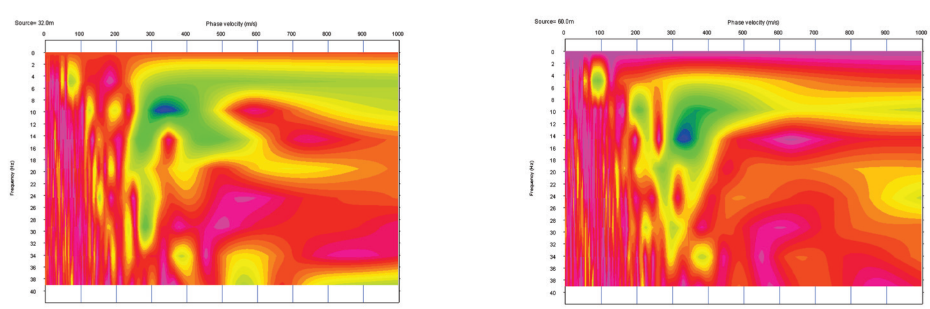


Figure 5.11 **Phase velocity depicting overtone image for frequencies at different site of Kolkata.**

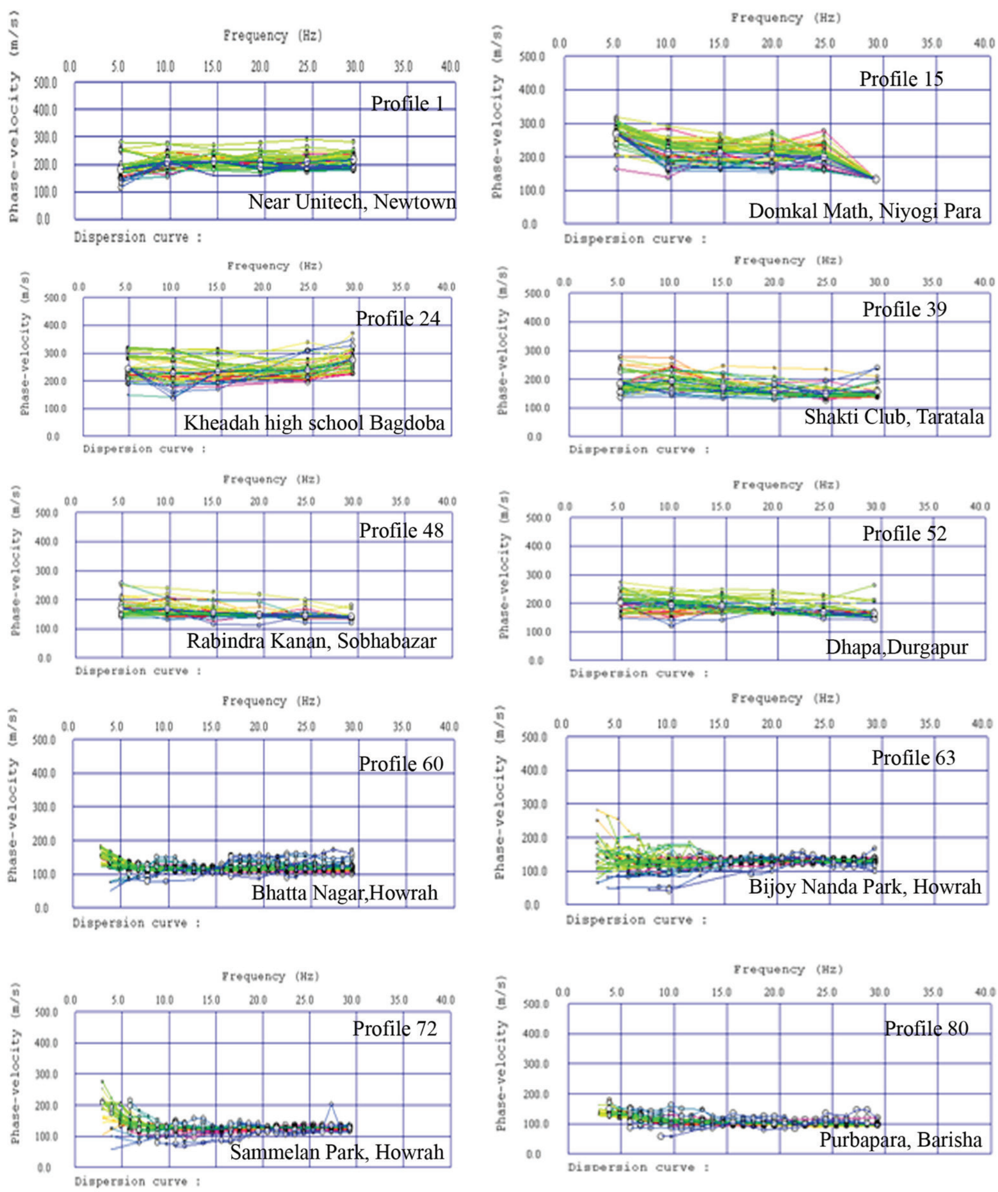
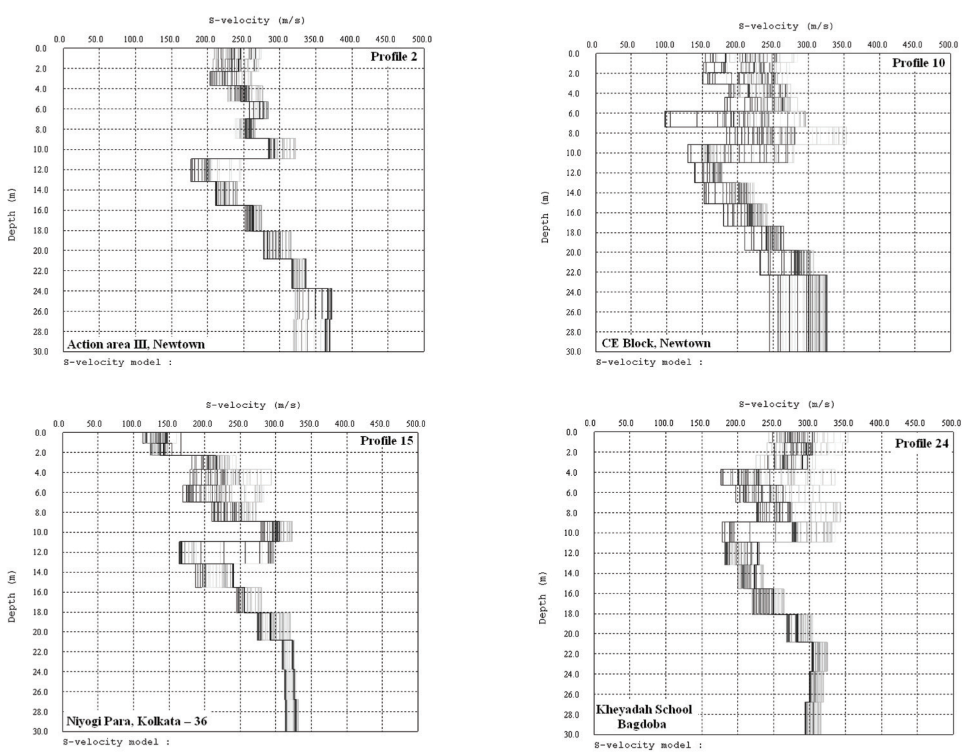


Figure 5.12 **Dispersion curves (phase frequency vs phase velocity) at representative sites in the city of Kolkata.**

The V_s profiles are estimated using an iterative inversion process that requires the dispersion data and the estimation of Poisson's ratio and density. For the method used here, only V_s is updated after each iteration process with Poisson's ratio, density and the model thickness remaining unchanged. An initial earth model needs to be specified as a starting point for the iterative inversion process. The earth model consists of velocity (P-wave and S-wave velocity), density, and thickness parameters. Among these four parameters, V_s has the significant effect on the reliable convergence of result with minimal error value. Several methods are proposed to ensure reliable and accurate convergence after estimating initial V_s profile (Heukelom and Foster, 1960; Vardoulakis and Vrettos, 1988). One inversion scheme formulated by Xia *et al.* (1999) ensures that the procedure converges to a reliable result even for a wide range of initial models. Thus 1-D subsurface shear wave velocity profiles are generated for each MASW profile through a nonlinear inversion of the dispersion curves using “WaveEq” module of the SeisImager/SW. Care is taken to remove the noise and higher mode dispersions in order to enhance the accuracy of data processing. The inversion algorithm matches the theoretical dispersion curve with the experimental dispersion curve obtained by dispersion analysis. The root mean square error (RMSE) generated during iterative inversion process is the display of match between the measured and the theoretical curves for each dispersion arc. Initially the theoretical curve is calculated using the initial V_s profile which is then compared with the experimental curve. The RMSE value if found greater than the minimum RMSE (E_{min}) specified in the control parameter, the algorithm will automatically modify the V_s profile and the iteration process is repeated to generate new theoretical curves. The iteration continues until the E_{min} value or the maximum number of iteration (I_{max}) is reached and finally the 1-D V_s profile is generated. The 1-D shear wave velocity model, obtained from MASW is regarded as the best approximation for the soil layer although it is recognized that the inversion from dispersion curve to velocity model is a non-unique problem. 1-D shear wave velocity structures obtained by inversion of extracted dispersion curves at various locations in Kolkata are shown in Figure 5.13.



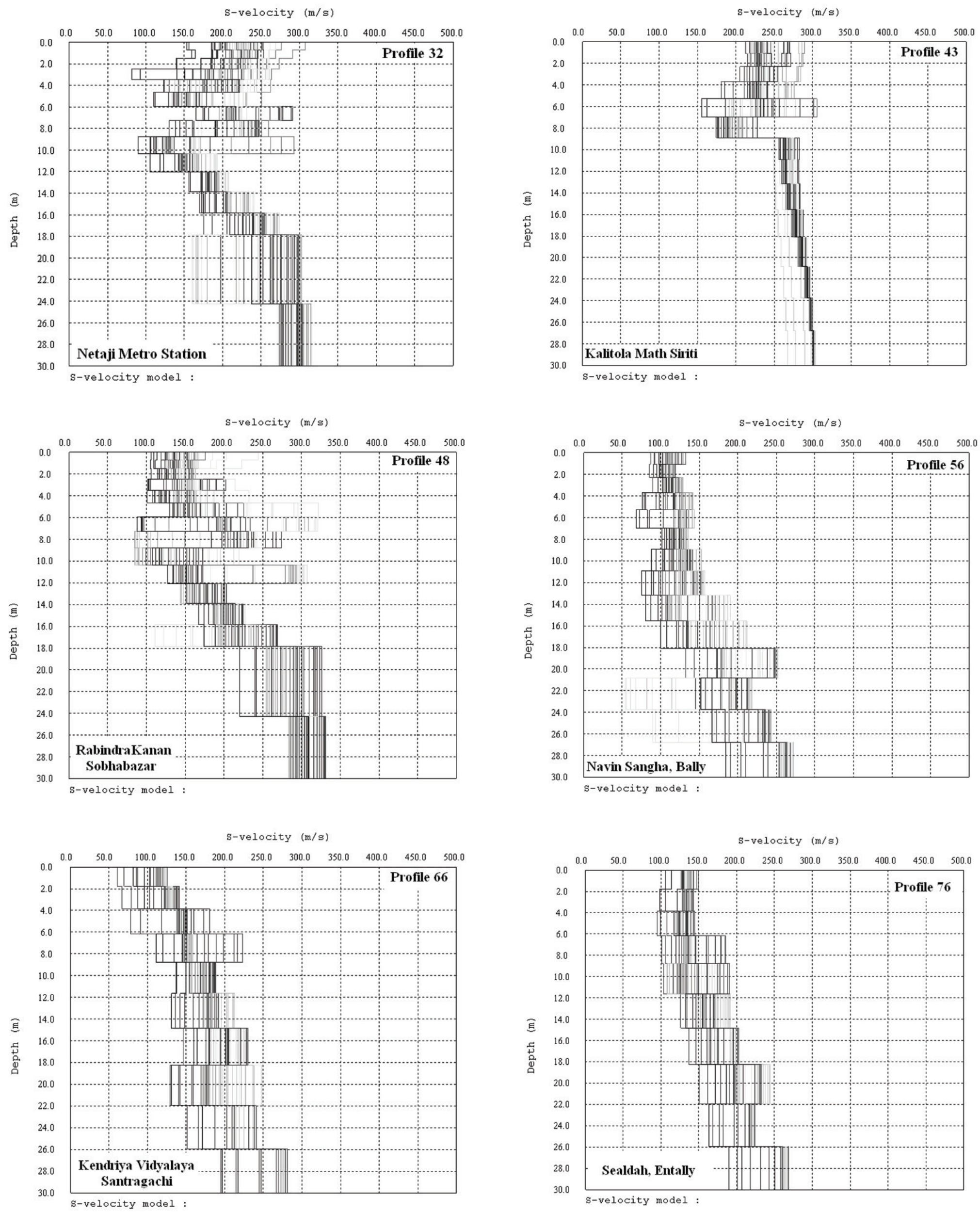
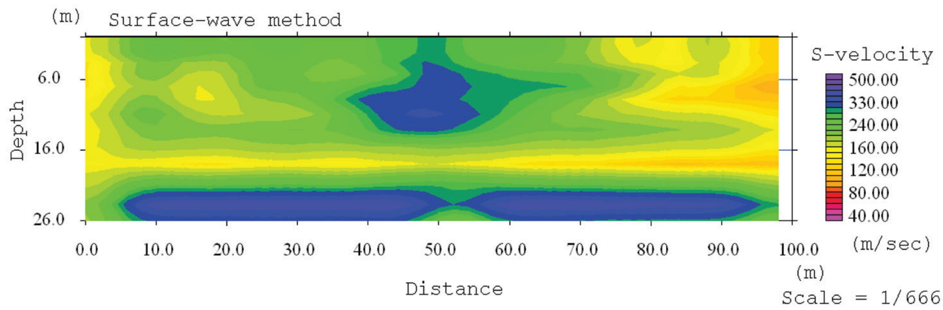


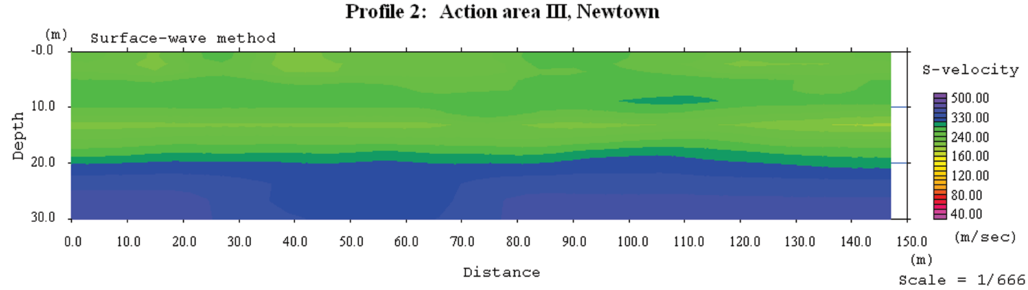
Figure 5.13 **1-D V_s profiles obtained from the inversion of dispersion curves at some representative sites in Kolkata**.

Finally all the 1-D shear wave velocity structures below each of the 49 shots fired along MASW survey profile are combined and interpolated through Kriging in 'Geoplot' module of SeisImager/SW software to generate the 2-D subsurface velocity structure of each MASW survey representing shear wave velocity in both the lateral and depth directions. Figure 5.14 depicts 2-D Shear wave velocity structures for several MASW profiles at various locations in Kolkata.

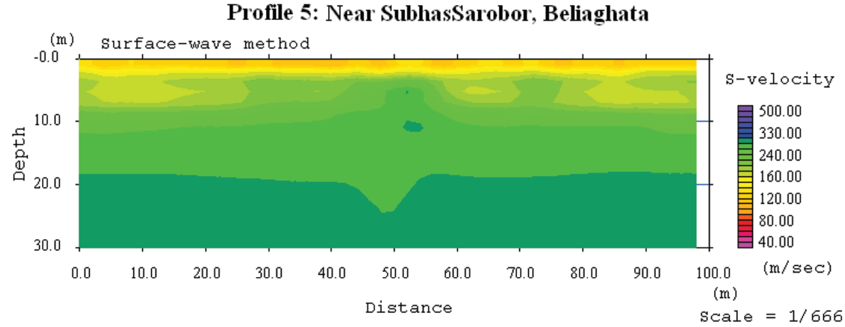
Profile 1 : Near Unitech, Newtown



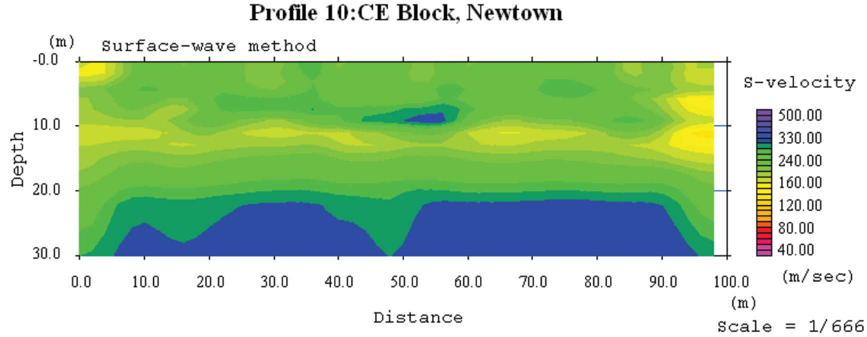
Profile 2: Action area III, Newtown



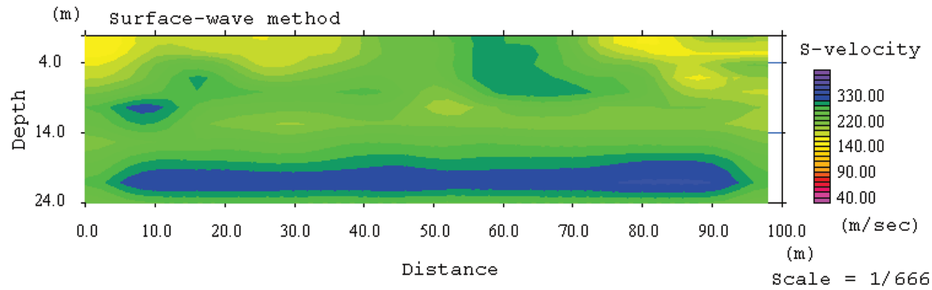
Profile 5: Near SubhasSarobor, Beliaghata



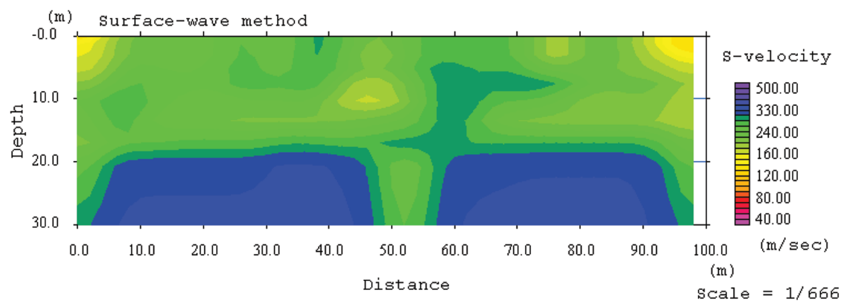
Profile 10:CE Block, Newtown



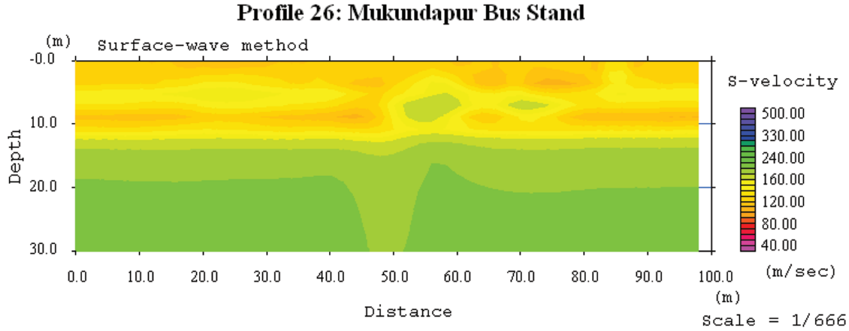
Profile 17: Nibedita Udayan, Bag bazaar



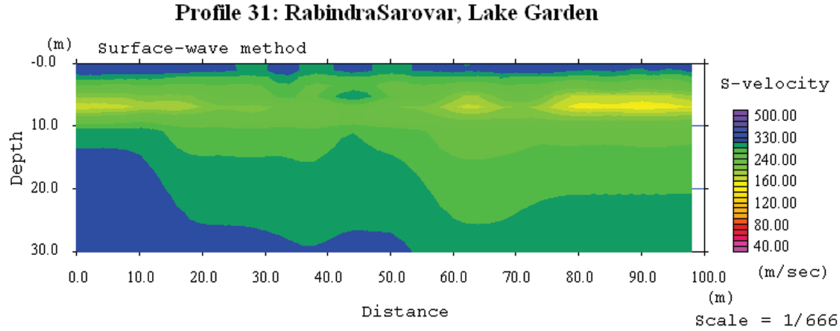
Profile 21: Kalibari Ground, Rajarhat



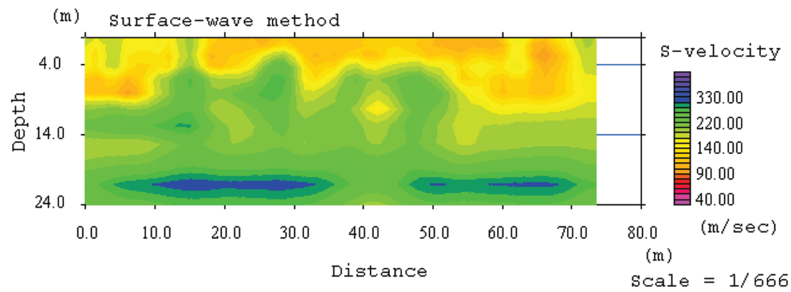
Profile 26: Mukundapur Bus Stand



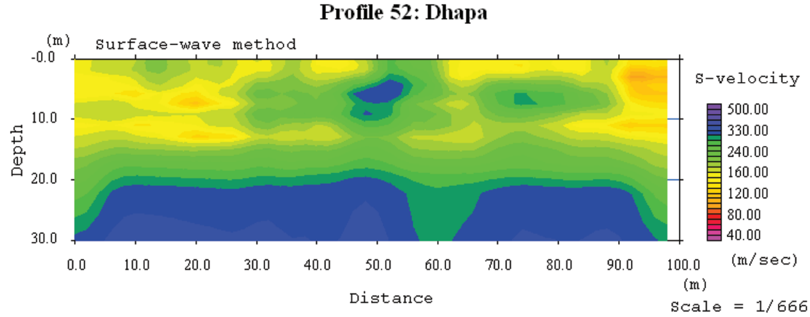
Profile 31: RabindraSarovar, Lake Garden



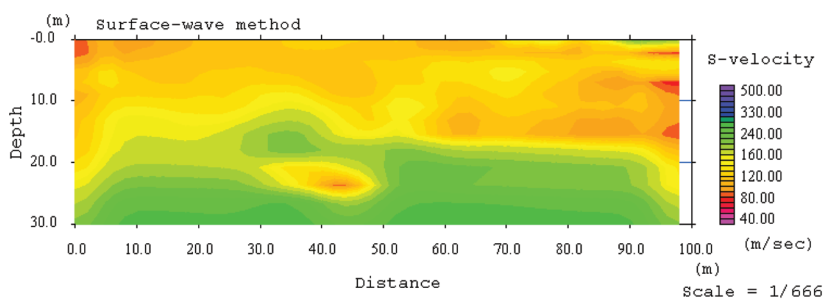
Profile 41: Maheshtala Post Office



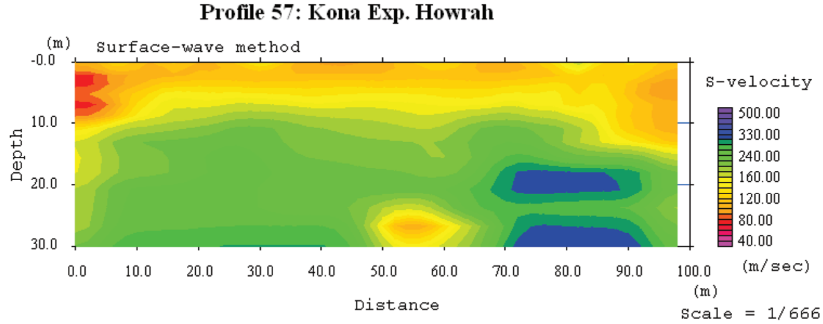
Profile 52: Dhapa



Profile 56: Navin Sangha, Bally



Profile 57: Kona Exp. Howrah



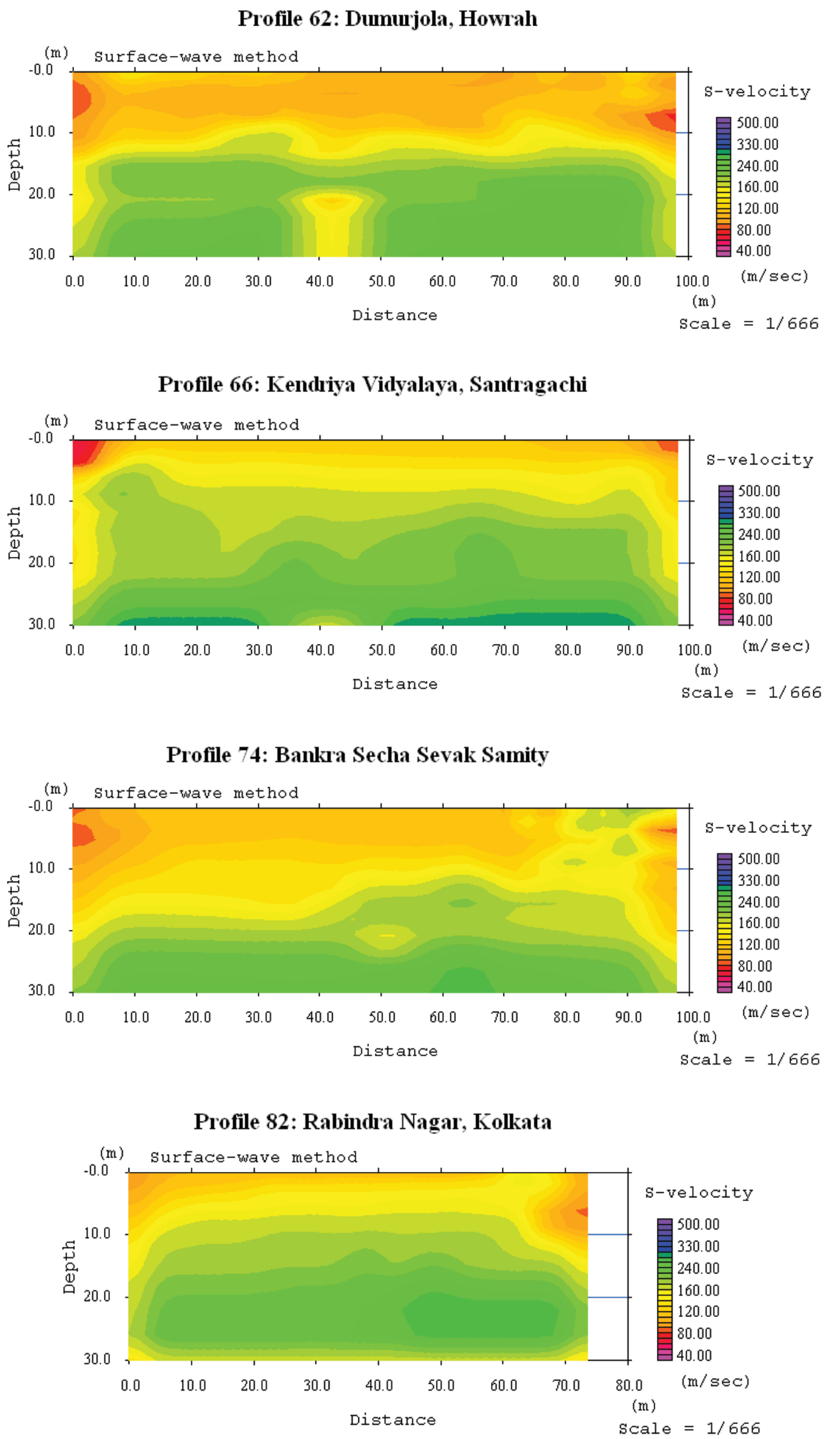


Figure 5.14 **2-D V_s profiles from MASW survey at some representative sites in Kolkata.**

5.4 Concluding Remarks

The Kolkata metropolitan city is located mostly on soft alluvial deposits which is more prone to site amplification. The amplification of ground motion over soft sediments occurs fundamentally due to the trapping of seismic waves and the resulting impedance contrast between sediments and the underlying bedrock where the trapped waves interfere with each other to produce resonance patterns. The significant input for the ground response analysis is the subsurface model that represents the variation of shear wave velocity with the thickness of soil layers which provide fundamental ground information for seismic micorozonation study of an earthquake prone region. Thus, Nakamura technique has been adopted for the microtremor measurements (HVSR) to determine the predominant frequency and also inversion has been performed to achieve the 1-D shear wave velocity structure at each of 1200 sites in Kolkata. MASW survey has also been carried out to derive the lateral and vertical variations in shear wave velocity in Kolkata. The results obtained by extensive and well-planned field survey in Kolkata will eventually facilitate estimation of site period, site classification, soil amplification factor and liquefaction hazard which will finally be used in the effective seismic hazard microzonation of the City.