Acquisition and Analysis of Surface Wave Data in the Indo Gangetic Basin

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Abstract. Seismic activity in the tectonically active Himalayan region can result in devastation in the contagious deep Indo-Gangetic Basin (IGB). It is filled by alluvial deposits and, therefore, prone to site amplification. IGB had experienced catastrophic earthquake damages due to the presence of thick soil depth of 0.05 km to about 4 km. However, very few studies have presented seismic site characterization of the IGB soil up to the shallow depth, and very limited attempts have been made to measure the dynamic properties of the deep soil column. Hence, in this study, shear velocity profile ($\mathbf{V_s}$) up to 400 m depth is measured using combined active and passive multichannel analysis of surface wave (MASW) survey in 275 selected locations in IGB. Acquisition and processing of the seismic surface wave data to obtain the $\mathbf{V_s}$ profiles at shallow and deep depths are discussed in this paper. Parametric study has been done to identify the variation in dispersion and $\mathbf{V_s}$ profiles by recording time, different sampling interval, different polarity and gain. It has been seen that changing any parameter during data recording may result in variation in $\mathbf{V_s}$. Further, the surveyed sites are classified and characterized based on time-averaged $\mathbf{V_s}$ in the upper 30 m depth as per National Earthquake Hazards Reduction Program seismic site classification. $\mathbf{V_{s30}}$ values vary from 157 to 1152 m/s in the entire stretch of IGB. This is the first time such extensive study was carried out in IGB for $\mathbf{V_s}$ determination at deep and shallow depths.

Keywords: Indo-Gangetic Basin · MASW · Data acquisition
Seismic site characterization · Passive data recording

1 Introduction

Local site conditions can have great influence on ground surface motion and structural damage by earthquakes. Two classic examples that emphasize the influence of site amplification due to local site effect are the 1985 Mexico and the 1989 Loma Prieta earthquakes. Similarly, many earthquakes in India (1934 Bihar-Nepal; 2001, Bhuj; 2015 Nepal earthquake) have also illustrated the importance of local site effects. The Indian subcontinent is one of the most seismically active regions in the world.

J. Wasowski and T. Dijkstra (Eds.): GeoMEast 2018, SUCI, pp. 60–72, 2019.
https://doi.org/10.1007/978-3-030-02032-3_6

The large strains are building along and within the plate boundary due to the ongoing collision between the Indian and Eurasian Plates. Moreover, crustal shortening increases the earthquake hazard, particularly in the northern part of the Indian Subcontinent. Various authors (Bilham and Ambraseys 2005; Bilham et al. 2001) have studied the seismotectonics of the Himalayan region and predicted the high seismicity along the entire stretch of the Main Boundary Thrust (MBT), the Main Central Thrust (MCT) and Indus-Tsangpo Suture (ITS). In the last two centuries, the Himalayan region has experienced many events of magnitude more than 7. The highly fertile and deep basin of Indo-Gangetic Basin (IGB), bound on the north side by the Himalayas, is one of the most populous areas. It is about 1000 km long to the south and filled-up by loose soil deposits. High seismicity region surrounds the IGB and this makes the damage scenario more destructive. Significant causalities to human life or infrastructure loss can result from any large earthquake in the future. Hence, there is a need to study the spatial variation of shear wave velocity in the IGB for determining the local site effect due to the presence of deep deposits contagious with high seismicity region. The proper characterization of deep soil deposits in the IGB also sets the priority for the determination of seismic site classification and the amplification factor for different periods due to local site effect.

Various authors (Boominathan et al. 2008; Anbazhagan and Sitharam 2008; Anbazhagan et al. 2010; Kumar et al. 2012; Desai and Choudhury 2014, 2015; Kumar et al. 2016) in India have attempted to determine the shear wave velocity at shallow depths in different study areas. Anbazhagan and Sitharam (2008), determined the shear wave velocity profile for shallow depth in Bengaluru. Desai and Choudhury (2015) and Kumar et al. (2012) respectively derived the V_s profile for Mumbai and Lucknow region in India. Jishnu et al. (2013) derived the V_s profiles at four different locations for Kanpur for site response study. Pandey et al. (2016) derived the V_s profile of seismic stations in Delhi region by carrying the multichannel analysis of seismic waves. Most of the previous studies were limited to soil column of 30 m depth. Additionally, in many of the studies, the measured SPT-N values were converted to V_s profiles and used for site response studies. Till today there are no studies available for determining the local site effect for the deep deposits of IGB from the measured V_s profiles exceeding 100 m depth.

There are several approaches for estimating V_s through surface wave analysis and with the developments in geophysical-indirect methods, the degree of uncertainty is reducing eventually. These geophysical methodologies integrate border soil volume and, therefore, are more representative of the seismic behavior of a site than local in-hole measurements (Humire et al. 2015). In this study, combined active and passive multichannel analysis of surface wave (MASW) survey has been used for determining the shear wave velocity profile at 275 locations in the IGB. For evaluating the dispersion characteristic both active and passive sources, linear and circular arrays have been used. Geophones of 2 Hz frequency have been used for performing the MASW survey. Ambient noise has been used as a source for both passive remote and roadside survey. Recordings have been done at different sampling intervals and record lengths. Measurements are performed at different locations in the entire stretch of IGB, stretching across the Indian states from Bihar to Punjab. The sites are classified and characterized based on time-averaged V_s in the upper 30 m depth as per NEHRP (BSSC 2003) seismic site classification.

2 Study Area

The IGB is shaped as a result of post-collision between Indian and Asian tectonic plates (Singh 1996). It is a peripheral foreland basin system, formed on a flexed Indian plate lithosphere (Lyon-Caen and Molnar 1985; Singh 1987). The Ganga Plain spreads from Aravalli-Delhi Ridge to Rajmahal hills along the west and the east respectively; Himalayan foothills in the north to the Bundelkhand Vindhyan Plateau in the south, occupying an approximate area of 250,000 km^2, lies between 77°E to 88°E (longitude) and 24°N and 30°N (latitude). The length of IGB is about 1000 km; with the variable width, ranging from 200 to 450 km, being wider and narrower, along the western and the eastern part (See Fig. 1). The IGB is irregular along with outcrops of rocks pounding out of the alluvial in the southern edge, whereas, the Siwalik rocks are exposed in the northern margin beside the Himalayan Frontal Fault (HFF) (See Fig. 1). The IGB shows all the foremost components of a foreland basin system, namely an orogen (the Himalaya), deformed foreland basin deposits adjacent to the orogen (Siwalik Hills), a depositional basin (Ganga Plain) and peripheral cratonic bulge (Bundelkhand Plateau) (Singh 1996). IGB established in the Early Miocene, and from Middle Miocene to Middle Pleistocene, the northern part of the IGB was uplifted, and thrust basin-wards; the Ganga plains moved southwards because of thrust loading in the orogen (Singh 1996).

Based on the geophysical study and deep drilling carried out by ONGC, various researchers (Rao 1973; Lyon-Caen and Molnar 1985) depicted the basement structure and sub-surface geology. As per, Rao (1973), the basement thickness of alluvium is $\sim$6 km near the foothill zone and decreases gradually southwards. Addition to variable thickness of sedimentary fill, the Ganga Basin exhibits number of ridges, fills and depressions. The important basement highs are the Delhi-Hardwar ridge in the west, the Faridabad ridge in the middle, the Monghyr-Ghazipur ridge in the east, a poorly developed high in the Mirzapur-Ghazipur area and smaller “highs” of Raxaul, Bahraich and Puranpur. There are two important basins or low areas, namely Gandak and Sarda depressions (see Fig. 1). The densely populated alluvial plain is characterized by the presence of several transverse and oblique subsurface faults. A number of subsurface faults trending NW-SE, WNW-ESE and NE-SW, transverse to the trends of the Himalayan, were reported and most of these are known to be seismically active (Valdiya 1987). The IGB is spatially variable in terms of geomorphology, tectonics, differences in geological deposits, and dynamics of river deposition, all resulting in the presence of different lithological units. MASW survey has been carried out in the entire stretch of IGB to capture the spatial variability in shear wave velocity.

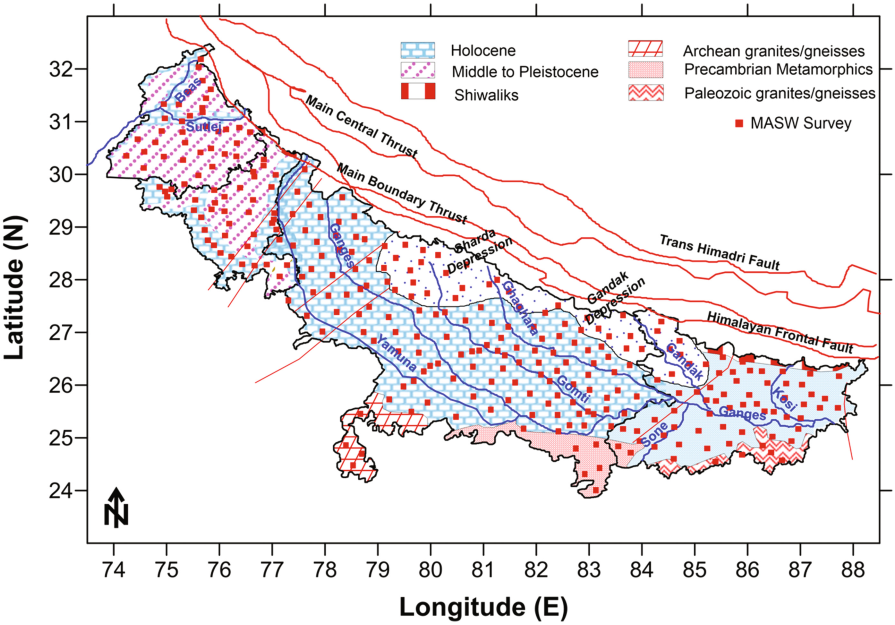

Fig. 1. Geological description of Indo Gangetic Basin along with the MASW survey locations

3 Field Survey

MASW is a geophysical survey that records Rayleigh waves on a multichannel record. It utilizes the dispersion properties of surface waves for determining the shear wave velocity profile in 1D and 2D format. Based on the source of the surface wave recorder, MASW is classified as Active or Passive MASW survey. In case of active MASW survey, surface waves are produced actively through an impact source like a sledgehammer. However, in case of Passive MASW survey, surface waves are produced passively by natural (e.g., thunder and tidal motion) or cultural (e.g., traffic) activities, (Park et al. 2007). The maximum reliable investigation depth is typically shallower than 50 m in case of active MASW survey. However, it can range a few hundred meters in case of passive MASW survey.

The entire process for developing V_s profiles through MASW involves three steps: procurement of ground roll, development of dispersion curve (a plot of phase velocity versus frequency), and back calculation (inversion) of V_s profile from the calculated dispersion curve. Multichannel methods permit a synchronized study of multiple geophone records which allow a transformation from time and space domains to another domain that acknowledges the recognition of energy peaks including the dispersive characteristics of the investigating site (Foti et al. 2001). Various approaches are available for this purpose. The most effective and widely used are the frequency-wavenumber analysis (f-k) and the spatial autocorrelation method (SPAC) proposed by Aki (1957). Analogous to f-k analysis, Park et al. (1998) recommended a transformation algorithm, in which all signals are delayed and summed for a selected phase velocity. This method helps in the determination of a velocity–frequency diagram that demonstrates peaks when the expected value coupled the phase velocity of the wave and allows the identification of dispersion curve. However, this method was generally appropriate for active measurements. Park and Miller (2008) comprehended this algorithm for ambient vibration measurement utilizing the linear arrays alongside a roadside. This method sums up the energy associated with all possible azimuths to construct the velocity–frequency diagram that enables the abstraction of the dispersion curve.

S-wave velocities fundamentally govern the modification in Rayleigh-wave phase velocities in case of a layered earth model. Thus, Rayleigh-wave phase velocities can be used in inverting S wave velocities. V_s profiles are determined from iterative inversion process which needs the dispersion data and approximations of Poisson’s ratio and density. Least-squares approach helps in automation of the process (Xia et al. 1999), it further outlines an objective function and a weighting matrix, derives a solution of minimizing the objective function by the Levenberg–Marquardt (L-M) method and the singular value decomposition (SVD) technique. An iterative solution of a weighted damping equation using the L-M method provides a fast and stable solution. Using the SVD technique, the efficient calculation can be attained by reconstructing a weighted damping solution. In this method, only V_s is restructured after each iteration, with Poisson’s ratio, density, however model thickness remaining unaffected throughout the inversion. As per Xia et al. (1999), the V_s profile is the most important parameter in the inversion process as fluctuations in density or Poisson ratio give insignificant effects in dispersion properties.

4 Data Acquisition and Processing

The raw data is acquired for 275 survey sites along the entire stretch of Indo Gangetic Basin. The data collection covers the major cities of Punjab, Haryana, Uttar Pradesh and Bihar states of India. Data acquisition sites are shown in Fig. 1. At each location, both Active and Passive MASW survey has been done to acquire the data at both shallow and deeper depths. Test setup consists of 24 channel Geode seismographs in combination with 24 vertical geophones with the frequency of 2.0 Hz. An impulsive source of 15-pound sledgehammer striking over a 30 cm × 30 cm size steel plate produces surface waves, in case of active survey. Figure 2 shows the acquisition of active data. However, the amount of energy generated by active source is not sufficient for producing dispersion curve at lower frequencies (e.g., 5–7 Hz). Hence to get the investigation depth of about several hundreds of meters, Passive noise is used. Passive surface waves generated from natural (e.g., tidal motion) or cultural (e.g., traffic) are used for generating low-frequencies (1–30 Hz). Depending on field conditions and type of V_s profiles to be obtained (1D or 2D); Passive MASW is divided into two types, i.e. passive remote and passive roadside MASW surveys. For acquiring the data for Passive MASW survey for the IGB both passive remote and roadside survey have been done; based on the availability of place (See Fig. 2). For obtaining the passive data, a passive roadside acquisition method is used by taking advantage of moving traffic for producing low-frequency ambient noise. Park and Miller (2008) recommended that when accomplishing a roadside surface wave using a linear receiver array, a 2-D dispersion analysis scheme that explains the offline nature of the passive surface waves is required. Hence, for obtaining the raw data using Passive survey, different sampling intervals and recording times are used to enhance the dispersion curve quality. After acquiring the data from both active and passive MASW survey, the individual dispersion curves have been extracted using velocity–frequency diagram.

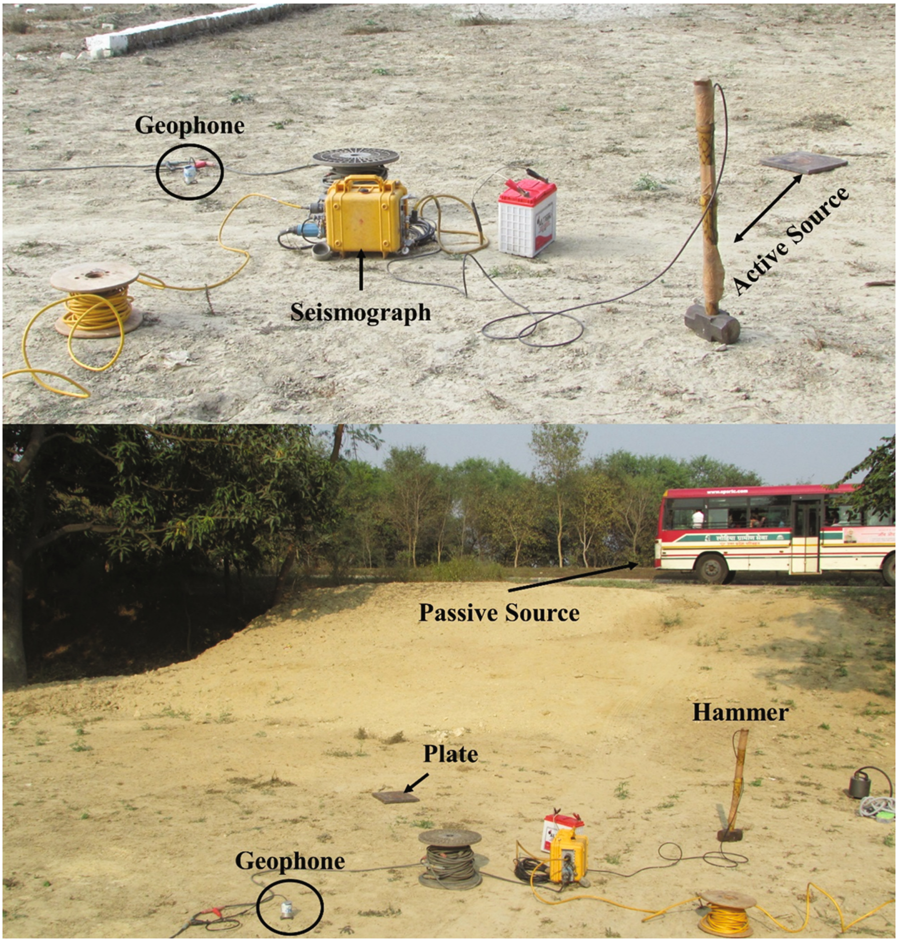

Fig. 2. Multichannel analysis of surface wave instrumentation indicating the sources used in active and passive survey

The obtained raw data has been further processed to obtain the dispersion curve and finally to obtain the 1D shear wave velocity profile. Algorithm for obtaining dispersion curve and V_S profiles through inversion are explained above. For obtaining the V_S profiles, window-based software named 'SurfSeis 5' and 'ParkSEIS 2' has been used.

These software process the Rayleigh type seismic wave and generate V_s profiles by analyzing the fundamental mode of dispersion curve of Rayleigh wave. The dispersion curve for passive as well as active is given as Fig. 3(a) and (b) respectively. For (a) enlarging the analyzable frequency (therefore depth) range of dispersion and (b) identifying the modal nature of dispersion trends, it is useful to combine the dispersion images of active and passive data. Hence, combining the active and passive dispersion image has also studied to quantify the depth corresponding to both lower and upper-frequency range. For most of the data to get the enhanced shear wave velocity at lower as well as deeper depth combined dispersion is used. The dispersion curve for combined data is given as Fig. 3(c).

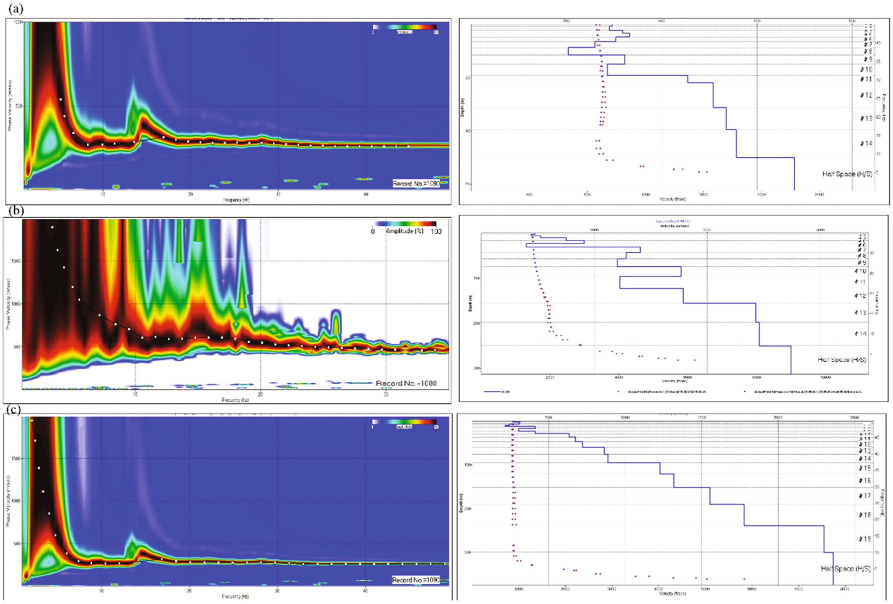

Fig. 3. Typical example of (a) Active, (b) Passive and (c) Combined MASW result for dispersion and shear wave velocity profile

5 Result and Discussion

5.1 Parametric Study on Dispersion Curve and vs Profiles

These are different ways of acquiring data using MASW. Different parameters, like recording time, sampling interval, number of geophones, geophone spacing governs the prediction of dispersion curve. This on other hand affects the layering and shear wave velocity of the site. Hence, in this study for different sites, these parameters are evaluated and variation on dispersion curve and V_s profiles are determined. For recording the passive data different recording time, sampling intervals, polarity and gain is tested. For example, data has been acquired for 120 s by changing the sampling interval as

8 ms, 4 ms and 2 ms and gain as high and low gain. Typical dispersion curve and V_s profiles for four cases have been given as Fig. 4(a). Case A1, A2, A3 and A4 corresponding to recording time interval of 60 s with sampling interval of 10, 8, 4 and 2 ms respectively. A significant change is observed at lower frequencies, due to that there is a variation in velocity at deeper depths. Standard deviation of 10 to 25 m/s is observed within a depth of 50 m. Further for the same site the data is recorded for different time intervals viz. 10, 30, 60 and 120 s. These cases are respectively referred as Case B1, B2, B3 and B4 in Fig. 4(b). Significant variation in dispersion curve is observed at lower frequencies, which affect the velocity at deeper depths. The difference of 150 to 200 m/s is observed at a depth more than 150 m. This may be due to the variability in traffic density and traffic loading. Hence, while capturing the passive data, recording must be done for different time intervals to obtain the proper energy bands at all the frequencies. Similarly, change in gain and for different recording time, there is a change in dispersion curve and corresponding variation in shear wave velocity. Hence for the final study, average of all the survey at same location has been used. You can also add how much error and difference.

Considering the dispersion curves and the corresponding velocity at different layers for various parameters for data recording following points are concluded

(1) The passive recording must be done for longer period, i.e. more than 60 s with larger sampling interval
(2) In case the traffic density is low, combined active and passive survey need to be done
(3) In case of poor energy bands, combining two passive images enhances the image to extract the dispersion curve
(4) To obtain the velocity at shallow as well as deeper depths both active and passive image need to be combined at the same site
(5) It is always good to do multiple experiments at a site, and average velocity need to be given.

5.2 Typical Comparison of vs with SPT-N Value and Lithology

SPT is a widely used in-situ test in a borehole to evaluate geotechnical properties of soil. The preliminary study has been done to compare the SPT N-value with the derived shear wave velocity at sites in Haryana, Punjab and Uttar Pradesh. All the recorded data has been used to compare the SPT N value and based on that input setting has been done for further data recording. The compared SPT N value and recorded V_s profile is given as Fig. 5(a). For different locations, V_s is compared with the SPT N value data and typical comparison is presented in Fig. 5(a). It can be seen that recorded shear wave velocity profiles is following almost the same trend as compared to SPT N value.

The lithology is also compared with the shear wave velocity profile developed in these regions using MASW and given as Fig. 5(b). On an average six shear wave velocity profiles are taken near to each of the sites where lithology is known. The average the shear wave velocity profiles obtained in each region is compared with the lithology profiles. It can be seen that the for 100 m thick idealized lithology profiles given by Singh (1996) is compared with the shear wave velocity profiles obtained in the present study. The V_s profile obtained in this study shows the three-distinct region

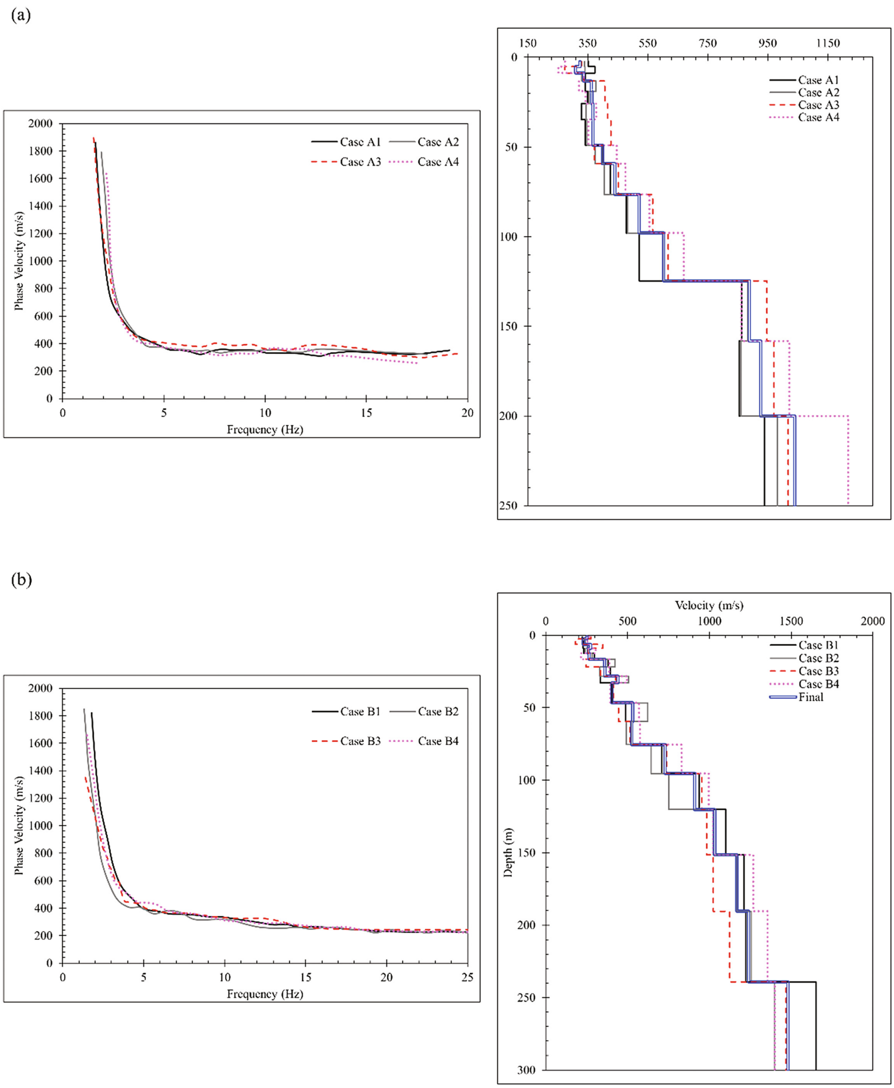

Fig. 4. Typical example of variation of dispersion curve and shear wave velocity profile for variability in (a) sample interval and (b) time of recording data acquisition

(a) a high gradient, low-velocity near-surface region, (2) an intermediate region with shear wave velocities of about 400–450 m/s, and (3) a high-velocity region at depth with velocities increasing to 600–800 m/s.

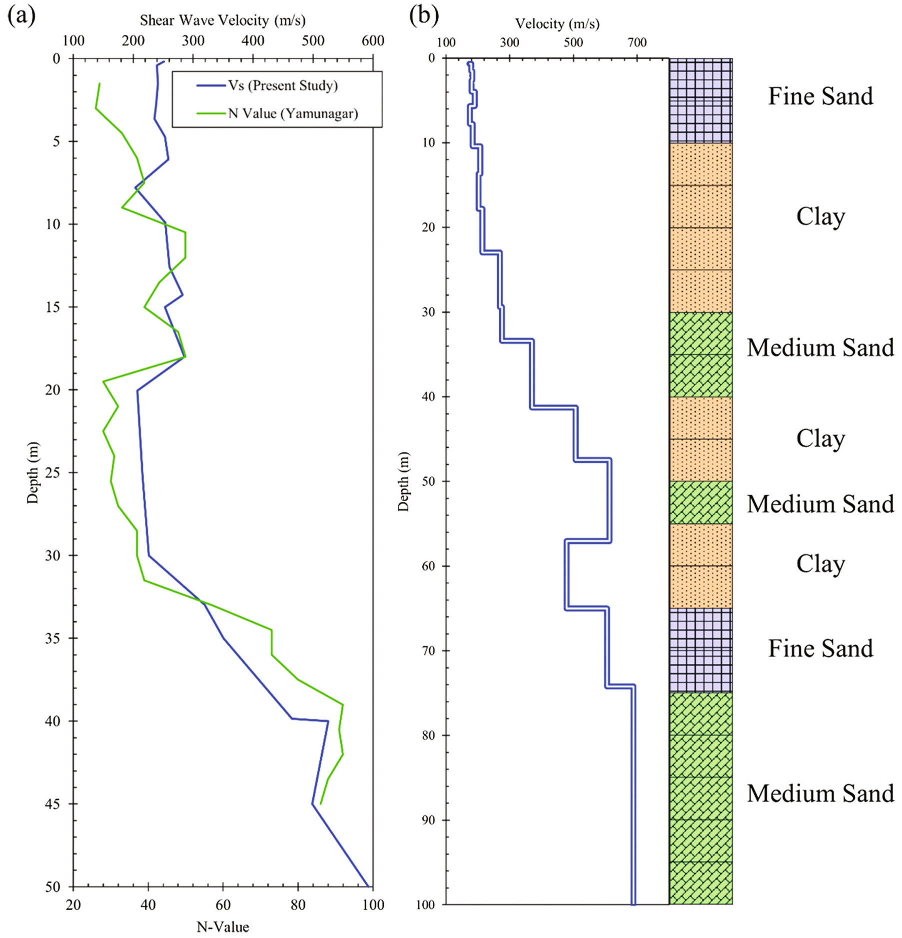

Fig. 5. Typical variation of shear wave velocity with (a) SPT-N value and (b) lithology

5.3 Seismic Site Classification

The shear wave velocity profiles have been developed for 275 sites in Indo Gangetic Basin. The time-averaged shear wave velocity at top 30 m has been calculated using

$$V_{s30} = \frac{\sum_{1}^{N} d_i}{\sum_{1}^{N} \frac{d_i}{V_{si}}} \tag{1}$$

where, d_i is the thickness of layer i and V_{si} is the shear wave velocity of the layer i and V_{s30} is the time average shear wave velocity in the top 30 m. Time average shear wave velocity up to 30 m depth has been calculated for all the entire IGB. Figure 6 shows the variation of V_{s30} along the IGB. The sites have been classified as per National Hazard Reduction Program (NEHRP, BSSC 2003). Profiles with $V_{s30} > 1500$ m/s,

$760 < V_{s30} \leq 1500$ m/s, $360 < V_{s30} \leq 760$ m/s, $180 < V_{s30} \leq 360$ m/s and $V_{s30} < 180$ m/s respectively correspond to Site class A, B, C, D and E.

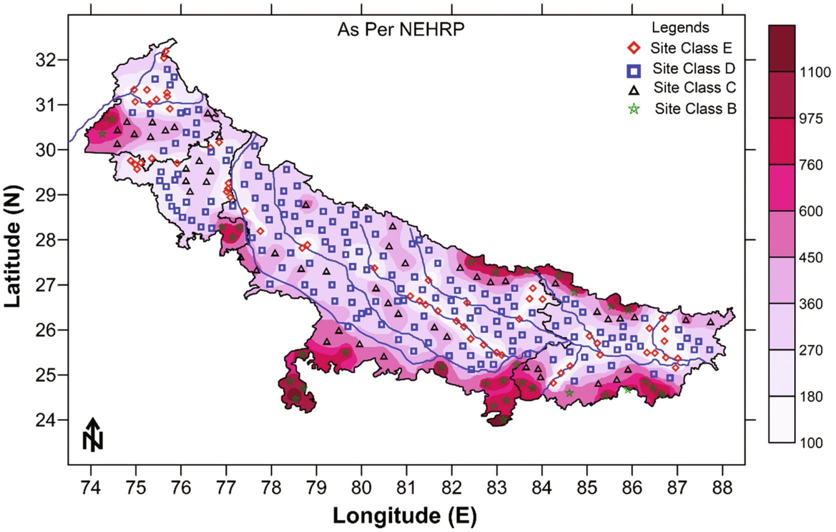

Fig. 6. Spatial variation of V_{s30} along the entire stretch of IGB with seismic site classification as per NEHRP

About 22% of the sites in Bihar is having V_{s30} between 153–180 m/s and classified as site class E. Majority of the sites in Uttar Pradesh is of site class D, however in Punjab and Haryana, mostly site class are either C or D. For Punjab and Haryana region, V_{s30} varies from 160 to 180 m/s, 206 to 340 m/s, 382 to 620 m/s and 795 to 1251 m/s respectively for site class E, D, C and B. For Uttar Pradesh, V_{s30} varies from 157 to 180 m/s, 247 to 358 m/s, 401 to 630 m/s and 822 to 1136 m/s respectively for site class E, D, C and B. For Bihar region V_{s30} varies from 153 to 180 m/s, 214 to 354 m/s, 387 to 615 m/s and 795 to 1152 m/s respectively for site class E, D, C and B.

Further the spatial variation of V_{s30} is compared with the existing geological map of the IGB (See Fig. 1). Most of the sites near to the Kosi, Satluj and Gomti river is of seismic site class E; this may be due to the active sedimentation since Quaternary. Channel alluvium is made up of medium to coarse sand near to Ghaggar river, hence V_{s30} variation is from 180 to 360 m/s. Further near to Sutlej river, low velocity is observed which is due to the presence of silt and clay along its territory. Most of the area of Uttar Pradesh having V_{s30} between 270 to 450 m/s. It is due to the presence of Varanasi Older Alluvium of the Quaternary sediments followed disconformably by Newer alluvium. Most of the sites in the southwest side of Yamuna in UPR is of site class B, which may be due to the presence of Bundelkhand Faridabad ridge and Archean granites and Precambrian Metamorphic (See Fig. 1). Similarly, due to the presence of Munger-Saharsa Ridge and Paleozoic granite in the south of Ganga in Bihar, most of the sites are either site class B or C. Many of the sites in northeast side of Uttar Pradesh and Bihar region is of site class B and C, which may be due to the presence of Siwalik Hills (See Fig. 1).

It can be noticed here that even though V_{s30} is widely used for seismic site characterization, but soil depth extends beyond 100 m. So, the applicability of V_{s30} moreover, its connection with actual amplification need to be examined for IGB region.

6 Conclusions

In addition to earthquake magnitude and its distance from the epicentre, soil characteristic places a major role in the extent of damages at any site due to any seismic event. In this study, an attempt has been made to determine the shear velocity profile up to 400 m depth using combined active and passive multichannel analysis of surface wave survey in 275 selected locations in IGB. Acquisition and processing of the obtained data has been explained to get the V_s profiles at shallower as well as deeper depths. Parametric study has been done to identify the variation in dispersion and V_s profiles by recording time, different sampling interval, different polarity and gain. On an average the difference of 5 to 50 m/s is observed for shallow depth and 150 to 250 m/s at deeper depths in V_s It has seen see that changing any parameter during data recording may result in variation in V_s. Passive recording need to be done for more than 60 s and to combined active and passive data should be collected in case of low background noise. Further, these sites are classified and characterized based on time-averaged V_s in the upper 30 m depth as per NEHRP seismic site classification. For Punjab and Haryana region, V_{s30} varies from 160 to 180 m/s, 206 to 340 m/s, 382 to 620 m/s and 795 to 1251 m/s respectively for site class E, D, C and B. For Uttar Pradesh, V_{s30} varies from 157 to 180 m/s, 247 to 358 m/s, 401 to 630 m/s and 822 to 1136 m/s respectively for site class E, D, C and B. For Bihar region V_{s30} varies from 153 to 180 m/s, 214 to 354 m/s, 387 to 615 m/s and 795 to 1152 m/s respectively for site class E, D, C and B. This is the first time such extensive study was carried out in IGB for V_s determination at deep and shallow depths.

Acknowledgment. The authors thank the Science and Engineering Research Board (SERB) of the Department of Science and Technology (DST), India for funding the project titled "Measurement of shear wave velocity at deep soil sites and site response studies", Ref: SERB/F/162/2015-2016. Authors also thanked to Geological Society of India for providing the Geological and Lithological map required for the study. The authors would like to extend their sincere appreciation to the Deanship of Scientific Research at King Saud University for funding Research group NO. (RG -1435-09).

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