Methodology for site-response studies using multi-channel analysis of surface wave technique in Dehradun city

A. K. Mahajan[1,*], Rob J. Sporry[3], P. K. Champati Ray[2], Rajiv Ranjan[2], Siefko Slob[3] and Westen Cees Van[3]

[1]Wadia Institute of Himalayan Geology, 33, GMS Road, Dehradun 248 001, India
[2]Indian Institute of Remote Sensing, Kali Das Road, Dehradun 248 001, India
[3]International Institute for Geo-information and Earth Observations, Enschede, The Netherlands

Two-dimensional shear wave velocity investigation using the multi-channel analysis of surface waves helps identify lateral and vertical variations of shear wave velocity at shallow depth. This information is required for predicting the ground motion response to earthquakes in areas underlain by thick soil cover. At one such area in Dehradun, at the foothills of the Himalaya, shear wave velocities of the near-surface soil were determined for 50 locations covering almost all representative units with respect to variation in local geology and geomorphology. Based on the average shear wave velocities of the upper 30 m of the soil, sites located in the south-southwestern and central part of the city are predominantly classified as class 'D' (180–360 m/s) except a few locations like Clement Town (site no. 43) and Majra (site no. 48), which can be classified as class 'E' due to very low shear wave velocity, in accordance with the NEHRP 1997 provision. The northern part of Dehradun city shows high velocities, ranging from 300 m/s at the surface to more than 700 m/s at depth of 30 m. These sites located in the northern and eastern parts of the city with average shear wave velocity (V_S) values more than 360 m/s have been classified as class 'C' site (360–760 m/s). The characteristic period estimated for each site of the soil column varies from 1.5 to 3.12 Hz. Based on the shear wave velocity, input motion, static and dynamic properties of different soil layers, site-response spectrum and amplification functions have been derived. The response spectrum suggests spectral acceleration value for two-storey structures of 3 to 8 times higher than the peak ground acceleration at the bed rock level, i.e. 0.05 *g*. The analysis also suggests peak amplification at 3–4, 2–2.5 and 1–1.5 Hz in the northern, central and south-southwestern parts of the city respectively.

Keywords: Multichannel analysis of surface waves, shear wave velocity, site-response studies.

SITE amplification is one of the important factors that control damage in urban areas due to large and moderate earthquakes. Recently, many studies have demonstrated that surface geology plays an important role in altering the observed seismic motion and thereby its damage potential. The amplitude and frequency content of the ground motion from an earthquake can be greatly influenced by properties such as impedance contrast and composition of the near-surface material. Moreover, seismic hazard calculations utilize attenuation function and soil amplification factors, which include the effect of ruptures, crustal structure and its effect on surface geology, soil column thickness and dynamic properties. Earthquake ground-motion response in thick soils requires knowledge of shear wave velocity and its variation in 2D. The ground motion amplitude/amplification depends primarily on the density and shear wave velocity of near-surface material. Since density has relatively less variation with depth, shear wave velocity is the logical choice for representing variations in site conditions[1,2]. The importance of field measurements of shear wave velocity was also highlighted[3] during an investigation on seismic microzonation of Delhi. Assuming that the shear wave velocity up to 30 m depth is the dominant factor in site amplification, it has been estimated using the multi-channel analysis of surface waves (MASW) technique, with an objective to produce a scenario on spatial variability of ground motion in different parts of Dehradun city.

Geological and geomorphological setting

Dehradun city is located in the intermontane valley within the Siwalik foreland basin of Garhwal Himalaya (Figure 1). It is a crescent-shaped, longitudinal and synclinal valley controlled by a series of tectonic faults on all sides. Most prominently it is bounded by the Main Boundary Thrust (MBT) that brings the Precambrian rocks of the Lesser Himalaya in contact with the Siwalik Group of rocks forming the northern boundary of the Doon Valley. The southern boundary of the Doon Valley is marked by the anticlinal structure known as Mohand anticline that in turn is separated from the plains in the south by the Himala-

*For correspondence. (e-mail: mahajan@wihg.res.in)

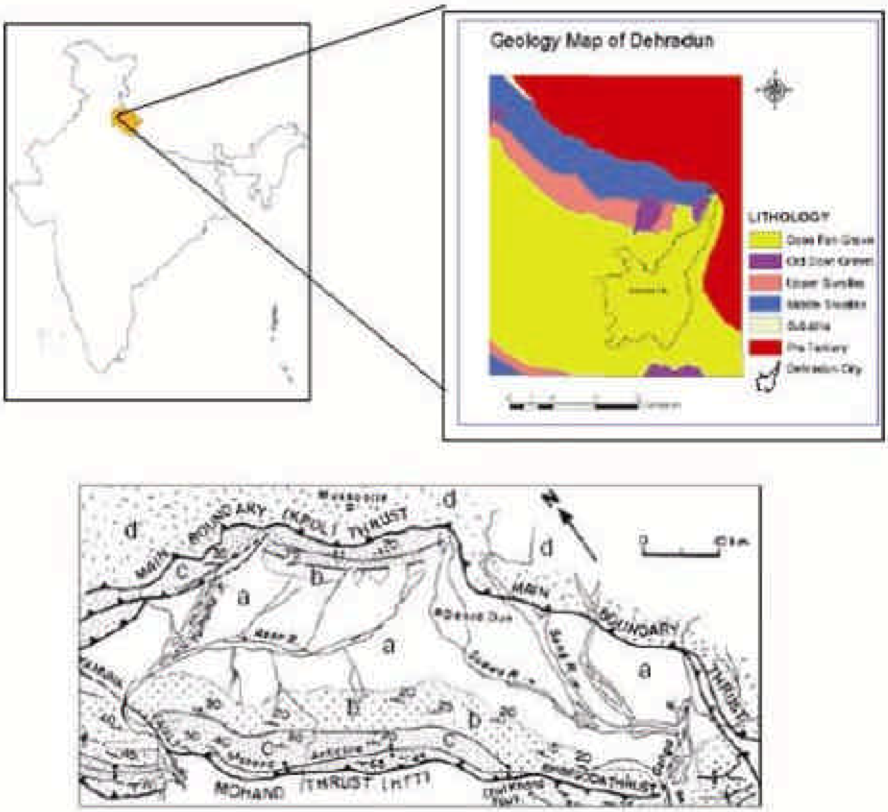

Figure 1. Geological map of the study area. (Inset) Location map and regional tectonic map of Dehradun valley (after Thakur[4]).

yan Frontal Thrust (HFT), locally known as the Mohand Thrust[4]. On the east and west, it is bounded by two prominent strike-slip faults known as Ganga Tear Fault and Yamuna Tear Fault respectively.

Doon Valley mainly consists of coalescing fan deposits derived from the Lesser Himalayan rocks in the north and Siwalik Group of rocks in the south. The fan deposits mainly consist of pebbles and gravels, with pockets of clay. The Doon gravels at places are hard and compact due to the presence of lime and clay acting as cementing material. The degree of compaction increases with depth. The depth level of this bed varies from 15 m in the north and central parts to more than 30 m in south-southwestern part of the city. Auden[5] postulated that the Doon gravels are underlain by Upper Siwalik deposits, which are lithologically similar to the former. The study area covering the entire urban part of the Doon Valley consists mainly of fan deposits, with the exception of the northern part, where Siwalik sandstones are exposed on the surface (Figure 2). Geomorphologically, Dehradun city can be differentiated into two major geomorphic surfaces[6]. These are the hilltop surface (residual hills) and piedmont surface (which can be further divided into Middle Dun Surface (MDS) and Lower Dun Surface (LDS)). The hilltop surface consists of thick boulder gravel beds, including boulders as large as 2 m across, occurring at the crest of the residual hills in the northern part of the city. Both the piedmont surfaces (MDS and LDS) comprise less consolidated and weathered gravel beds. The LDS is recognized as the lowest alluvial fan of the major tributaries of the Ganga and Yamuna rivers in the central part of the Doon Valley. This surface is composed of boulder gravel beds that overlay the finer deposits of the MDS. The thickness of the LDS is not more than 10 m, but the surface is quite extensive on which Dehradun city is located[6,7].

Multi-channel analysis of surface waves

MASW is a nondestructive seismic method to evaluate thickness and shear wave velocity of the soil column. This technique and a standard common depth point (CDP) roll along acquisition format is similar to conventional seismic reflections for petroleum exploration and is mainly used to construct a vertical section of the near-surface shear wave velocity. Both the dispersion curve and the ellipticity of Rayleigh waves are controlled by the subsurface velocity structure. In principle, one can invert either of them for shear wave velocity. Surface waves traditionally have been viewed as noise on multi-channel seismic data designed to image environmental, engineering, and groundwater targets by reflection seismic techniques[8]. The concept of spectral analysis of surface waves (SASW) using multi-channel seismic acquisition methods as commonly used for petroleum exploration[9], has been extended to estimate 1D shear wave velocities using a multi-channel approach of data acquisition, that permits the generation of a laterally continuous 2D shear wave velocity cross-section[10,11]. Similar to the SASW approach, the MASW method derives V_s wave velocities for a layered earth model by inverting Rayleigh wave phase velocities. The MASW technique was tested at several sites in the Fraser river delta using a 24-channel array of vertical broadband geophones (4.5 Hz) at 5 m spacing[12]. In the present study, this technique has been applied in Dehradun to determine the shear wave velocity at shallow depth and subsequently site characterizations. In this method, a one-dimensional shear wave velocity profile is obtained by inverting phase velocities. This 1D profile appears to be most representative of the materials directly below the middle of a geophone spread. Multiple 1D profiles of *S*-wave velocity are generated as the source and receivers roll along a survey line. Finally, a two-dimensional vertical cross-section of *S*-wave velocity is generated by combining all 1D shear wave velocity profiles. The combination of inverting the phase velocity for shear wave velocity and the standard CDP roll-along acquisition format makes this an effective and time-efficient method of imaging two-dimensional shear wave velocity along a survey line.

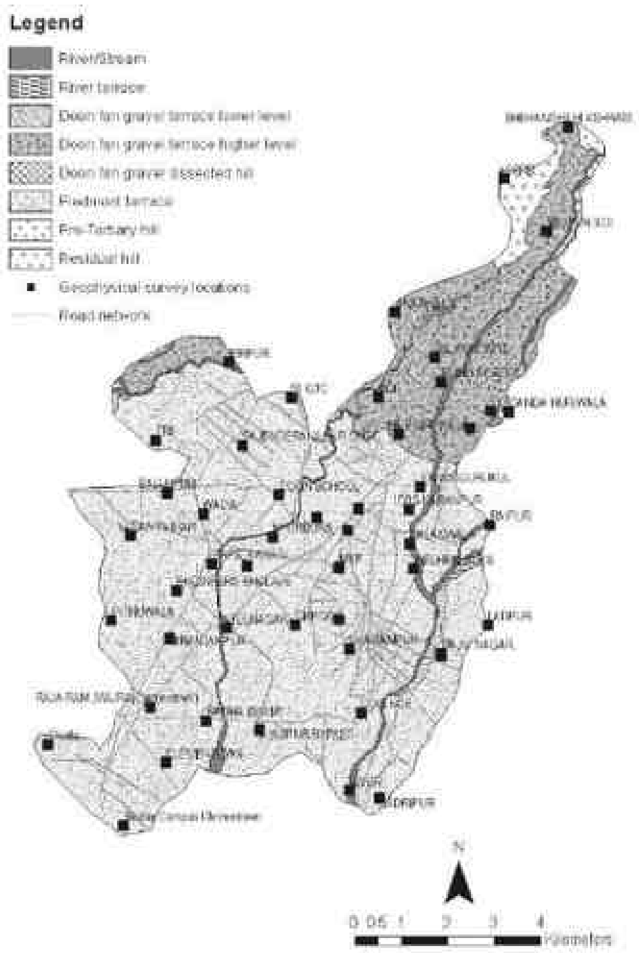

Figure 2. Geomorphological map of Dehradun city, modified after Nossin[7] and Nakata[6].

Acquisition and processing of surface wave data

Acquisition of MASW data requires open space to carry out the survey at the desired location. Many urban areas such as Dehradun provide limited open space to survey long profiles. However, based on high-resolution satellite data (IKONOS and IRS-PAN) and field observations, open spaces corresponding to school playgrounds and parade grounds were selected within city limit and eventually data were acquired at fifty such sites (Figure 3 *a*) covering the entire Dehradun city using a 24-channel seismograph (Geometrics Geode), with 14 Hz geophones. An instrumented sledge hammer weighing 8 kg and a 1 sq. ft metal plate of 2.5 cm thickness were used as a source. Using a roll-along technique and keeping 12 channels active at a time, a total of 36–48 traces have been recorded in different sites depending upon the availability of ground length (Figure 3 *b*).

The entire process of generating the V_s profile through the MASW method involves three steps, i.e. acquisition of ground rolls, construction of dispersion curves (a plot of phase velocity vs frequency), from which 1D profile of shear wave (V_s) values for ten-layers earth model was obtained using the SurfSeis 1.5 software, which utilizes the inversion algorithm of Xia *et al*.[11]. Combination of a sequence of individual 1D profiles produced a 2D section, presenting the variation of shear wave velocity in horizontal and vertical direction.

Data processing was performed using the SurfSeis 1.5 software, developed by Park and Brohammer[13] at Kansas Geological Survey (KGS). This package offers a complete suit of routines to perform data conversion from SEG2 to KGS format, displaying quality control of data and preparation of walk-away spreads (24 to 36 traces). Before running the dispersion analysis (surface wave velocity and frequency distribution), a wide range of pre-processing options were executed. Under this option the program tries to estimate the optimum range, increment of frequencies and optimum (upper and lower) bounds of phase velocity. After viewing the overtone image of the record and analysing the frequency spectra, parameters can be changed on the control panel and dispersion analysis can be performed as summarized by Park *et al*.[14]. Dispersion analysis results in the generation of a dispersion curve for each geophone station (Figure 3 *c*).

Analysis

According to our experiment carried out at different sites, significant amount of surface wave energy has been recorded at frequencies as low as 7 Hz (Figure 4). According to Park and Brohammer[13], 40 Hz geophones showed significant amount of surface wave energy at frequencies as low as 5 Hz. In Dehradun city it was also possible to record significant energy at 7 to 20 Hz and phase velocity up to 900–1000 m/s (Figure 4)[15]. Similar investigation[16] carried out using 10 Hz geophones also showed equally strong energy at lower frequency of 5 Hz. It has been observed that the lower frequency limits of high frequency geophones are not limited by their natural frequency. According to Park *et al.*[17], the 10 Hz geophones give almost identical results as the 4.5 Hz geophones all the way down to 5 Hz, while the 40 Hz geophone recorded down to about 10 Hz. Therefore, it seems that 10 to 40 Hz geophones can be used to record surface waves as low as 5 to 10 Hz in most cases. In the present investigation, the depth of penetration goes up to 30 m in general and 40–60 m in some cases. The estimated shear wave velocity shows high signal-to-noise ratio, suggesting high confidence level in the obtained phase velocity–frequency curve. Selected shear wave velocity profiles obtained at representative sites have been presented to provide a detailed description of the sub-surface information.

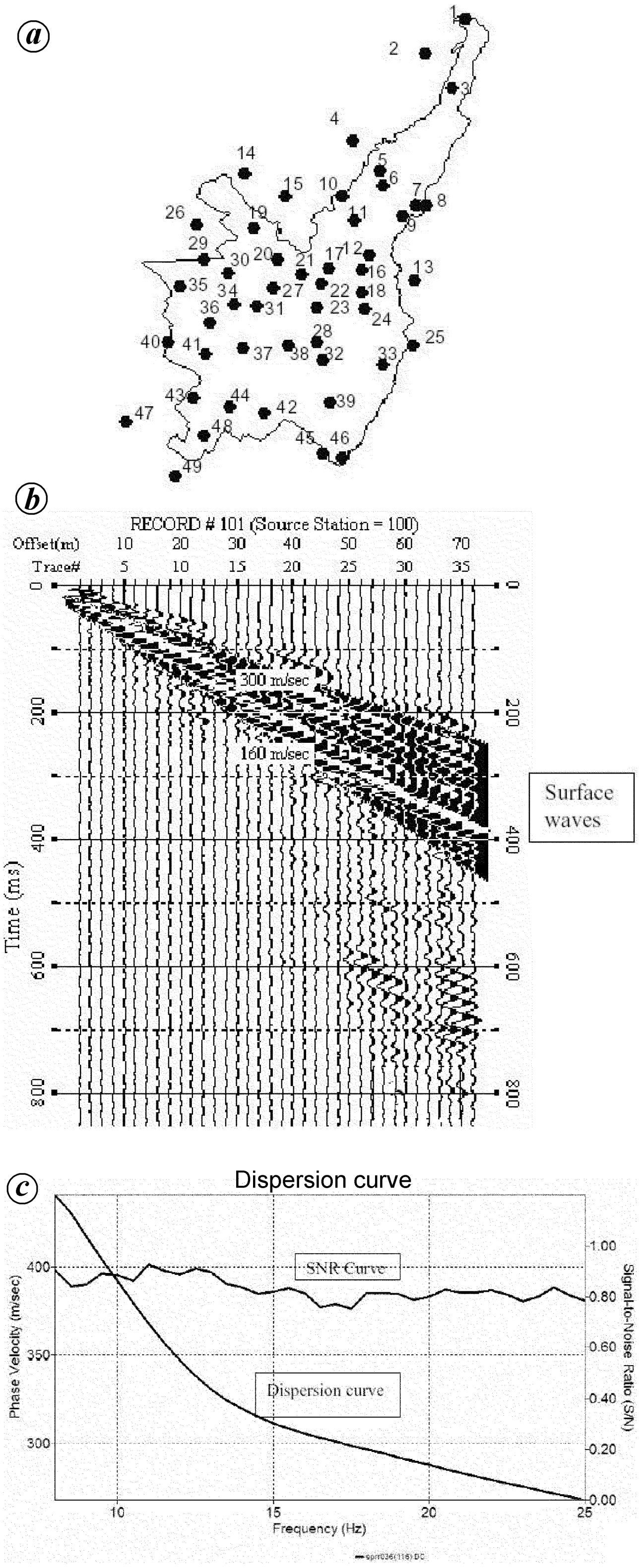

Figure 3. ***a***, Location of different shear wave velocity profiles. ***b***, Configuration of field parameters. ***c***, Formatting of raw data from SEG to KGS format.

Site-specific results

In the northern part of the city, the shear wave velocity is higher compared to sites located in the middle and south-western parts of the city. The shear wave velocity in this part of the city varies from almost 220 m/s at the top to about 700 m/s at a depth of 30 m, as recorded at a representative SPRR site no. 2 (Figure 5 *a*). This location shows a velocity inversion between 9 and 13 m depth, suggesting erosion and deposition of Doon fan gravels of different time period and composition. Velocity variation between 17 and 27 m depth may indicate heterogeneity of the sub-surface. Shear wave velocity variation at a depth of almost 30–31 m represents the bed rock level as the area is close to MBT and bed rock is exposed along the nearby river

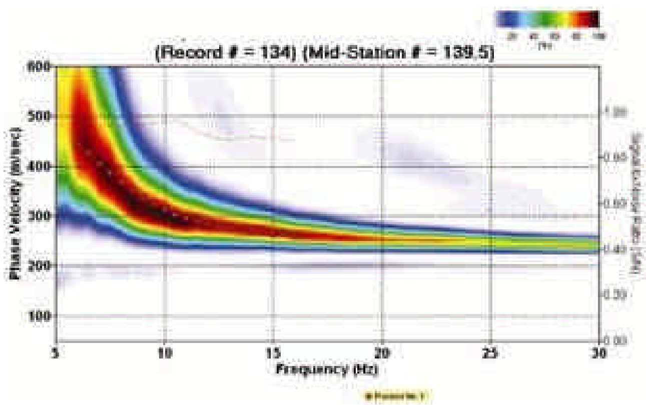

Figure 4. Dispersion curve (frequency vs phase velocity) depicting overtone image. For frequencies as low as 7 Hz, significant amount of energy of surface waves has been recorded using 14 Hz geophones from Danda Nuriwala site.

cuttings. The low root mean square error in estimating shear wave velocity in this site suggests higher reliability in the estimated value (Figure 5 *b*).

At Anarwala site no. 4, the survey line runs in the east-west direction located in the northern part of the city near Anarwala village. Surface wave data from this site show a usable band from 8 to 20 Hz, allowing investigation up to a depth of 45 m. Three to four layers can be identified on the basis of shear wave velocity variation in depth (Figure 6 *a*). The first layer is about 8–10 m thick with a velocity up to 330 m/s; the second layer is 10–22 m thick with a velocity up to 600 m/s, and the third layer is observed at 22–40 m depth with velocity close to 700 m/s. This underlying formation seems to have been incised at stations 109–110 to a depth of around 45 m. This incision and absence of the layer beyond station 128 could be attributed to erosion. High velocity at the bottom of the section may represent the layer equivalent of bedrock. Variations in velocity within the third layer at station 110 and from station 122 up to 136 may be due to degree of compaction or variation in composition. The low-velocity zone located below station location 116 is attributed to the presence of palaeo-channel/cavity. A joint exercise carried out using resistivity imaging, MASW reflection and time domain electromagnetic survey shows the same anomaly at same location and depth[18].

Surface wave data from Danda Nuriwala at site no. 8 show a usable frequency band from 6 to 20 Hz (Figure 4). The shear wave velocity profile shows an investigation depth up to 60 m, with an RMS error value of less than 2. The profile suggests a three-layer model: the top layer up to 15–17 m mostly consists of river terrace deposits (coarse sand mixed with clay) and has a shear wave velocity > 250 m/s; the second layer from 17 to 50+ m shows shear wave velocity ranging from 475 to 600 m/s, which could be due to the presence of gravel beds mixed with sand or stiff soil, and the third layer, with a thickness of about 8–10 m shows velocity more than 750 m/s, which can also be grouped in the dense soil. The bottom layer represents the half space with velocity more than 900 m/s (Figure 6 *b*).

At Darawala site (site no. 40) in the southwestern part of the city, the shear wave velocity section shows broadly three layers (Figure 6 *c*). The top-most layer shows low velocity in the upper 10 m of soil cover, mainly representing the clay horizon (*S*-wave velocity less than 180 m/s). Below 10 m up to a depth 30 m, the material has a velocity in the range 200–350 m/s, and increases further to 450 m/s beyond 30 m. Thus this site has been classified as class 'E' according to National Earthquake Hazard Reduction Program (NEHRP), USA classification.

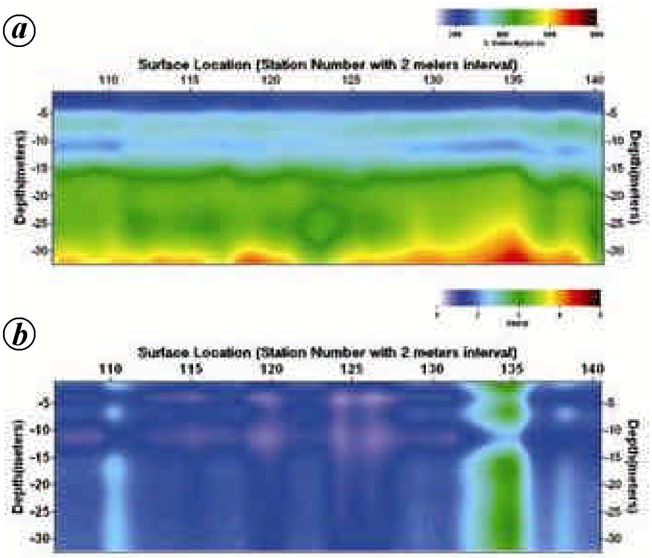

Figure 5. Shear wave velocity section at Surya Prasth Ashram (SPRR site no. 2) trending southwest-northeast.

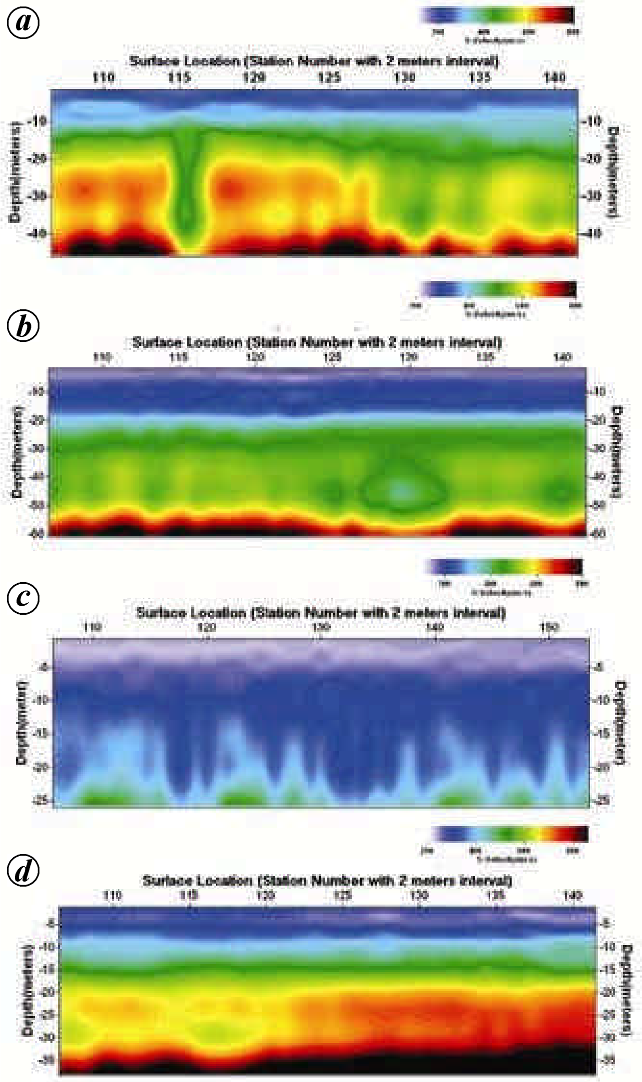

Figure 6. Shear wave velocity profile at (***a***) Anarwala (site no. 4) trending east-west, (***b***) Danda Nuriwala site (site no. 8) trending north-west-southeast, (***c***) Darawala site (site no. 40) trending south/south-west-north/northeast and (***d***) Badripur site (site no. 46) trending southwest-northeast.

Badripur (site no. 46) located southeast of Dehradun shows horizontal layers of different formations (Figure 6 *d*). The survey line was aligned in the east-west direction with a gentle slope from west to east. Surface wave data collected from this site have a frequency range of 10–24 Hz. The maximum investigation depth of 35 m has been attained with an RMS error of about 1. High signal-to-noise ratio indicates high confidence in the obtained phase velocity–frequency curve. The top layer of the river terrace (8–9 m) has an average shear wave velocity of about 300 m/s. The second layer goes down to a depth of almost 16 m, showing an average shear wave velocity of 500 m/s and the third layer extends to a depth of around 30–34 m with a shear wave velocity of 700 m/s. This layer can be classified as dense soil. The deepest layer has a shear wave velocity of more than 900 m/s and may represent the bed-rock level.

Variation of shear wave velocity with depth in different parts of the city indicates change in composition and thickness of the sediments deposited during different time periods. A sharp boundary has been identified at many sites that may represent the Doon gravels with some degree of compaction. The velocity of Doon gravel is found to be around 600 m/s and above. The depth of onset of Doon gravels varies from north to south and southwest. It is shallower in the north and deeper in the southwestern part of the city.

Site characterization

The local site condition profoundly influences the effect of ground motion that has been demonstrated during earthquakes triggered around the world as well as in India during the 1905 Kangra, 1991 Uttarkashi, 1999 Chamoli and 2001 Bhuj earthquakes. Seismic microzonation aims to divide the area in small zones to display the variation in seismic response of the subsurface and subsequently determines where ground motion is likely to be amplified to a level that may cause damage to existing buildings and/or other structures at that location. Frequently, peak ground acceleration is used to determine the maximum expected horizontal forces. However, merely determining the spatial variation of peak ground acceleration is not adequate, as peak acceleration often corresponds to high frequencies which are out of range of the natural frequencies of most structures. Therefore, large values of peak ground acceleration alone may not be the cause of large-scale damage in many cases[19].

Therefore, during site characterization it is necessary to determine the variation in soil stratification and engineering properties of soil and rock layers observed at the site. Wills and Silva[20] suggested the use of shear wave velocity for classifying site conditions rather than geological units. However, the geological map may be regarded as basic information to plan detailed site investigations and to control the reliability of the results obtained by site characterization and site response. According to Slob *et al.*[21], propagation is particularly affected by the local geology and geotechnical ground conditions. Therefore, borehole data and lithology exposed along the river sections were compared with shear wave velocity data for defining layers. The nature and distribution of earthquake damage is strongly influenced by the response of soils to cyclic loading. The behaviour of soil subjected to cyclic loading is governed by dynamic soil properties such as stiffness, damping, Poisson ratio and density. Therefore, in the present study, dynamic soil properties were analysed using a 1D ground response model as given in the 'SHAKE2000' program[22,23]. It simulates the net effect of rock-level motion propagating vertically through the soil layers, as in the case of a one-dimensional medium, to arrive at the surface in a modified fashion by incorporating nonlinear effects and layering properties of soil horizons.

Characterization of input parameters

In the present study for SHAKE2000 analysis, one of the most important input parameters, actual strong motion data of Chamoli earthquake (6.8) recorded at Tehri site (80 km from the epicentre) has been considered as the reference input motion to display variation in site amplification at different places in Dehradun city. Other input parameters such as shear wave velocity as a measure of stiffness and layer thickness were taken from MASW analysis as described before. Each 2D shear wave velocity profile has been averaged into three to four layers vertically, assuming lateral homogeneity in the layers. In the present case the upper 30 m of soil horizon is considered with the following reasoning. In engineering site investigations, 30 m is a typical depth of boring and detailed site characterizations. Therefore, most of the site effect studies[24–27] in earthquake ground motion are based on the properties in the upper 30 m. According to Borcherdt[27], the upper 30 m soil column is considered to be responsible for site amplification. This has been incorporated by NEHRP[28], for classification of sites on the basis of average shear wave velocity of the column. Anderson *et al.*[25] have also used the upper 30 m column of the soil for ground-motion analysis. Recently, a comprehensive study to identify soil deposits susceptible to ground-motion amplification in the Central United States has revealed that the 30 m depth is a conservative estimate; if little or no information is available for greater depths, the 30 m assumption may be adequate to estimate site response[29]. Therefore, in the present case the upper 30 m of soil column was considered for ground response analysis.

In the Dehradun region, the upper 30–40 m of soil column mainly consists of 3–4 layers: the first layer consists of surface clay mixed with sand, the second layer mainly consists of sand in combination with boulders/pebbles/gravels and can be considered equivalent to rock-fill layer, the third layer consists of Holocene conglomerate, mostly gravel, boulder in combination with sand, silt and clay, and the last dominant layer mainly consists of massive boulders with minor clay, equivalent of the Upper Siwalik boulder bed. However, borehole data and geophysical survey suggest that these layers do not occur uniformly at all the places. One example can be cited from the central part of the city at Forest Research Institute (FRI) site no. 26, which shows an average velocity of around 180 m/s for the upper 8–10 m of soil cover (Figure 7). In the next 6 m the velocity changes to 350 m/s, thus representing change in layer composition. At a depth of 16 m, the velocity changes to more than 400 m/s, indicating presence of gravels, pebbles mixed with clay, sand and lime that can be considered equivalent to rock-fill. At a depth of 30 m the velocity changes to 600 m/s, representing compact cemented gravel beds. Inference on material composition is also confirmed by the litholog of a site close to FRI (Figure 7). Similar observations can also be made from the representative shear wave velocity profiles obtained from the northeast to southwestern parts of the city (Figure 8). The top-most layers show velocity of about 200 m/s, which is thin in northeastern part compared to south-southwestern part of the city. The second layer shows velocity of 200–400 m/s, followed by a layer showing velocity of 400–600 m/s and the last layer shows velocity more than 600 m/s, suggesting the presence of boulder layers similar to the Upper Siwalik boulder beds.

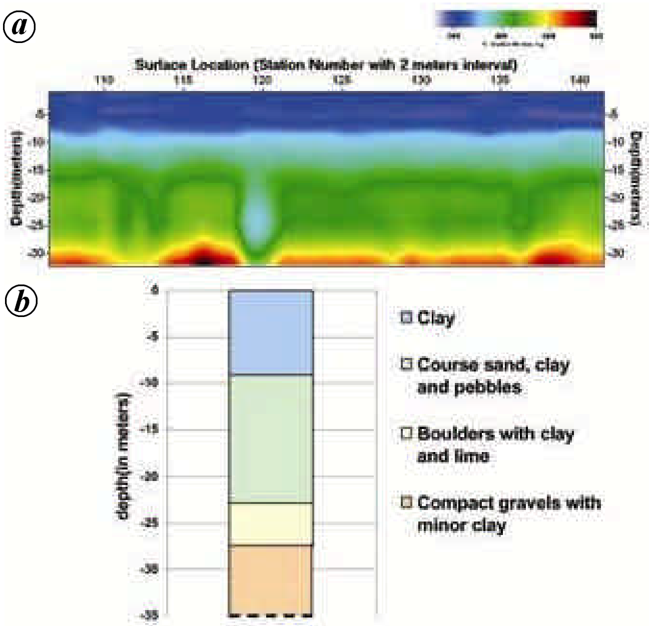

Figure 7. ***a***, Shear wave velocity profile in the Forest Research Institute (FRI) site no. 26. The profile shows 10 m of upper layer having V_s of about 200 m/s that increases to 500 m/s at a depth of 30 m. The second layer is thick in this section compared to site no. 2. ***b***, Tubewell litholog of a site close to FRI site no. 26 and corresponding V_s profile.

As the variation in geotechnical properties of the individual soil layers could not be modelled due to lack of data, the static and dynamic soil properties, like shear modulus, damping ratio and unit weight have been taken from the database of material properties provided with SHAKE2000 for corresponding materials as observed in tube well lithologs and shear wave velocity profiles[30–34]. Shear wave velocity and layer thickness have been taken directly from the geophysical database with different unit weight values for clay (0.108), rock-fill (0.114), gravels (0.12) and rock (0.146).

Output of site-response analyses

The SHAKE2000 program based on defined input parameters provides information about natural period and average shear wave velocity of the soil column, shear modulus, maximum stress, maximum strain and peak acceleration. The average shear wave velocity, natural period and response spectra of different sites have been added to the attribute table of the site location map for visualization in ARC GIS. The values have been interpolated and produced in grid format with output cell size of 200 m × 200 m. The whole range of the data values has been classified into a number of classes using natural breakpoints.

According to the shear wave velocity map, six zones have been identified in the city with different velocity ranges (Figure 9). However, based on the NEHRP classification[28], three main zones have been identified: Zone-I covers sites under Class ‘E’ (V_s < 180 m/s), i.e. area in the extreme southern part of the city. Zone-II covers majority of the city that can be classified as Class ‘D’ (V_s = 180–360 m/s). Zone-III corresponds to the northern and southeastern parts of the city that can be classified as Class ‘C’ (V_s = 360–760 m/s). Average shear wave velocity of the soil

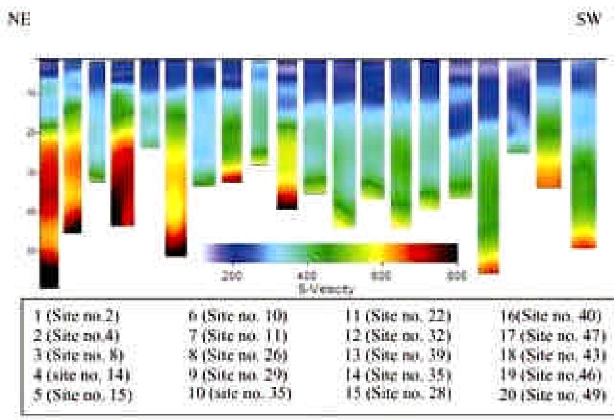

Figure 8. Shear wave velocity section for 20 sites located from northeastern to southwestern parts of the city indicating variation in depth of various soil layers. The top-most layer with a velocity of about 200 m/s is thin in northeastern part compared to the south-southwestern part of the city.

column is slightly higher in the northern and southeastern parts of the city, whereas the southwestern parts of the city shows low shear wave velocity. This is attributed to the presence of thick alluvial deposits (up to 30 m) with shear wave velocity less than 350 m/s, e.g. site nos 47, 40 and 49. The northern and southeastern parts of the city are represented by high shear wave velocity below 20 m depth (site nos 2 and 46). This could be attributed to the presence of thin fan deposits underlain by *in situ* rock which has higher stiffness than the piedmont terrace deposits, generally found in the central and southern parts of the city.

Most importantly, SHAKE2000 provides response spectrum that has been computed between sub-layer no. 1 and the outcrop using different damping ratios, i.e. 0.03, 0.05, 0.1 and 0.2. The response spectrum represents maximum response of a single degree-of-freedom (SDOF) system to a particular input motion as a function of natural frequency and damping ratio, and is normally used to model the response of the structures widely used in the field of engineering for construction[35]. The response spectrum for each site has been derived using SHAKE2000 software for different damping levels, 5 and 10% and frequencies such as 5 and 10 Hz. The response spectrum of three different representative sites is shown in Figure 10. The spectral acceleration values at 5 and 10 Hz have been calculated from the response spectrum and added in the attribute table of the site location map, to prepare spectral acceleration maps using Arc View/Arc GIS (Figure 11 *a* and *b*).

The characteristic site period (or natural frequency) is the period (or frequency) at which the soil column will resonate, resulting in the largest possible amplifications. The characteristic period for each site has been estimated using the SHAKE2000 program that shows variation from 0.75 s (almost 1.3 Hz) in the south-southwestern parts of the city to 0.24 s (4.2 Hz) in the northern parts of the city.

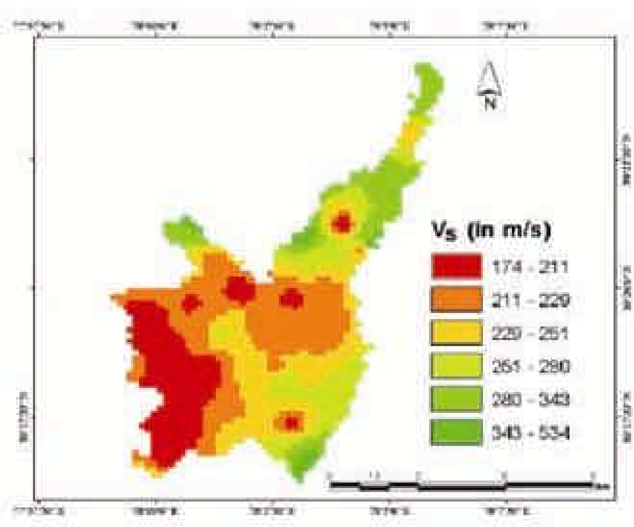

Figure 9. Mean shear wave velocity map of Dehradun city.

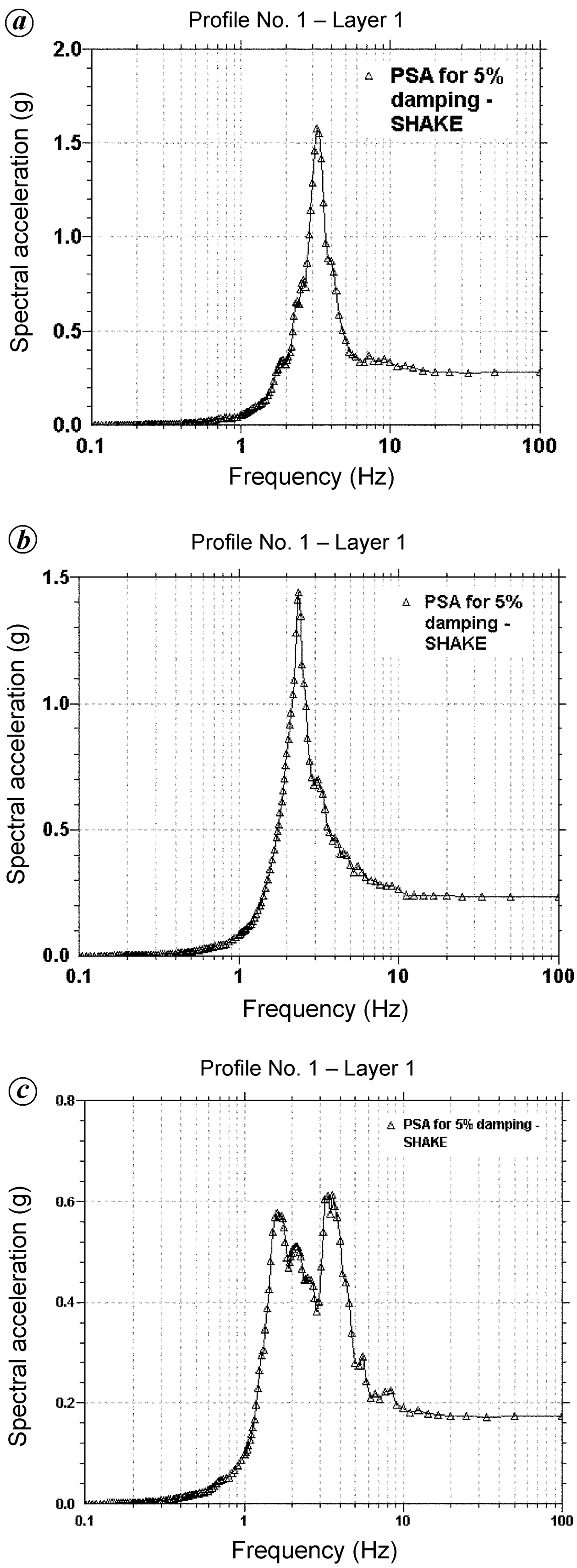

Figure 10. Response curve of Surya Prasth Ashram (***a***), Anarwala (***b***), Darawala (***c***) sites at 5% damping.

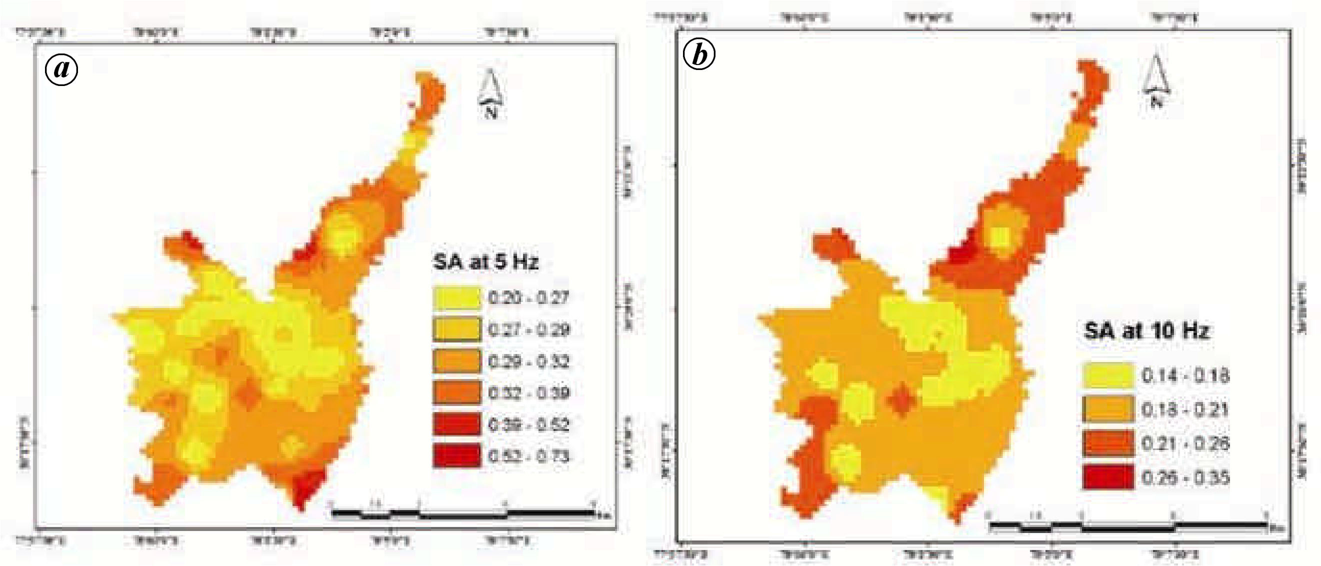

Figure 11. Seismic microzonation map in terms of spectral acceleration at 5% damping for 5 Hz (***a***) and 10 Hz (***b***) frequency.

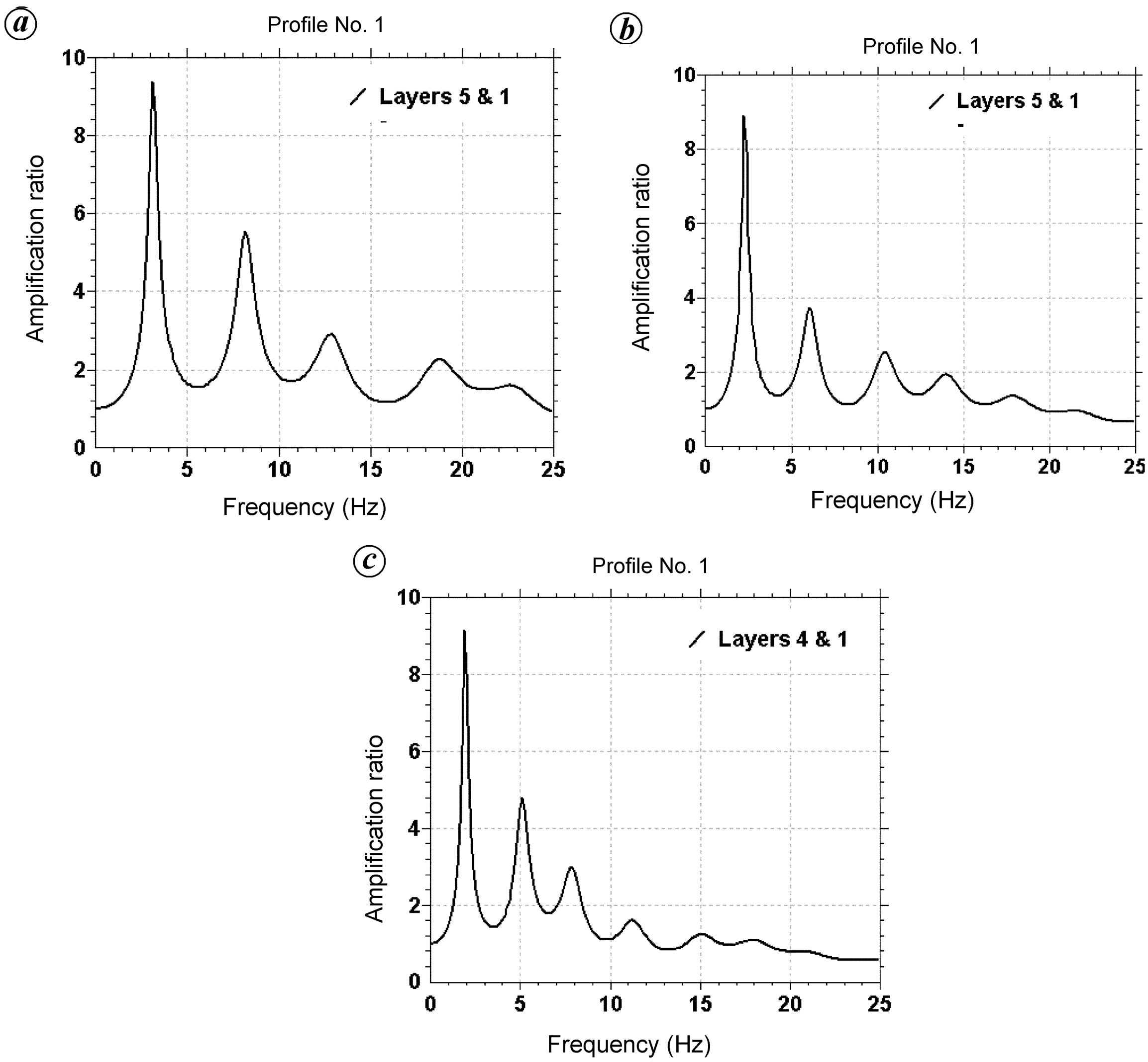

Figure 12. Amplification spectrum for Surya Prasth Ashram (***a***), Anarwala (***b***) and Darawala (***c***) between the top and bottom layers of each shear wave velocity profile.

Since Dehradun city is mainly covered by fan deposits which are a product of weathering, erosion and deposition over a long period of time, it is natural to expect higher amplification at many places. The amplification function derived between the free surface and the bedrock shows a peak at ≥3 Hz in the northern part (site nos 1, 2 and 3) of the city, 2–2.5 Hz in the middle of the city (e.g. sites nos 4, 11, 16, 17, 18, 21 and 22) and 1–1.75 Hz in the south and southwestern parts of the city (site nos 40, 41, 43, 44, 47, 48 and 49; Figure 12). This suggests less thickness of alluvial sediments in the northern parts of the city compared to the south and southwestern parts. Observation of microtremors also reveals amplification in frequency range such as 0.8–2 Hz in the south and southwest zone, 2–3 Hz in the central zone and 4–8 Hz in the northern zone[36], which is in good agreement with results of the present study. Similar comparison between results obtained by MASW and refraction microtremor shows deviation within 15% in the frequency range of 1–10 Hz, thus validating the reliability of such investigations[37].

Using the Chamoli earthquake strong motion data (horizontal component) and the shear wave velocity of each site in Dehradun city, spectral acceleration values have been derived using the SHAKE2000 software. The spectral acceleration values range from 0.14 to 0.36 *g* (10 Hz frequency) for single-storey buildings and 0.24 to 0.74 *g* for double-storey buildings (5 Hz frequency). The response spectrum suggests spectral acceleration values for two-storey structures of the order 3 to 8 times higher than peak ground acceleration at bed-rock level, i.e. 0.05 *g*. The analysis also suggests peak amplification at 3–4, 2–2.5 and 1–1.5 Hz in the northern, central and south-southwestern parts of the city respectively (Figure 12). If the magnitude of the earthquake increases to 8.0, acceleration could be different for single- and two-storey buildings. However, the present analysis shows variation in spectral acceleration in different sites of Dehradun city based on actual shear wave velocity data obtained through MASW technique.

Conclusion

The study demonstrates the potential of MASW-based shear wave velocity measurement that was considered as one of the main inputs for generating scenarios of seismic hazard in different parts of Dehradun city. Based on the above methodology, shear wave velocity for each site has been derived for the upper 30 m of soil column and site amplification has been derived with respect to a reference input motion. Based on the average *S*-wave velocities of the upper 30 m of the soil, sites within the heart of Dehradun city (LDS) are classified as Class 'D' (180–360 m/s) in accordance with the NEHRP 1997 provision. Sites located close to hilltop surface (residual hills) and MDS showed average *S*-wave velocity greater than 360 m/s, thereby qualifying them as Class 'C' (360–760 m/s). Areas with very low shear wave velocity show amplification at 1.5 Hz, whereas those with higher shear wave velocity show peak amplification at 4 Hz. The peak of the response spectrum, i.e. spectral accelerations is consistent with the characteristic period of each site. Different scenarios of spectral acceleration have been presented using reference strong motion data. The major limitation has been the non-availability of strong motion data recorded at Dehradun. Nevertheless, the present study provides basic information on prevailing site conditions in different part of Dehradun city. It also provides a sound basis for taking up future investigation for site response and vulnerability analysis in urban areas.

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