# Seismic Site Characterization in Delhi Region using Multi channel Analysis of Shear wave Velocity (MASW) Testing

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## ABSTRACT

After the Bhuj earthquake the national capital region of Delhi attracted major attention of several scientific studies in the recent times. Since Delhi falls in zone IV (IS 1893:2002) with high seismic activity, there is a great need for site characterization and seismic hazard mapping of the area. Multi Channel Analysis of Surface Wave (MASW) tests were done in Delhi at 118 sites in predefined grids of 2kmX3km each. Shear-wave velocity, $V_S$, is an important parameter for evaluating dynamic behavior of soil. This test carried outdone using 48 channel digital engineering seismograph with 4.5 Hz geophones. Data was analyzed using SeisImager/SW software and two dimensional shear wave velocity models at every 5m depth from ground surface was developed. Also, the average shear wave velocity up to 30m ($V_{S30}$) is measured which is used for site characterization. Based on the $Vs_{30}$ value, Delhi is divided into three zones i.e., zone A ($V_{S30}$ >350m/s), zone B ($V_{S30}$ = 250-350m/s) and zone C ($V_{S30}$< 250m/s).

KEYWORDS: Shear wave velocity, Multi channel Analysis of Shear Wave, Site Characterization.

## INTRODUCTION

Geophysical tests based on the generation and propagation of seismic waves are widely used in Earthquake Geotechnical Engineering. Seismic in-situ tests are often the only way to determine soil stiffness in undisturbed conditions, especially for coarse soils, in which undisturbed sampling is problematic. The shear modulus can easily be derived if the velocity of propagation of shear waves and the soil density are known. The shear wave disturbances, as they travel through the soil media, map out dilational and rotational strains. Hence, Vs is currently used as one of the important factors in site characterization. Shear wave velocity structure could be ascertained through invasive techniques like down hole, up hole, cross hole and non invasive methods such as Spectral Analysis of Surface Wave (SASW) method and Multichannel Analysis of Surface Wave (MASW) method (Park et al., 1999, Xia et al., 1999), utilizing theoretically proven relation between Rayleigh and Shear wave velocity as

$$V_R = 0.9\ V_S \tag{1}$$

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. But in MASW multi -station recording permits a single survey of a broad depth range and high levels of redundancy with a single field configuration. Multi channel analysis of surface waves overcomes the drawbacks associated with SASW method. Multistation technique increases the reliability of the results and shortens the execution time both in the field and during interpretation for surface wave tests. In the recent years, MASW method attracted researchers all over the world. MASW method is powerful, rapid and cost effective tool for constraining shallow wave velocity structures. This tests were done in Delhi at 118 locations by spreading multiple geophones for estimating 2D velocity profiles.

In this survey spacing between the geophones and source increment had been made equal to 6 meters. The McSeis-SX 48 digital seismograph of 48 channels for the first time in the country is used in this study. Frequency of the equipment ranges from 4.5 to 4600Hz. Geophones of 4.5 Hz are used in the survey and they are connected to the seismograph with connecting cables. A wooden hammer of 11 kg weight is used as a source for creating the energy. Fixed receiver configuration is used and source is placed between each receiver and at both ends of the survey line. Data for each site is recorded and saved in the equipment. The acquired data is then transferred from the seismograph for the analysis using SeisImager/SW software. The two dimensional velocity model is generated for all test locations and the average shear wave velocity up to 30m ($V_{S30}$) is also calculated.

## GEOLOGICAL AND GEOTECHNICAL DETAILS OF DELHI

Geology of Delhi is interesting on account of its being the end of exposed ancient Aravali (Pre-Cambrian) mountain ranges extending NE in this area. It is presumed underneath the river alluvium, the Aravalis might have extended as far as up to the Himalayas, which makes Delhi susceptible to seismic events in the Himalayas. Delhi and its adjoing region are surrounded in the north and east by Indo-Gangetic plains, in the west by the extension of the great Indian Thar desert and in the south by the Aravali ranges. The terrain is generally flat except for a low NNE-SSW trending Delhi ridge in the central portion of the region with river Yamuna flowing towards south direction in the eastern side of Delhi. The south eastern side of Delhi has a natural depression in the surface topography, which is called as Najafgarh basin. The area can be divided into three major geomorphological units i.e., Delhi ridge, older alluvium (Pleistocene) and newer alluvium (Holocene). The detailed geological map of Delhi is shown in Fig 1. Table 1 gives the geological successions of the Delhi region (Naqvi and Roger, 1986). The exposed rock outcrops in Delhi are mainly quartzites of the Alwar series. The Alwar quartzites are the basement rocks exposed in the area and belong to the Pre-Cambrian age. These are composed mainly of quartzites with interbeds of mica schists and are intruded locally by pegmatites and quartz veins (Krishnan, 1982). The rocks of the Delhi quartzite have undergone multiple folding and different phases of metamorphism. The quartzites are white, pale grey or pinkish purple in color and mottled with brown and red depending up on the amount of iron oxide present. The strike of the quartzites varies from NE-SW to NNE-SSW with steep slips towards the east and south east direction.

**Table 1:** Stratigraphic Succession of Delhi Region (Naqvi and Roger, 1986)

| Geological Unit | Series | Characteristics |
|---|---|---|
| Present and Sub-recent (Pleistocene) | Younger Alluvium | Yamuna river bed sand and other sediment deposits in the stream bed |
| | Older Alluvium | Yellow and reddish soil comprising silt, clay with kankar beds, sand pockets and sometimes small ferruginous concretions |
| Unconformity | | |
| Post Delhi Intrusives | | Quartz veins and Pegmatites |
| Delhi Super Group (Pre- Cambrian) | Alwar series | Quartzites, grayish, bluish and pinkish in color, fine to coarse grained |
| Base Unknown | | |

Three sets of joints are common in Delhi quartzites. Of these two sets are almost vertical and one is horizontal. One of the vertical joints trend north south while the other is at right angles to it. The north south joints are more in number than the other two sets. The effects of weathering are more pronounced along the joint plains. The weathering of pegmatites gives rise to clay which is available in many areas of the Delhi.

The Alwar series and the post Delhi intrusives are covered by the quaternary deposits in the form of aeolian and alluvial deposits. The alluvial deposits belong to the Pleistocene period, i.e., older alluvial deposits and of recent age i.e., newer alluvium. The older alluvium occurs extensively in the western part of the Delhi region. Older alluvium deposits consists of mostly inter bedded lenticular and inter fingering deposits of clay, silt and sand along with kankar. In the central part of the Delhi the older alluvium deposits are associated with kankar which are resulted from the weathering of the exposed Delhi quartzite. In the Chattarpur basin, the alluvium has been derived from the weathering of the surrounding quartzites and subsequent transportation and deposition. This is closed by the quartzite ridge. The general slope of the land is towards the centre of the basin from the surrounding ridge. The newer alluvium, which occurs mainly on the eastern part of the region and extends from north to south east of the Delhi. These alluvial deposits were laid down to the east of Delhi ridge extending to the western side of river Yamuna. The soils in these formations have medium to coarse grained sands with flakes of mica in abundance. These deposits are characterized by the absence of kankar. The thickness of the alluvium both on eastern and western sides of the ridge is varying and it is thicker in western side.

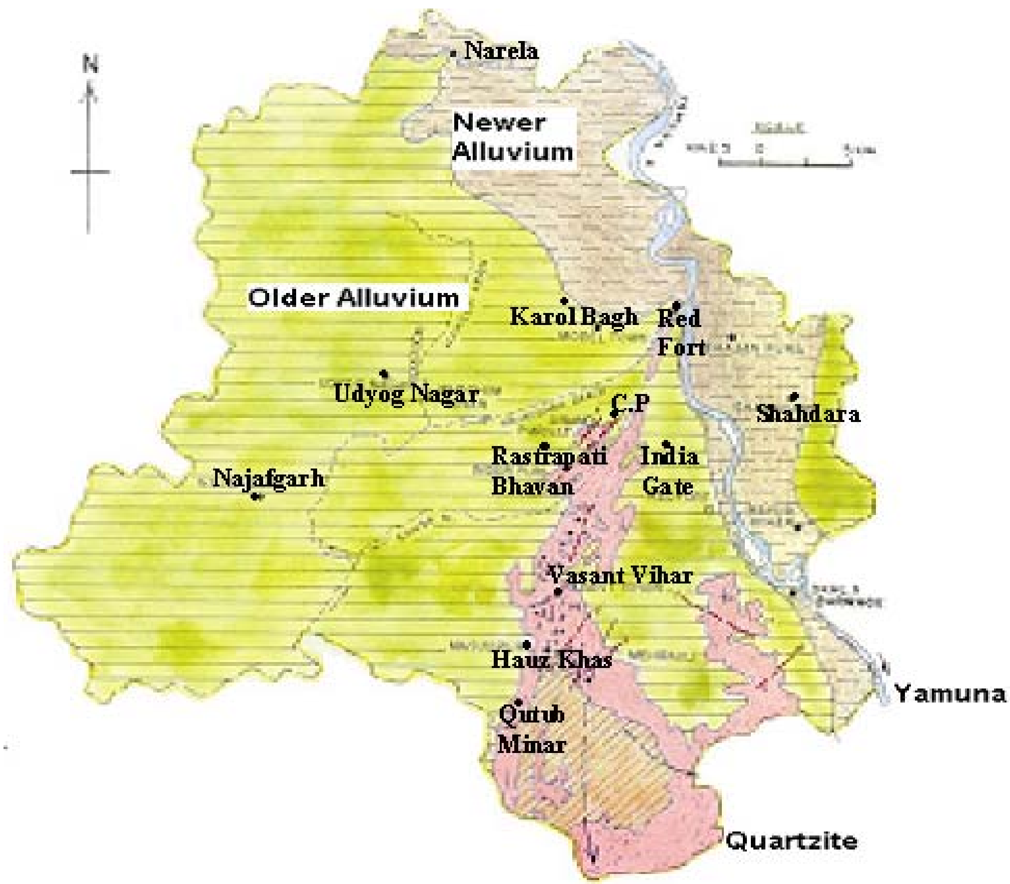



**Figure 1:** Geological Map of Delhi Region (Naqvi and Roger, 1986)

The geotechnical heterogeneity of Delhi has been studied in detail using soil profiles prepared, grain size analysis, X-ray diffraction analysis, SEM studies, bedrock depth depths and ground water details. Vertical soil profiles covering almost the entire area are made using the geotechnical borehole information collected from several organizations. The grain size distribution curves at four different depths are made for north, east, west, south and central blocks of Delhi and the percentage of sand, silt and clay fractions are calculated. The mineralogical composition of the samples was determined using X-ray diffraction and scanning electron microscopic (SEM) techniques. The silt and sand fractions of these sediments were mostly quartz, which indicate the sediments were developed under medium to high weathering intensities for a long period of time. The clay fraction was mainly kaolinite. The XRD analyses show that quartz, felspar, mica, kaolinite, illite, chlorite and calcite are present in all the investigated soil samples. The bedrock topography in Delhi is undulating in nature with several humps and depressions. Water table is very high in trans Yamuna region and in western side of Delhi towards Najafgarh area (Rao and Neelima, 2004).

## MULTI CHANNEL ANALYSIS OF SURFACE WAVE (MASW) METHOD

Multichannel analysis of surface wave (MASW) method overcomes the drawbacks of SASW. The multichannel analysis of surface wave method (Park et al., 1999) is similar to SASW method but multiple geophones or receivers are used for the data acquisition. It extracts the fundamental mode dispersion curve from the shot record then the extracted dispersion curve is inverted (Xia et al., 2000) to obtain the velocity model. The entire process involves three major steps i.e., acquisition of the data, construction of dispersion curve (phase velocity versus frequency) and inversion process to get the velocity model. This method provides reliable estimation of S wave velocity profiles with in upper 30m below ground surface.

The method can be used for solving various 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 generation of S wave velocity profiles (Xia et al. 1999).

Extraction of accurate dispersion curve is very important step in MASW method also because error in dispersion curve would cause inversion to produce an inaccurate value of $V_S$. Other seismic waves such as direct waves, refracted waves, higher modes of surface waves and air waves may act as noise. MASW test can handle such types of noise only if several acquisition parameters are met. The most important parameter is the large receiver spread.

Multi station technique increases the reliability of the results and shortens the execution time both in the field and during interpretation for surface wave tests. In the recent years, MASW method attracted researchers all over the world (Hayashi and Suzuki, 2004). This method is a powerful, rapid and cost effective tool for estimating the shear wave velocity structures. Surface wave profiling using this MASW method will provide a quick and accurate shallow subsurface image of the shear wave velocities. It is clear that this method is useful for geotechnical engineers/seismologists who need a quick assessment of site characterization or a reliable velocity structure, which is used in earthquake ground motions.

### *Data Acquisition*

In the study, a 48 channel engineering seismograph McSEIS-SX 48 (Model-1126C) from OYO Corporation, Japan is used for the seismic refraction and MASW testing. This is highly efficient digital seismograph featured with lightweight, handy type, low power consumption. A total of 118 MASW tests were completed to do the detailed site characterization of Delhi.

A 2D Vs map is constructed from the acquisition of multichannel seismic data using the 48 channel signal enhancement seismograph. Twelve geophones of 4.5 Hz natural frequency which are connected to the seismograph with connecting cables are used in the survey. A wooden hammer of 11 kg weight manually impacted on 165cm$^2$ aluminum plate is used for creating the energy. In this study 12 geophones are laid out in a linear array with 6m spacing and are connected to the seismograph. This made the total survey length of 72m. Seismic energy is generated at an offset distance of 3m (distance to nearest geophone). Figure 2 shows the field set up of the MASW test. Fixed source receiver configuration is adopted in this survey. So the survey depth will be 36m (half of survey length). The source is shifted every time with 6m interval and a total of 13 shots are made at each test location. Also, a trigger geophone is used to initialize the recording. The generated Rayleigh wave data are recorded at all shot points. Data for each shot is digitally recorded and saved in the equipment. Figures 3 and 4 show the multichannel records (shot gathers) of the geophones at JNU campus and Sec 51 Noida with the shifting of the source along the survey line. The acquired data is then transferred for the analysis using SeisImager/SW software. Table 2 gives the recording parameters for MASW testing during the acquisition process.

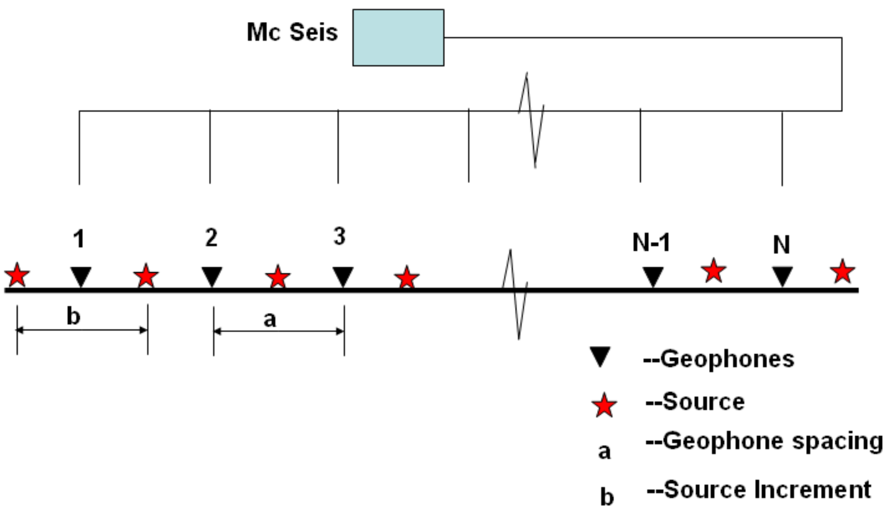
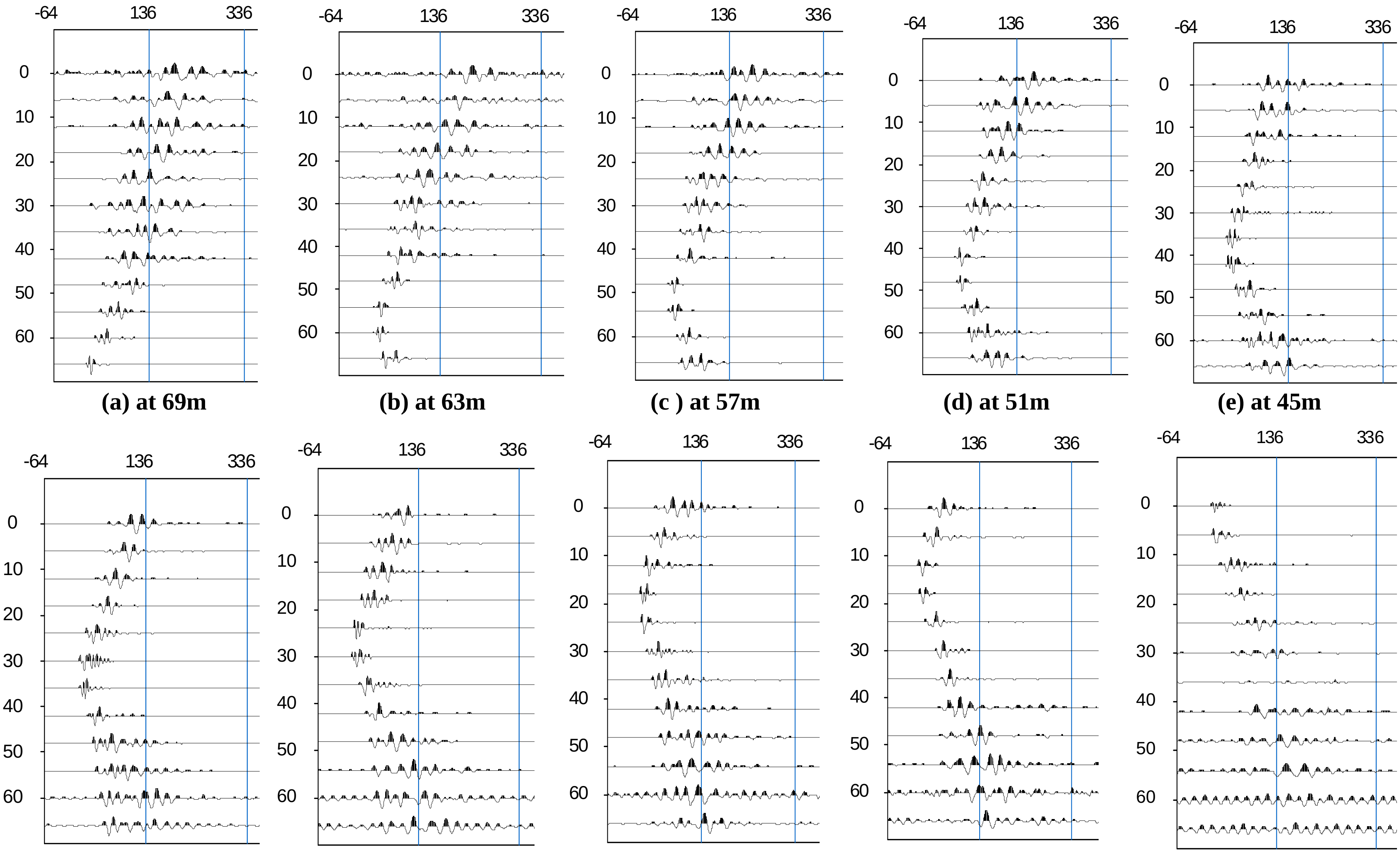



**Figure 2:** Sketch of MASW Test Spread

**Table 2:** Seismic Data Recording Parameters for MASW Testing

| | |
|---|---|
| Recording System: | McSEIS-SX 48 |
| Sampling Interval: | 500 μs |
| Memory: | 4kb |
| Recording Format: | SEG-2 |
| Pre Trigger: | ON |
| Stack Mode: | Summation |
| Geophones: | 12 geophones of 4.5 Hz frequency |
| Geophones Array: | Linear with geophone spacing of 6m |
| Source: | 11kg sledge hammer |
| Source Array: | 6m interval |
| Offset Distance: | 3m |




(a) at 69m (b) at 63m (c ) at 57m (d) at 51m (e) at 45m

(f) at 39m (g) at 33m (h) at 21m (i) at 9m (j) at 3m

**Figure 3:** Multichannel Records (Shot Gathers) at JNU Campus (28⁰32'45.41'', 77⁰09'42.11'') with Source Shifting Along the Survey Length

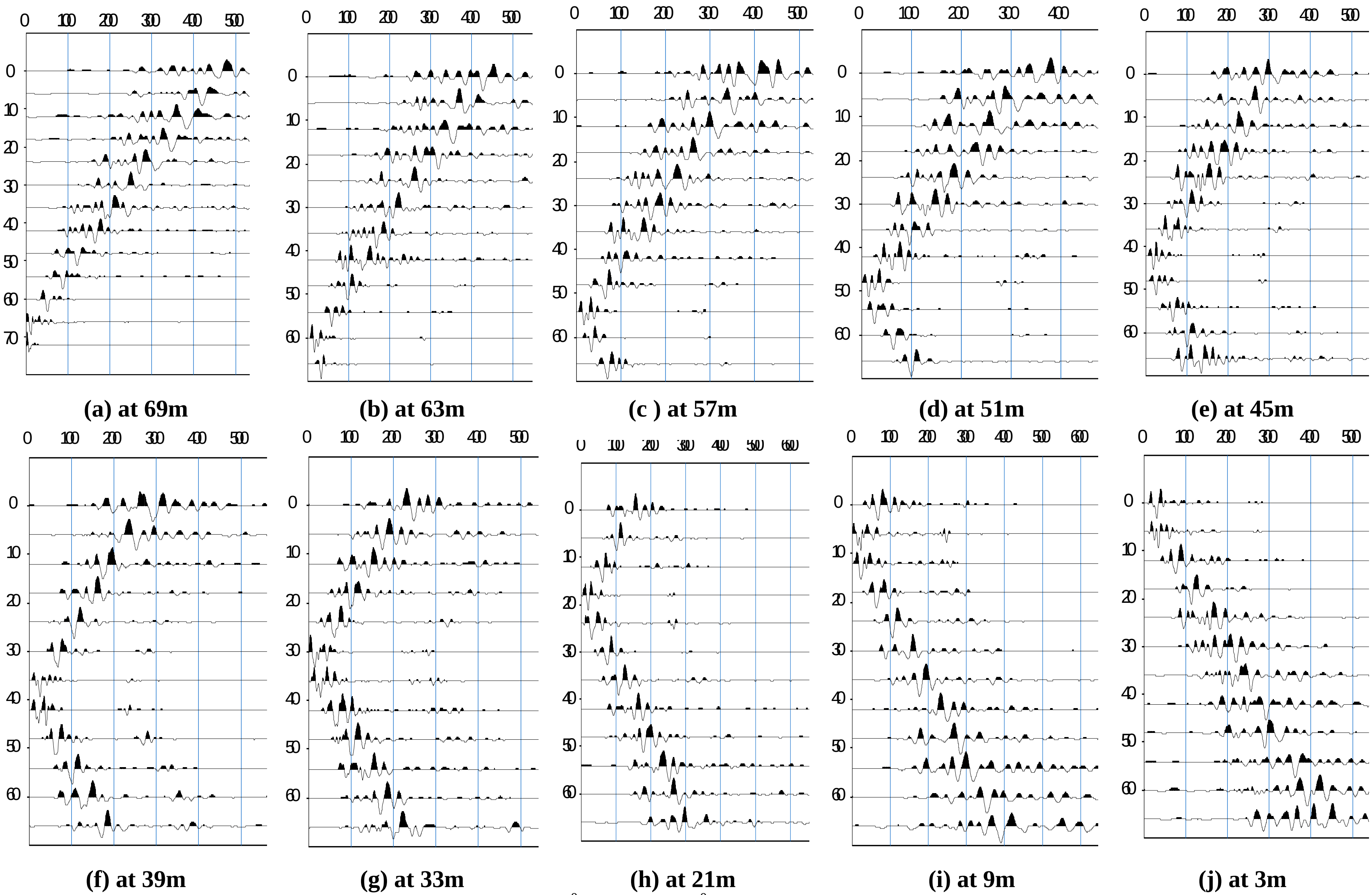



**Figure 4:** Multichannel Records (Shot Gathers) at Sec 51 Noida ($28^0$34' 41.92", $77^0$ 22' 03.44") with Source Shifting Along the Survey Length

## *Analysis of the Data*

Acquired surface wave seismic data is transferred to the computer and it is processed using SeisImager/ SW software through spectral inversion to obtain 1D and 2D MASW shear wave velocity profiles. This SeisImager/SW software has three more softwares i.e., PickWin95, WaveEq and GeoPlot. The first step in the analysis is making the file list in which all waveform files and source receiver configuration are mentioned. The next step is to extract all pairs that have common mid point (CMP) from all traces and to calculate its cross correlation CMP gathers. Cross correlation CMP gather files are saved as pseudo shot gather files for each CMP locations.

Then the dispersion curves are generated by converting it into frequency domain for each cross correlation CMP gathers and then checked. Generation of a dispersion curve is one of the most critical steps for generating an accurate shear wave velocity profile. Dispersion curves are generally displayed as phase velocity versus frequency. This relation can be established by calculating the phase velocity from the linear slope of each component of the swept frequency record. The 1D shear wave velocity profiles are calculated using the dispersion curves obtained from waveform data by non linear least square method. Then, by placing each 1D Vs profile at a surface corresponding to the middle of the survey line, a 2D Vs map is constructed in Geoplot software. That is, multiple Vs profiles obtained are then used for a 2D interpolation to create the final map. The kriging method is used for this interpolation. This is a geostatistical interpolation method that considers both the distance and the degree of variation between known data points when estimating unknown areas. Kriging method is particularly appropriate where best estimates are required, data quality is good, and error estimates are essential. The depth wise shear wave velocity values of all the 118 test sites are given in Table 5.

It is observed that the $V_S$ values estimated from the MASW testing are in good agreement with the geotechnical characteristics of the soil strata. That means the value of Vs is ranging from 400 to 480 m/s in the locations like JNU, Vasanth Kunj, Ladha sarai, Jarera, Nangloi Sayied, which are in southern part of Delhi with rock at shallow depth. It is 120 to 250m/s in trans Yamuna region where soils are loose sandy silts (newer alluvium) and the value of Vs is ranging from 250 to 370m/s in western side of the area where soils are dense silty sands and sandy silts (Older alluvium).

## *Average Shear Wave Velocity up to 30m Depth*

The shear wave velocity averaged over the top 30m of soil is referred as $V_{S30}$ and is computed by dividing 30 m with the travel time from the surface to 30 m as given in Eqn. 2.

$$V_{S30} = \frac{30}{\sum_{i=1,N} \frac{h_i}{V_i}} \tag{2}$$

where, $h_i$ and $V_i$ denote the thickness and shear wave velocity of the N layers existing in the top 30meters.

Modern seismic codes like NEHRP, UBC97, IBC2000 and Eurocode8 use $V_{S30}$ for doing the site characterization. These codes are developed after the recent strong earthquakes in America, Europe, Japan and other countries. In general the parameters describing in site effects in seismic codes are expressed through soil characterization and spectral amplification factor.

The site classes estimated from shallow shear wave velocity models are also important in deriving strong motion prediction equations (Boore et al., 1997) and in applications of building codes to specific sites. The $V_{S30}$ for all the test sites are calculated using the above equation. It is ranging from 185 to 495 m/s in Delhi region. In the locations like JNU, Vasant Kunj, Ladha Sarai, Jarera, Nangloi Sayied that are in southern part of Delhi has very high $V_{S30}$ because of rock outcrops at shallow depths. The locations falling in the North and eastern side has the average shear wave velocity value less than 250 m/s and the locations in the western side of the area has the values ranging from 250 to 350 m/s. The detailed site characterization based on $V_{S30}$ is done by dividing the area into four zones ZA, ZB, ZC1 and ZC2. Figure 5 shows the $V_{S30}$ map of Delhi. The zone ZA ($V_{S30}$ > 350m/s) is falling in the central and southern part of Delhi where quartzite rock outcrop is available with dense gravely sands and the zone ZB ($V_{S30}$ = 250 to 350 m/s) is having dense sandy silts and silty sands with clay seams i.e., Pleistocene soils. The zones ZC1 and ZC2 ($V_{S30}$ < 250m/s) are falling in the trans Yamuna region where soils are very loose sandy silts with low N value (Holocene).

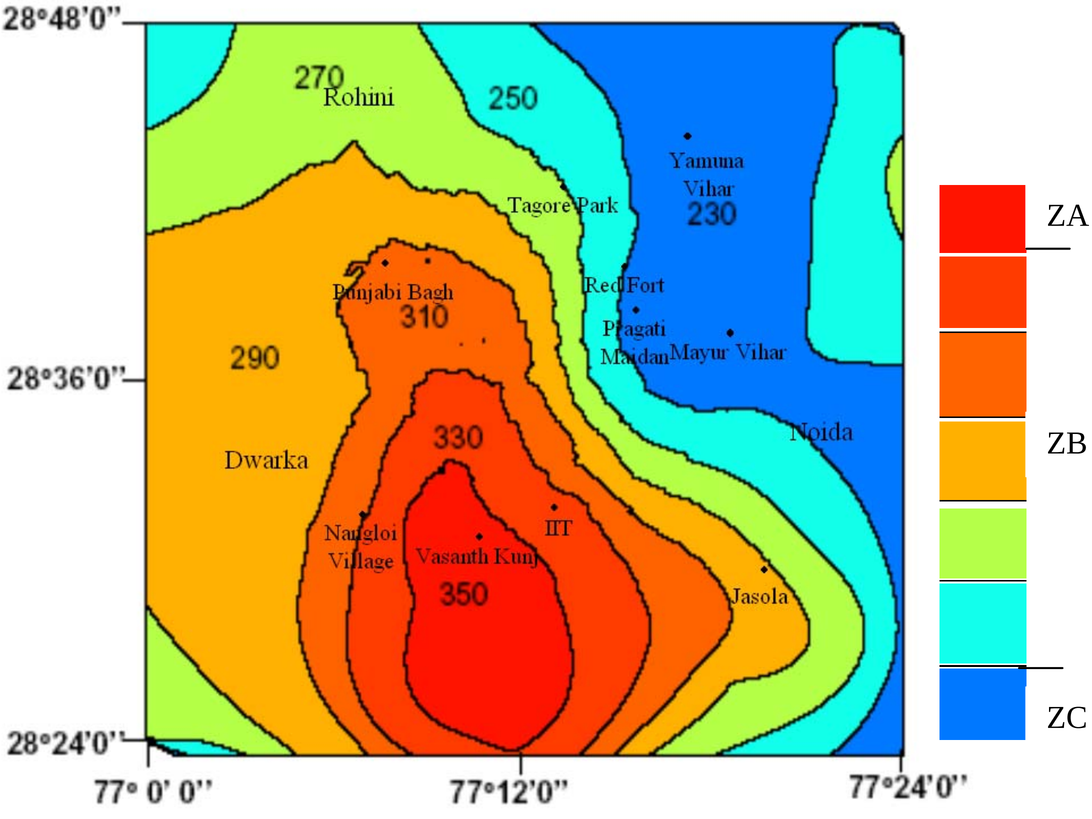



**Figure 5:** Average Shear Wave Velocity $V_{S30}$ Map for Delhi

**Table 5:** Depth Wise Shear Wave Velocity Values at Different Test Locations

| Eicher Grid No. | Location | Station Code | Latitude | Longitude | Depth (m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 2 | 4 | 8 | 12 | 16 | 20 | 24 | 30 |
| 128G4 | IIT Main Stadium | IITM | $28^0$32’39.25’’ | $77^0$11’23.02’’ | 250 | 250 | 260 | 280 | 290 | 320 | 340 | 340 |
| 128G4 | IIT Playground, Taxila Gate | IITT | $28^0$32’43.25’’ | $77^0$10’49.32’’ | 290 | 290 | 300 | 320 | 310 | 340 | 340 | 340 |
| 128F3 | BSF Colony, Near JNU | BSF | $28^0$32’45.41’’ | $77^0$09’42.11’’ | 280 | 280 | 290 | 310 | 400 | 410 | 410 | 410 |
| 127D3 | JNU Campus, Opp. Girls Hostel | JNU | $28^0$32’40.11’’ | $77^0$09’50.84’’ | 380 | 380 | 450 | 460 | 450 | 480 | 480 | 480 |
| 126G6 | AICTE Ground, Vasant Kunj | VK1 | $28^0$32’56.08” | $77^0$10’07.04” | 390 | 390 | 440 | 430 | 530 | 570 | 570 | 570 |
| 141D3 | DDA Park, Sec 6 Vasant Kunj | VK2 | $28^0$31’35.25” | $77^0$ 09’34.66” | 300 | 300 | 420 | 410 | 420 | 440 | 440 | 440 |
| 124G3 | Opp Centaur Hotel, Nangal Deo Village | NDV | $28^0$32’56.31” | $77^0$06’00.15” | 270 | 270 | 270 | 280 | 300 | 380 | 390 | 390 |
| 123B2 | Shahabad Mohamadpur Village | SHV | $28^0$33’12.10” | $77^0$ 04’32.12” | 240 | 240 | 270 | 290 | 300 | 300 | 300 | 300 |
| 142C4 | Ladha Sarai | LSA | $28^0$30’58.78” | $77^0$10’54.28” | 440 | 460 | 470 | 450 | 360 | 480 | 480 | 480 |
| 158 | Sharma Farm House, Sat Bari | SAB | $28^0$ 28’ 40.21’’ | $77^0$ 1’22.92’’ | 320 | 320 | 310 | 340 | 340 | 340 | 340 | 340 |
| 144F2 | Sec-6, Pushpa Vihar | PVI | $28^0$41’40.56’’ | $77^0$13’24.13’’ | 280 | 360 | 280 | 280 | 380 | 380 | 380 | 380 |
| 143B3 | Opp. DDA Park, Lado Sarai | LAS | $28^0$31'26.84’’ | $77^0$11’47.91’’ | 220 | 240 | 300 | 320 | 360 | 370 | 370 | 370 |
| 146F6 | Near Tuglakabad Fort | TVF | $28^0$30’25.92’’ | $77^0$15’56.08’’ | 390 | 420 | 370 | 210 | 340 | 430 | 430 | 430 |
| 131B6 | Chandra Shekhar Park, GK-II | GKII | $28^0$32’26.42’’ | $77^0$14’29.24’’ | 340 | 330 | 350 | 420 | 440 | 440 | 440 | 450 |
| 132F3 | DDA Land Near Lotus Temple | LTE | $28^0$ 35’ 06.00’’ | $77^0$15’08.66’’ | 400 | 340 | 300 | 180 | 180 | 110 | 190 | 190 |
| 133D5 | Netaji Sports Complex, Jasola | JAS | $28^0$ 32’ 22.23’’ | $77^0$17’24.40’’ | 300 | 330 | 250 | 380 | 380 | 390 | 390 | 390 |
| 117A4 | Ashoka Park, Friends Colony | NFC | $28^0$35’43.25’’ | $77^0$23’45.32’’ | 290 | 300 | 270 | 300 | 300 | 350 | 350 | 350 |
| 116E2 | Pocket-C, Sidhartha Nagar | SIN | $28^0$ 34’ 23.01’’ | $77^0$22’11.27’’ | 280 | 290 | 290 | 330 | 330 | 380 | 380 | 380 |
| 114H2 | Near Jawahar Lal Nehru Stadium | JNS | $28^0$ 35’ 02.29’’ | $77^0$13’51.45’’ | 260 | 260 | 250 | 250 | 270 | 290 | 290 | 300 |
| 115B2 | M Block, Jangpura | JAN | $28^0$ 35’31.95’’ | $77^0$13’52.05’’ | 260 | 230 | 280 | 310 | 390 | 420 | 420 | 420 |
| 113A3 | Sarojini Nagar | SAN | $28^0$34’24.19’’ | $77^0$12’19.63’’ | 340 | 270 | 300 | 370 | 300 | 300 | 300 | 420 |
| 112E6 | Sec-5, R.K. Puram | RKP | $28^0$33’48.41’’ | $77^0$10’30.73’’ | 250 | 260 | 280 | 270 | 270 | 280 | 280 | 280 |
| 111C1 | Bhagwan Mahvir Kendra | BMK | $28^0$38’ 04.09’’ | $77^0$09’38.73’’ | 410 | 450 | 470 | 360 | 430 | 470 | 470 | 470 |
| 110F2 | APS Colony, Jharera | APS | $28^0$38’43.25’’ | $77^0$08’49.32’’ | 400 | 400 | 460 | 450 | 460 | 430 | 390 | 390 |
| 108H2 | Shekhawati Lines,Near Prahaldpur Village | SHL | $28^0$ 34'51.71" | $77^0$ 06'35.65" | 280 | 290 | 280 | 330 | 330 | 300 | 220 | 220 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 107A4 | Sec-8, Dwaraka | D08 | 28$^0$ 34'11.17" | 77$^0$04' 16.32" | 230 | 220 | 270 | 270 | 300 | 300 | 300 | 360 |
| 122G1 | Sec-22, Dwaraka | D22 | 28$^0$ 33' 43.2" | 77$^0$04' 08.24" | 200 | 210 | 220 | 270 | 360 | 360 | 360 | 360 |
| 106F3 | Sec-20,Dwaraka | D20 | 28$^0$34' 4.61" | 77$^0$03' 28.27" | 240 | 250 | 300 | 310 | 310 | 330 | 340 | 340 |
| 089B6 | Sec-10,Dwaraka | D10 | 28$^0$35' 17.16" | 77$^0$03' 16.24" | 240 | 240 | 270 | 310 | 330 | 330 | 330 | 330 |
| 089B4 | Sec-5, Dwaraka | D05 | 28$^0$35'54.78" | 77$^0$03' 11.84" | 200 | 210 | 270 | 300 | 310 | 330 | 330 | 350 |
| 088F3 | Sec-13, Dwaraka | D13 | 28$^0$36' 9.60" | 77$^0$02' 04.86" | 190 | 220 | 200 | 320 | 290 | 260 | 330 | 330 |
| 087B3 | Sec-16B, Dwaraka | D16 | 28$^0$36' 6.48" | 77$^0$01' 11.98" | 240 | 240 | 260 | 290 | 290 | 300 | 320 | 320 |
| 105D2 | Sec-19, Dwaraka | D19 | 28$^0$35’03.73’’ | 77$^0$02’46.20’’ | 220 | 200 | 240 | 290 | 310 | 310 | 310 | 310 |
| 090G3 | Nasirpur, Near Dakshinpuri | DAP | 28$^0$36'06.98" | 77$^0$05' 05.76" | 200 | 220 | 250 | 310 | 300 | 320 | 440 | 440 |
| 091C1 | Institutional Area , Janakpuri | JAP | 28$^0$36'36.58" | 77$^0$06' 00.07" | 210 | 220 | 320 | 350 | 350 | 280 | 280 | 370 |
| 074F5 | Near Tihar Jail, Janakpuri | TIJ | 28$^0$37' 14.42" | 77$^0$05' 45.34" | 240 | 250 | 300 | 320 | 320 | 280 | 280 | 280 |
| 073A2 | DDA Multigyan Playground, Vikaspuri | VIP | 28$^0$ 38' 04.91" | 77$^0$ 04' 24.14" | 250 | 260 | 240 | 270 | 330 | 330 | 330 | 330 |
| 075D3 | DDA Park, Hari Nagar | HAN | 28$^0$ 37' 51.37" | 77$^0$ 07' 24.58" | 360 | 380 | 320 | 340 | 280 | 310 | 290 | 290 |
| 054F4 | Block-C, Kirtinagar | KIN | 28$^0$38' 59.88" | 77$^0$08' 22.02" | 250 | 250 | 260 | 260 | 260 | 230 | 230 | 230 |
| 076G4 | Agarsain Park, Inderpuri | INP | 28$^0$57' 05.98" | 77$^0$ 10' 26.52" | 340 | 370 | 320 | 320 | 320 | 480 | 490 | 490 |
| 052E4 | Chaukhandi Village, Khayala | KHY | 28$^0$39' 00.93" | 77$^0$ 05' 34.36" | 270 | 270 | 250 | 350 | 250 | 270 | 270 | 270 |
| 035C5 | Punjabi Bagh West | WPB | 28$^0$40' 15.92" | 77$^0$ 08' 18.49" | 300 | 270 | 390 | 310 | 310 | 450 | 450 | 450 |
| 034F6 | Bock-B, Puschim Vihar | PUV | 28$^0$48' 30.87" | 77$^0$ 07' 05.71" | 440 | 420 | 320 | 280 | 280 | 340 | 340 | 340 |
| 034G3 | Near Rly Stn, Sakurbasti | SAB | 28$^0$40' 46.78" | 77$^0$ 07' 25.13" | 240 | 250 | 230 | 280 | 390 | 390 | 390 | 390 |
| 032F3 | Surajmal Stadium, Rohtak Road | ROR | 28$^0$40' 55.86" | 77$^0$ 04' 30.65" | 210 | 230 | 260 | 280 | 300 | 310 | 320 | 320 |
| 051C2 | Nangloi Sayied | NAS | 28$^0$39' 24.72" | 77$^0$ 04' 38.43" | 280 | 210 | 320 | 470 | 470 | 510 | 510 | 510 |
| --- | Near AirForce Radar Station, Nangloi | ARS | 28$^0$ 39'55.80" | 77$^0$ 02' 35.69" | 260 | 250 | 300 | 330 | 330 | 330 | 330 | 330 |
| 015A4 | Bhagya Vihar, Near Mubarakpur Dabas | MUD | 28$^0$ 42' 38.81" | 77$^0$ 02' 15.11" | 190 | 200 | 270 | 300 | 290 | 320 | 360 | 360 |
| 016F4 | Nithari Village | NIV | 28$^0$42' 11.92" | 77$^0$ 03' 14.47" | 210 | 200 | 230 | 240 | 230 | 260 | 260 | 260 |
| 118H2 | Sec-15, Noida | N15 | 28$^0$34'48.88" | 77$^0$18' 42.67" | 180 | 180 | 210 | 200 | 200 | 340 | 340 | 340 |
| 119B2 | Sec-3, Noida | N03 | 28$^0$ 34'50.57" | 77$^0$ 19'18.33" | 260 | 260 | 240 | 250 | 250 | 340 | 340 | 340 |
| 120E3 | Sec-30, Noida | N30 | 28$^0$ 34' 21.71" | 77$^0$ 20' 19.79" | 160 | 240 | 110 | 340 | 280 | 270 | 240 | 240 |
| 121B3 | Sec-51, Noida | N51 | 28$^0$34' 41.92" | 77$^0$ 22' 03.44" | 190 | 170 | 230 | 250 | 250 | 250 | 260 | 260 |
| 103C3 | Sec-55, Noida | N55 | 28$^0$36' 13.92" | 77$^0$ 20' 52.63" | 120 | 190 | 230 | 280 | 310 | 280 | 270 | 270 |
| 104G4 | Sec-61, Noida | N61 | 28$^0$35' 53.78" | 77$^0$ 22' 06.59" | 90 | 270 | 130 | 260 | 290 | 280 | 280 | 280 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 101A5 | Mayur Vihar Phase I | MVX | $28^0$ 35'30.63" | $77^0$ 17' 51.07" | 190 | 190 | 180 | 170 | 280 | 280 | 380 | 380 |
| 102F1 | Varun Enclave, Kondli | VAE | $28^0$ 36' 37.61" | $77^0$ 19' 13.17" | 210 | 190 | 160 | 240 | 280 | 290 | 310 | 310 |
| 084H4 | Mayur Vihar, Phase II | MVI | $28^0$ 37' 28.15" | $77^0$ 18' 25.75" | 170 | 160 | 190 | 180 | 300 | 350 | 350 | 350 |
| 083D1 | Block A, Preet Vihar | PRV | $28^0$ 38' 23.03" | $77^0$ 17' 50.93" | 150 | 140 | 230 | 250 | 240 | 240 | 250 | 250 |
| 099D2 | Commonwealth Games Site | CWG | $28^0$36' 53.81" | $77^0$ 16' 33.49" | 180 | 160 | 190 | 190 | 220 | 220 | 220 | 220 |
| 100G4 | Near Noida Link Road, Mayur Vihar-I | MVII | $28^0$36' 03.17" | $77^0$ 16' 54.58" | 150 | 140 | 170 | 200 | 250 | 260 | 260 | 260 |
| 086H3 | Noida Institutiona Area, Ph II, Sec-62, Noida | N62 | $28^0$37' 50.06" | $77^0$ 21' 24.13" | 230 | 220 | 270 | 300 | 340 | 370 | 420 | 420 |
| 081D1 | Inside Gandhi Darshan | GAD | $28^0$38' 11.15" | $77^0$ 15' 04.58" | 140 | 140 | 160 | 230 | 220 | 230 | 230 | 230 |
| 060G3 | MCD Park, Geeta Colony | GEC | $28^0$39' 24.49" | $77^0$ 18' 54.18" | 150 | 150 | 160 | 200 | 200 | 220 | 220 | 220 |
| 062E2 | Vishwas Nagar | VIN | $28^0$39' 38.30" | $77^0$ 18' 05.09" | 170 | 130 | 170 | 260 | 270 | 350 | 370 | 370 |
| 040F4 | Silampur | SIP | $28^0$40' 31.99" | $77^0$ 15' 35.44" | 170 | 150 | 180 | 220 | 280 | 280 | 310 | 310 |
| 042H3 | Near GTB Hosp, Nand Nagri | NAN | $28^0$41' 20.63" | $77^0$ 18' 32.33" | 180 | 140 | 240 | 280 | 250 | 280 | 280 | 280 |
| 026E5 | Block C, Yamuna Vihar | YAV | $28^0$41' 54.77" | $77^0$ 16' 26.45" | 180 | 160 | 150 | 220 | 270 | 300 | 300 | 300 |
| 013C3 | DLF Ankur Vihar | ANV | $28^0$44' 13.48" | $77^0$ 15' 48.36" | 150 | 150 | 180 | 240 | 280 | 270 | 290 | 290 |
| 014F3 | Lal Bagh Colony, Loni | LBC | $28^0$45' 27.51" | $77^0$ 16' 20.43" | 190 | 170 | 200 | 250 | 270 | 270 | 290 | 290 |
| 023B4 | Tagore Park | TAP | $28^0$ 42' 14.69" | $77^0$ 12' 00.55" | 170 | 150 | 320 | 330 | 290 | 280 | 330 | 330 |
| 024E3 | Dr. Mukherjee Nagar | MUN | $28^0$42' 33.84" | $77^0$ 12' 52.30" | 300 | 290 | 160 | 310 | 350 | 380 | 380 | 380 |
| 038F6 | Malka Ganj | MAL | $28^0$40’23.81’’ | $77^0$11’47.78’’ | 260 | 290 | 200 | 240 | 350 | 360 | 360 | 360 |
| 039D1 | Majnu Ka Teela | MKT | $28^0$ 41' 35.46" | $77^0$ 13' 41.10" | 320 | 420 | 290 | 270 | 310 | 320 | 420 | 420 |
| 129C1 | Green Park | GRP | $28^0$33' 18.92" | $77^0$ 12' 10.58" | 280 | 240 | 290 | 360 | 380 | 380 | 380 | 380 |
| 130G1 | Sadiq Nagar | SDQ | $28^0$33' 24.95" | $77^0$ 13' 25.09" | 210 | 200 | 240 | 260 | 260 | 260 | 260 | 260 |
| 156H4 | Ghitorni | GHT | $28^0$29'14.03" | $77^0$ 08' 44.39" | 210 | 210 | 310 | 320 | 310 | 310 | 320 | 320 |
| 155B4 | Argun Garh | ARG | $28^0$29' 42.69" | $77^0$ 06' 35.04" | Data Corrupted | | | | | | | |
| 139A3 | Rajokri | RKR | $28^0$31' 25.37" | $77^0$ 05' 30.91" | 340 | 330 | 300 | 310 | 320 | 390 | 390 | 390 |
| 157D1 | Suri Farm House | SFH | $28^0$30' 06.88" | $77^0$ 10' 30.56" | 310 | 300 | 260 | 270 | 270 | 330 | 330 | 330 |
| 159B3 | Maidan Garh | MAG | $28^0$29' 47.05" | $77^0$ 11' 49.99" | 470 | 470 | 430 | 470 | 500 | 500 | 500 | 500 |
| 160F4 | South Sainik Farm | SSF | $28^0$29' 18.36" | $77^0$ 13' 09.12" | 200 | 300 | 380 | 350 | 310 | 260 | 380 | 380 |
| 147D2 | District Park, Sarita Vihar | SAV | $28^0$ 31'38.41" | $77^0$ 17' 26.65" | 270 | 230 | 350 | 390 | 390 | 390 | 390 | 390 |
| 148F2 | Ali Vihar | ALV | $28^0$31' 00.17" | $77^0$ 18' 17.68" | 210 | 200 | 260 | 240 | 240 | 360 | 360 | 360 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 007B5 | Sec 25, Rohini | R25 | $28^0$44' 06.25" | $77^0$ 05' 19.15" | 360 | 370 | 140 | 140 | 140 | 400 | 400 | 400 |
| 008F3 | Sec 16, Rohini | R16 | $28^0$44' 16.05" | $77^0$ 07' 95.66" | 330 | 280 | 360 | 390 | 380 | 400 | 400 | 400 |
| 097B6 | Jor Bagh, Lodhi Colony | LOC | $28^0$35' 55.52" | $77^0$ 13' 20.54" | 230 | 210 | 250 | 320 | 330 | 380 | 380 | 380 |
| 098G1 | Bhairo Bala Mandir, Pragati Maidan | PRM | $28^0$ 36' 33.12" | $77^0$ 16' 46.80" | 120 | 130 | 230 | 350 | 340 | 320 | 350 | 350 |
| 019A4 | Sec 3, Rohini | R03 | $28^0$42' 02.66" | $77^0$ 06' 04.36" | 230 | 220 | 210 | 290 | 330 | 330 | 340 | 340 |
| 020E1 | Sec 14, Rohini | R14 | $28^0$43' 05.04" | $77^0$ 08' 11.31" | 220 | 200 | 230 | 320 | 330 | 330 | 330 | 330 |
| 017A1 | Sec 23, Rohini Ext | R23 | $28^0$44' 23.27" | $77^0$ 04' 47.50" | 230 | 210 | 260 | 280 | 290 | 290 | 300 | 300 |
| 018E5 | Sec 1, Avantika Rohini | AVR | $28^0$42' 19.87" | $77^0$ 06' 00.36" | 280 | 250 | 250 | 330 | 360 | 370 | 380 | 380 |
| 055A5 | Patel Nagar | PAN | $28^0$38' 49.34" | $77^0$ 08' 57.80" | 360 | 350 | 310 | 300 | 340 | 350 | 360 | 360 |
| 003C6 | Mohalla | MOH | $28^0$45' 26.01" | $77^0$ 08' 45.94" | 150 | 160 | 320 | 430 | 380 | 300 | 430 | 430 |
| 004G1 | Kadipur | KAP | $28^0$ 4' 31.35" | $77^0$ 10' 14.61" | 160 | 140 | 250 | 270 | 270 | 260 | 270 | 270 |
| 056G1 | Railway Col., Sarai Rohilla | SAR | $28^0$39' 52.52" | $77^0$ 11' 11.71" | 240 | 240 | 240 | 250 | 330 | 360 | 370 | 370 |
| 163C5 | Suraj Kund | SVK | $28^0$29' 92.11" | $77^0$ 16' 59.73" | 260 | 270 | 340 | 370 | 370 | 370 | 370 | 370 |
| 078H2 | Near Gangaram Hospital | GAH | $28^0$38' 07.59" | $77^0$ 11' 11.13" | 420 | 420 | 410 | 400 | 400 | 430 | 440 | 440 |
| 077B4 | DDA Park, Todapur Village | TOV | $28^0$57' 32.33" | $77^0$ 09' 16.37" | 230 | 230 | 320 | 300 | 260 | 260 | 320 | 320 |
| 009C3 | Near Badli Village | BAV | $28^0$44' 20.23" | $77^0$ 08' 30.42" | 240 | 210 | 250 | 280 | 290 | 340 | 340 | 340 |
| 010H3 | Near Bhalswa Lake | BHL | $28^0$44' 20.69" | $77^0$ 10' 10.86" | 160 | 130 | 200 | 240 | 270 | 280 | 280 | 280 |
| 006G4 | Deep Vihar, Pansali | DPV | $28^0$44' 10.69" | $77^0$ 04' 39.05" | 230 | 220 | 280 | 280 | 270 | 270 | 280 | 280 |
| 005A3 | Rajiv Nagar Ext | RJN | $28^0$44' 11.89" | $77^0$ 03' 12.62" | 220 | 220 | 220 | 240 | 250 | 250 | 250 | 250 |
| 011C2 | Mukundpur near Burari | BUR | $28^0$45' 06.99" | $77^0$ 10' 50.17" | 160 | 140 | 170 | 250 | 250 | 240 | 250 | 250 |
| 012F3 | Sasnt Nagar Village | SAN | $28^0$44' 47.75" | $77^0$ 11' 50.30" | 160 | 150 | 170 | 230 | 240 | 240 | 250 | 250 |
| 021C3 | DDA Park, BR Block, Shalimar Bagh | SLB | $28^0$42' 59.10" | $77^0$ 09' 31.95" | 210 | 200 | 230 | 250 | 270 | 270 | 270 | 270 |
| 037B2 | Ashok Vihar III | ASV | $28^0$ 41' 07.59" | $77^0$ 10' 10.23" | 250 | 240 | 240 | 250 | 310 | 340 | 340 | 340 |
| 136G2 | Bhatnagar Farms | BHF | $28^0$31' 45.95" | $77^0$ 04' 41.92" | 300 | 300 | 320 | 310 | 310 | 290 | 290 | 290 |
| 135D2 | Palam Vihar Road | PVR | $28^0$31' 24.97" | $77^0$ 03' 0.24" | 230 | 220 | 280 | 300 | 310 | 310 | 310 | 310 |
| 137A5 | Sec 21, Dundahera | DUH | $28^0$31' 06.91" | $77^0$ 04' 37.88" | 240 | 240 | 250 | 210 | 210 | 270 | 270 | 270 |
| 138 | Opp Pushpanjali Farm House | PJF | $28^0$32' 06.19" | $77^0$ 05' 11.13" | 320 | 330 | 240 | 280 | 280 | 350 | 350 | 350 |
| --- | UP Delhi Border, Yamuna Bank | YAB | $28^0$32' 38.18" | $77^0$ 18' 40.10" | 210 | 210 | 230 | 230 | 260 | 260 | 260 | 260 |
| --- | Near Greater Noida Expressway | GNE | $28^0$32' 02.35" | $77^0$ 21' 02.94" | 220 | 280 | 170 | 200 | 240 | 220 | 220 | 220 |
| 041C5 | Shahdara | SHD | $28^0$40' 28.63" | $77^0$ 17' 01.84" | 200 | 190 | 180 | 200 | 200 | 220 | 220 | 220 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 043B2 | DDA Park, Dilshad Garden | DLG | $28^0$41' 15.35" | $77^0$ 19' 18.25" | 210 | 190 | 220 | 240 | 300 | 350 | 350 | 350 |
| 025A2 | Sonia Vihar, Pusta Road | SOV | $28^0$43' 04.00" | $77^0$ 15' 25.43" | 160 | 150 | 170 | 200 | 220 | 220 | 220 | 220 |
| 022H3 | Model Town | MOT | $28^0$ 42' 48.21" | $77^0$ 11' 24.03" | 160 | 150 | 200 | 250 | 290 | 330 | 330 | 330 |
| 036G3 | Kanhaya Nagar | KAN | $28^0$ 40' 55.73" | $77^0$ 09' 42.81" | 330 | 480 | 120 | 380 | 380 | 480 | 480 | 480 |

## RESULTS AND DISCUSSIONS

The MASW tests were carried out in Delhi by spreading multiple geophones for estimating two dimensional shear wave velocity profiles. In this survey 12 geophones are used with a spacing of 6m between them. The offset distances i.e., distance between the source and the nearest geophone is fixed to 3m and the source is shifted with 6m intervals. The entire procedure in MASW testing usually consists of three steps i.e. acquiring multichannel records (or shot gathers), extracting the fundamental mode dispersion curves and inverting these curves to obtain one-dimensional Vs profiles. Acquired surface wave seismic data is transferred to the computer and it is processed using SeisImager/SW software through spectral inversion to obtain 2D MASW shear wave velocity profiles. It is observed that the value of Vs is ranging from 400 to 480 m/s in the rocky sites, it is 120 to 250m/s in trans Yamuna region and 250 to 370m/s in western side of the area.

The average shear-wave velocity over the upper 30 m ($V_{S30}$) of the soil profile for all the test sites are calculated using the formula given by the Uniform Building Code (International Conference of Building Officials, 1997). $V_{S30}$ is ranging from 185 to 495 m/s in Delhi region. In the locations which are falling in southern part of Delhi, have very high $V_{S30}$ because of rock at shallow depths. The locations falling in the North and eastern side has the average shear wave velocity value less than 250 m/s and the locations in the western side of the area has the values ranging from 250 to 350 m/s. The detailed site characterization based on $V_{S30}$ is done by dividing the area into four zones ZA, ZB, ZC1 and ZC2. These zones are exactly matching with the geology and soil characteristics of the region. That is the zone ZA ($V_{S30}$ > 350m/s) is falling in the central and southern part of Delhi where quartzite rock outcrops are available with dense gravely sands and the zone ZB ($V_{S30}$ = 250 to 350 m/s) is having dense sandy silts and silty sands with clay seams i.e., Pleistocene soils. The zones ZC1 and ZC2 are falling in the trans Yamuna region where soils are very loose sandy silts with low N value.

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