J Seismol (2007) 11:355–370
DOI 10.1007/s10950-007-9055-1

ORIGINAL ARTICLE

Seismic microzonation of Dehradun City using geophysical and geotechnical characteristics in the upper 30 m of soil column

A. K. Mahajan · Siefko Slob · Rajiv Ranjan ·
Rob Sporry · P. K. Champati ray ·
Cees J. van Westen

Received: 23 November 2006 / Accepted: 4 May 2007 / Published online: 24 July 2007

Abstract The understanding of geotechnical characteristics of near-surface material is of fundamental interest in seismic microzonation. Shear wave velocity (Vs), one of the most important soil properties for soil response modeling, has been evaluated through seismic profiling using the multichannel analysis of surface waves in the city of Dehradun situated along the foothills of northwest Himalaya. Fifty sites in the city have been investigated with survey lines between 72 and 96 m in length. Multiple 1-D and interpolated 2-D profiles have been generated up to a depth of 30–40 m. The Vs were used in the SHAKE2000 software in combination with seismic input motion of the recent Chamoli earthquake to obtain site response and amplification spectra. The estimated Vs are higher in the northern part of the study area (i.e., 200–700 m/s from the surface to a depth of about 30 m) as compared to the south and southwestern parts of the city (i.e., 180–400 m/s for the same depth range). The response spectra suggest that spectral acceleration values for two-story structures are three to eight times higher than peak ground acceleration at bedrock. 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. The spatial distributions of Vs and spectral accelerations provide valuable information for the seismic microzonation in different parts of the urban area of Dehradun.

Keywords Seismic microzonation · Shear wave velocity (Vs) · Spectral acceleration · Response spectrum · Multichannel analysis of surface waves (MASW) · SHAKE2000 · Northwest Himalaya

1 Introduction

The unconsolidated materials of young sedimentary basins can have a profound effect on the spatial distribution of earthquake ground motion amplification, resulting in a large variation in the severity of damage to buildings, transportation corridors, and other lifeline infrastructures. This has been experienced during the earthquakes of Mexico City in 1985, San

---

A. K. Mahajan (✉)
Wadia Institute of Himalayan Geology,
33 GMS Road, Dehradun, India
e-mail: mahajan@wihg.res.in

S. Slob · R. Sporry · C. J. van Westen
International Institute for Geo-information Science
and Earth Observation (ITC),
7500 AA Enschede, The Netherlands

R. Ranjan
RMSI, Sector 16, A-7, Noida, India

P. K. Champati ray
Indian Institute of Remote Sensing,
4-Kalidas Road, Dehradun, India
e-mail: champati_ray@iirs.gov.in

Francisco in 1989, Los Angeles in 1995, and Ahmedabad (India) in 2001. To be able to carry out a seismic microzonation study for such sedimentary basins, a large amount of input data is required on the 3-D structure of the basin, the stratigraphy of the unconsolidated deposits, and their geotechnical and geophysical characteristics (Kramer 1996). In many locations in developing countries, such data are lacking or only available for a few sites.

The purpose of this study is to demonstrate a methodology for soil response modeling that is applicable in areas with limited subsurface information. Soil response modeling requires many input parameters related to subsurface conditions, many of which are difficult to obtain through geotechnical and geophysical investigations (Slob et al. 2002). Among all elastic parameters of materials, shear wave velocity (Vs) is considered the best indicator of stiffness (Bullen 1963; Aki and Richards 1980), and therefore, it has long been recognized as a key factor in ground motion amplification and site response in sedimentary basins (Borcherdt 1970). It is used as an important parameter in building codes and design applications (Kramer 1996; Street et al. 2001). In the present study, Vs of near surface material was determined using the technique of multichannel analysis of surface waves (MASW) (Miller et al. 1999; Xia et al. 2000), and site response modeling was carried out using SHAKE2000. The city of Dehradun, in northern India, was used a test area.

2 Geological and Geomorphological setting

Dehradun City is located in the broad intermontane depression, known as Doon valley within the Siwalik foreland basin of Garhwal Himalaya (see Fig. 1). The Doon valley is a crescent-shaped, longitudinal, synclinal valley bounded in the north by the main boundary thrust, where pre-Tertiary rocks of the Lesser Himalaya zone override the Tertiary rocks from the Siwalik group. The southern margin of the Doon valley is marked by a sudden break in topography defined by the Himalayan Frontal Thrust, locally known as the Mohand Thrust (Thakur 1995), where the rocks from the Siwalik group override the recent alluvial sediments towards the south (Fig. 1). Doon valley is bounded in the east by the Ganga tear fault and in the west by the Yamuna tear fault.

On the seismic hazard map of India, this area is located in the second highest category (zone 4) and damages to buildings were reported due to earthquakes of Kangra in 1905, Uttarkashi in 1991, and Chamoli in 1999 (Middlemiss 1910; Kumar and Mahajan 1993; Mahajan and Virdi 2001). Paleoseismic evidences, active tectonics, and seismic hazard studies of the region indicate (Thakur and Pandey 2004; Phillip 1995; Mahajan et al. 2002) that this area is situated in a very high seismic hazard zone. Seismic hazard studies and vulnerability analysis predict that an overdue Himalayan earthquake similar to the Kangra earthquake in 1905 could cause as many as 200,000 fatalities, most of which would be likely to occur in growing urban centers like Dehradun (Bilham et al. 2001; Arya 2000).

Doon valley is primarily underlain by piedmont fan deposits, locally known as Doon gravels, which overlay the Siwalik rocks. Doon gravels consist of gravel beds that become coarse with depth, with occasional clay lenses and layers. Doon gravels are absent in the northern part of Dehradun City, where Siwalik rocks are exposed, and increase in thickness towards the south (see Fig. 1). The maximum depth of the Doon gravels is estimated to be several hundred meters in the middle of Doon valley; however, at depths of more than 40–50 m, Doon gravels resemble the underlying upper Siwalik rocks dominated by sandstone and boulder conglomerates (Auden 1936). The Doon gravels are cemented in some locations due to possible lime enrichment from the nearby limestone of the Lesser Himalaya (see Fig. 1). The depth of this cemented layer varies from 20–25 m in the northern and central part to more than 30 m in the south-southwestern part of the city, whereas in the southeastern side, the depth is even less than 25 m.

Geomorphologically, the Dehradun area can be differentiated into two major geomorphic surfaces identified as the hilltop surface (residual hill) and the piedmont surface (Singh et al. 2004). The latter can be further divided into middle Doon surface (MDS) and lower Doon surface (LDS), which were already described by Nossin (1971) and Nakata (1972). The hilltop surface consists of thick boulder and gravel beds with boulders as large as 2 m occurring near the flat crest of the residual hills in the northernmost part of the city. Both of the piedmont surfaces (LDS and MDS) comprise less consolidated and weathered gravel beds. The LDS

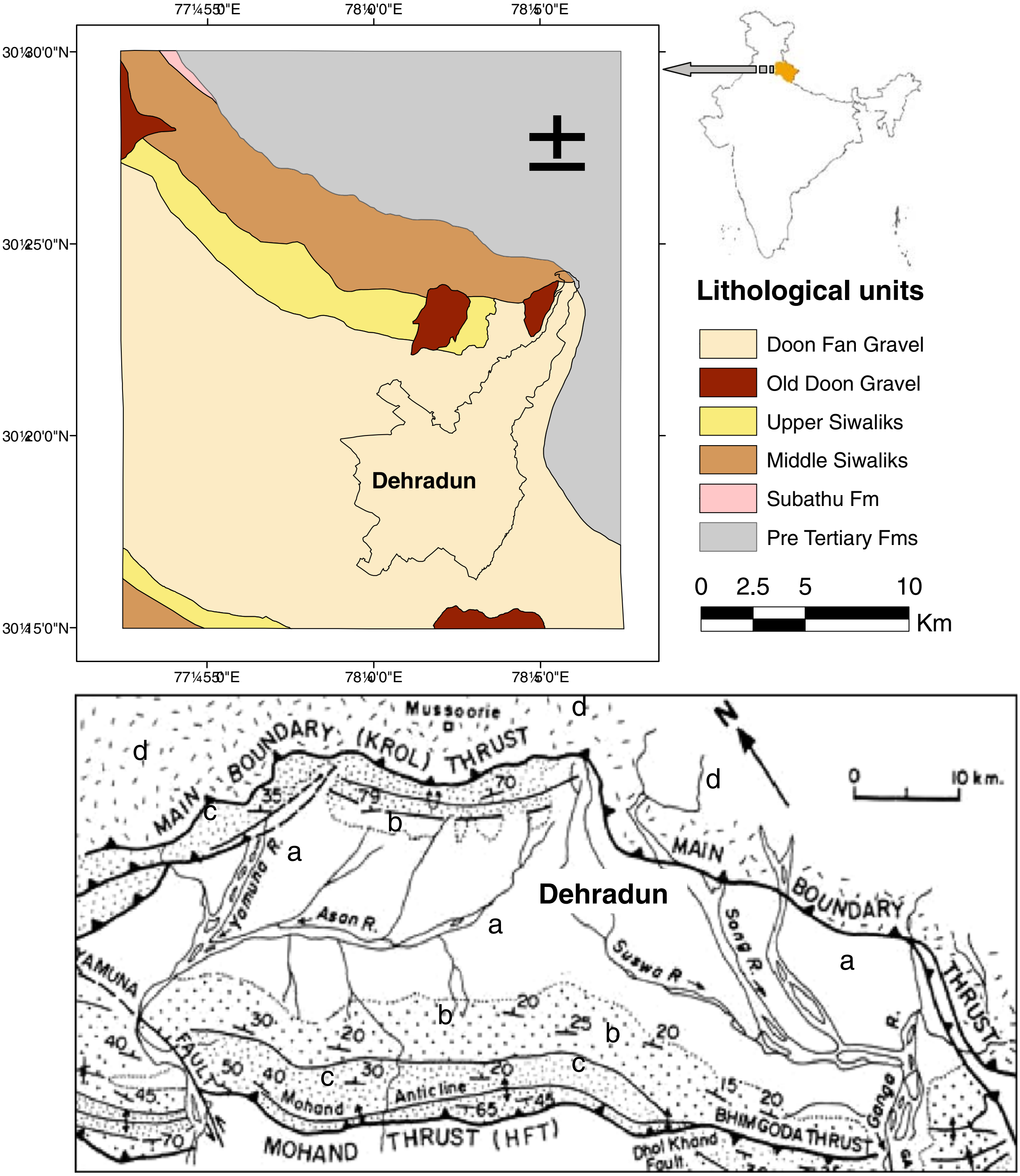


Fig. 1 Location map with regional geology and tectonics of Dehradun region (after Thakur 1995). *a* Doon fan, *b* upper Siwalik group, *c* middle Siwalik group, and *d* pre-Tertiary rocks

(piedmont terrace), which is found mostly in the central part of the Doon valley, is recognized as the lowest alluvial fan deposit of the major tributaries of the Ganga and Yamuna rivers. The deposits related to the LDS are less than 10 m and are underlain by the less coarse deposits of the middle Dun surface (Doon fan gravels), which cover most of the Dehradun area (Nakata 1972).

3 Multichannel analysis of surface waves

The analysis of fundamental mode Rayleigh waves was one of the most common ways to use the dispersive properties of surface waves. The extraction of different modes by dispersion analysis of surface waves has been demonstrated by a number of authors in the past, indicating the wealth of information available in the surface wave spectrum (Bullen 1963; Mooney and Bolt 1966; Tsai and Aki 1969; Mitchell 1973). The presence of more than one single surface wave mode in a surface wave spectrum was first resolved by developing the multiple filter analysis technique to determine the group velocity of dispersed waves (Dziewonski et al. 1969). Herrmann (1973) used narrow band pass filtering of multimode surface wave signals to extract information concerning the group velocity and spectral amplitude of each mode. The incorporation of the spectral analysis of surface waves technique, developed for civil engineering application with multitrace seismic acquisition method commonly used for petroleum exploration, shows good potential for detecting, and in some cases delineating, anomalous subsurface materials (Nazarian et al. 1983). The concept has been extended to multichannel data acquisition and processing by Park et al. (1999) and Xia et al. (1999). The multichannel approach has been extensively used to investigate surface waves by extracting fundamental mode dispersion curves (Ivanov et al. 2000; Park et al. 2002). Xia et al. (2000) have demonstrated the MASW technique to extract the fundamental mode in surface wave spectrum from shot records using phase velocity. The multichannel approach to dispersion curve analyses and the large receiver spread are key parameters in the MASW technique to handle noises like direct waves, refracted waves, guided waves, air waves, and higher modes of surface waves (Ivanov et al. 2000). This approach can significantly improve the signal-to-noise ratio (SNR), as well as pattern recognition that enables the identification of different types of seismic waves from their arrival and attenuation patterns (Park et al. 1998). The MASW method is a relatively new and noninvasive method to evaluate Vs using the dispersive properties of Rayleigh waves and has been successfully used in a number of studies (Xia et al. 1999, 2000, 2002; Park et al. 1999; Tian et al. 2003).

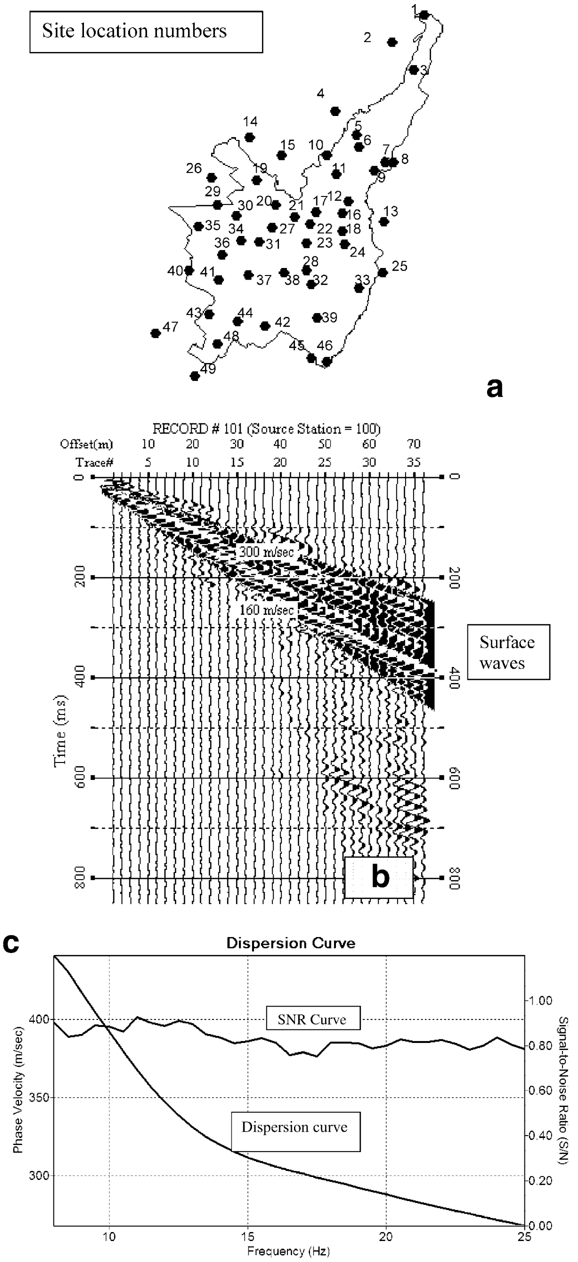


Fig. 2 **a** Location of sites for Vs measurement with administrative boundary. **b** Seismic record with preprocessing parameters showing optimum ranges of frequency and phase velocity. **c** Dispersion curve of Surya Prasth Ashram site no. 2

4 Acquisition and processing of surface wave data

Geophysical survey poses challenges in thickly populated urban areas such as Dehradun, as very little free space is available for long survey lines. However, in Dehradun, it was possible to carry out surveys at selected school playgrounds and parade grounds that were large enough for such surveys, and seismic noise generated by traffic in the streets was also very limited or nonexistent. At 50 such selected locations (Fig. 2a), data were acquired using a 24-channel seismograph (Geometrics Geode) unit with 14-Hz geophones and an 8-kg sledge hammer as a source. A small rectangular (12×12 in) metal plate was used as a strike plate to maximize energy transfer between the hammer and the ground. Multiple shot gathers were collected along a linear survey line of 72–96 m by moving both the source and the receiver spread in a manner similar to common depth point roll-along technique used in conventional seismic reflection survey. For each measurement, a number of hammer blows was used to enhance the signal.

Data processing was carried out using SurfSeis 1.5 software, developed by the Kansas Geological Survey (Park and Brohammer 2003). The raw seismic data (SEG-2) were first converted into Kansas Geological Survey format, combining all shot gathers for processing into a single file. Field geometry was assigned

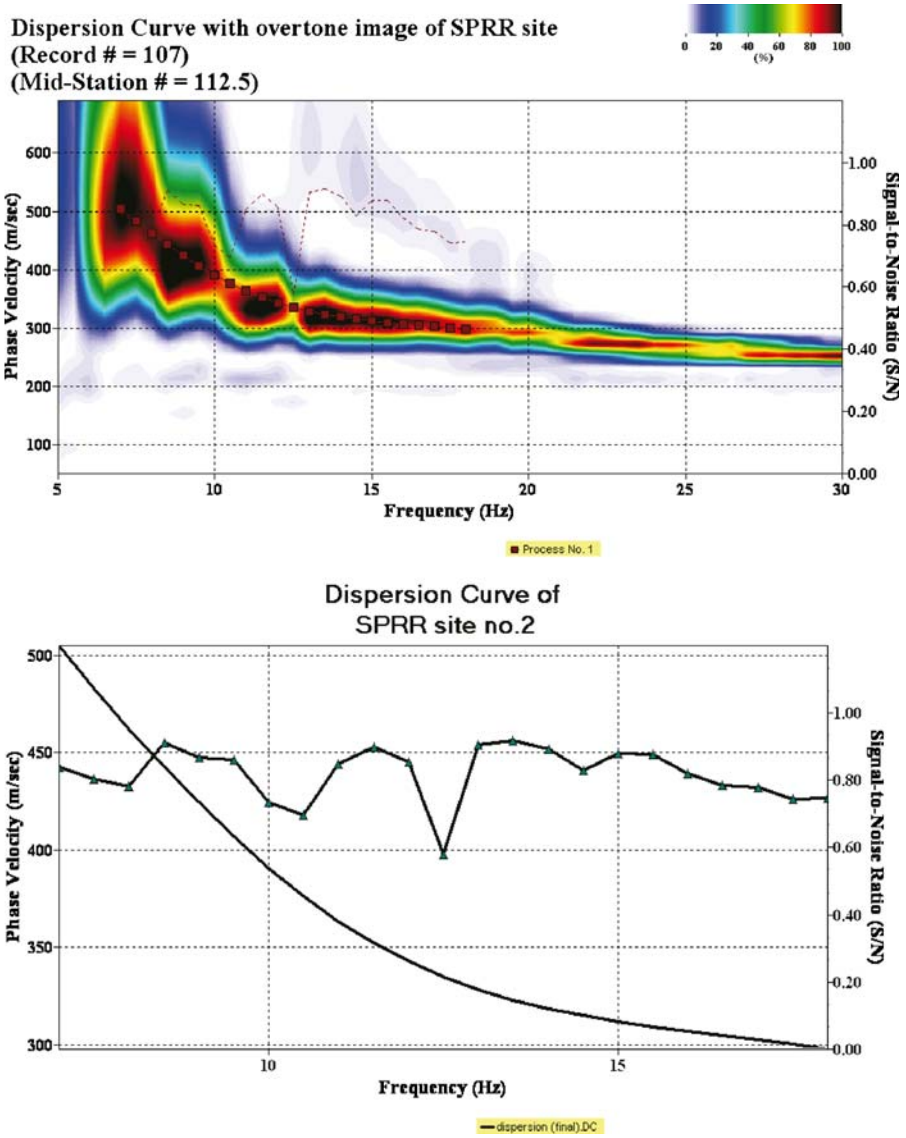


Fig. 3 Example of dispersion curve with overtone image from Surya Prasth Ashram site no.2 and Survey of India (SOI) site no. 5 showing significant energy below 10 Hz using 14-Hz geophones and an 8-kg sledge hammer in Dehradun City

and acquired data were recompiled into the roll-along mode data set. Shot gathers from the near, middle, and far offset of the survey line were configured with field parameters to generate seismic record for each shot using a walk away method. This method consists of incrementing the distance of the seismic source to the geophone spread fixed in the same location; thus, a record could be constructed with 36 traces covering a spread of 96 m from the first geophone. Each seismic record was then used for preliminary processing to assess optimum ranges of frequency and phase velocity (Fig. 2b). After analyzing the overtone image (which represents three variables, i.e., phase frequency vs phase velocity, while color represents amplitude), reference phase velocity and phase frequency could be assigned for dispersion analysis. In the next

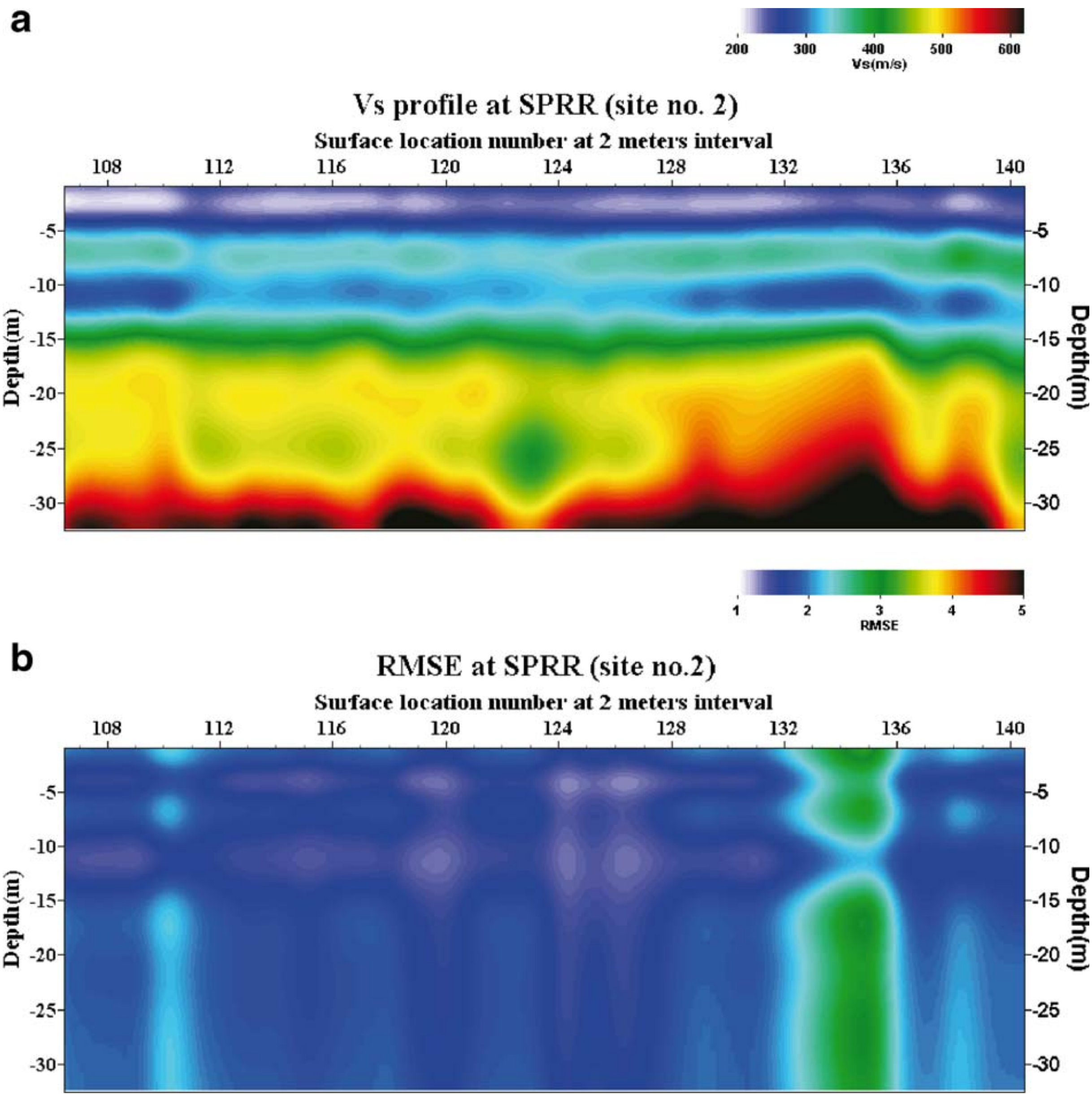


Fig. 4 **a** Vs profile at Surya Prasth Ashram site no. 2. The profile shows increase of Vs with depth from 200 m/s (5-m-thick layer) to 700 m/s up to a depth of 30 m. Reversal of Vs is noticed at a depth of about 10 m, which may be attributed to variation in composition of fan sediments. **b** Low RMSE of the site in estimating the Vs suggests high confidence in the acquired data

step, each record is processed to generate a dispersion image to analyze the fundamental mode. The dispersion analysis was carried out by normalization of complex number with Fourier transformed seismic traces. It implies that even very weak surface waves can be clearly imaged and analyzed as very strong ones. Therefore, the surface wave energy analyzed by SurfSeis v.1.5 is not limited by the "usual" dominant bandwidth of surface waves, which may be the case with the earthquake waves (Park et al. 1998). The dispersion analysis results in the generation of a dispersion curve (frequency vs phase velocity) for each geophone station (Fig. 2c). Once all necessary dispersion curves were extracted, they were inverted to generate a 1-D Vs profile using the inversion algorithm given by Xia et al. (1999). These 1-D profiles appear to be most representative of the material directly below the middle of a geophone spread. Multiple 1-D plots of Vs vs depth were generated using a source and receiver roll along a survey line as discussed before. A set of 1-D plots of Vs profiles have been interpolated to produce 2-D Vs profile at each site. The quality of the dispersion image is assessed by the SNR, which is calculated by considering the fundamental mode surface waves as the signal and all body waves and higher mode surface waves as noise. Confidence in the dispersion can be estimated through measure of SNR displayed along with the dispersion curve.

In the present analysis, a significant amount of surface wave energy was recorded at frequencies as low as 7 Hz using 14-Hz geophones (Mahajan et al. 2005). Similar investigation carried out using 10-Hz geophones also shows equally strong energy at a lower frequency of 5 Hz (Xia et al. 2000). It has been observed that the lower-frequency limits of higher-frequency geophones are not limited by their natural frequency. According to Park et al. (2002), the 10-Hz geophones give an almost identical result to the 4.5-Hz geophones all the way down to 5 Hz, while the 40-Hz geophones recorded down to about 10 Hz. The dispersion image of 4.5-Hz geophones, however, clearly indicates that the lowest recordable frequency cannot be lower than 2–3 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. The dispersion curves of different sites in Dehradun City indicate that the lowest recordable frequency using 14-Hz geophones can be as low as 7 Hz. In our analysis we observed phase velocity of 450 to 650 m/s at lower frequencies, i.e., 7 Hz in general (Fig. 3). Because wavelength (λ) is a function of phase velocity (c) as well as frequency (f), it was feasible to obtain information from a depth of 30–40 m. The estimated Vs section shows high SNR, indicating high confidence in the obtained phase velocity–frequency curve (Fig. 2c).

5 Results at representative sites

In the northern part of the city, the Vs is higher as compared to the sites located in the central and southwestern part of the city. In the northern part of the city at Surya Prasth Ashram site no. 2, the Vs varies from 250 m/s at the top 6 m to about 700 m/s at a depth of 30 m, which may represent the Vs of the underlying Siwalik rocks (Fig. 4a). The low root mean square error (RMSE) in estimating the Vs at this site suggests a high level of confidence (Fig. 4b). The RMSE is calculated based on the Vs profile of a layer whose theoretical dispersion curve best matches the calculated dispersion curve using RMSE as a guide and constraint. RMSE is a measure of relative error for each layer in comparison to theoretical criteria and can be used as a measure of confidence (Xia et al. 1999). In this section, velocity inversion between 9 and 13 m of depth suggests variation in composition of the Doon fan gravels deposited in different time periods. A similar situation can be observed in stratigraphic logs from different parts of the Dehradun fan (Singh et al. 2004; Rautela and Sati 1996).

The central part of the city shows an average velocity of around 180 m/s for the upper 8–10 m of soil cover, as observed at Forest Research Institute (FRI) site no. 26 (Fig. 5a). In the next 6 m, the velocity changes to 350 m/s, thus representing change in layer composition. A sharp drop in Vs at station number 120 from 16 to 30 m could be due to the presence of relatively soft sediments/clay pockets deposited after erosion of the older fan deposits. At a depth of 16 m, the velocity changes to more than 400 m/s, representing 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. Similar observation is also made in Las Vegas valley where calcite

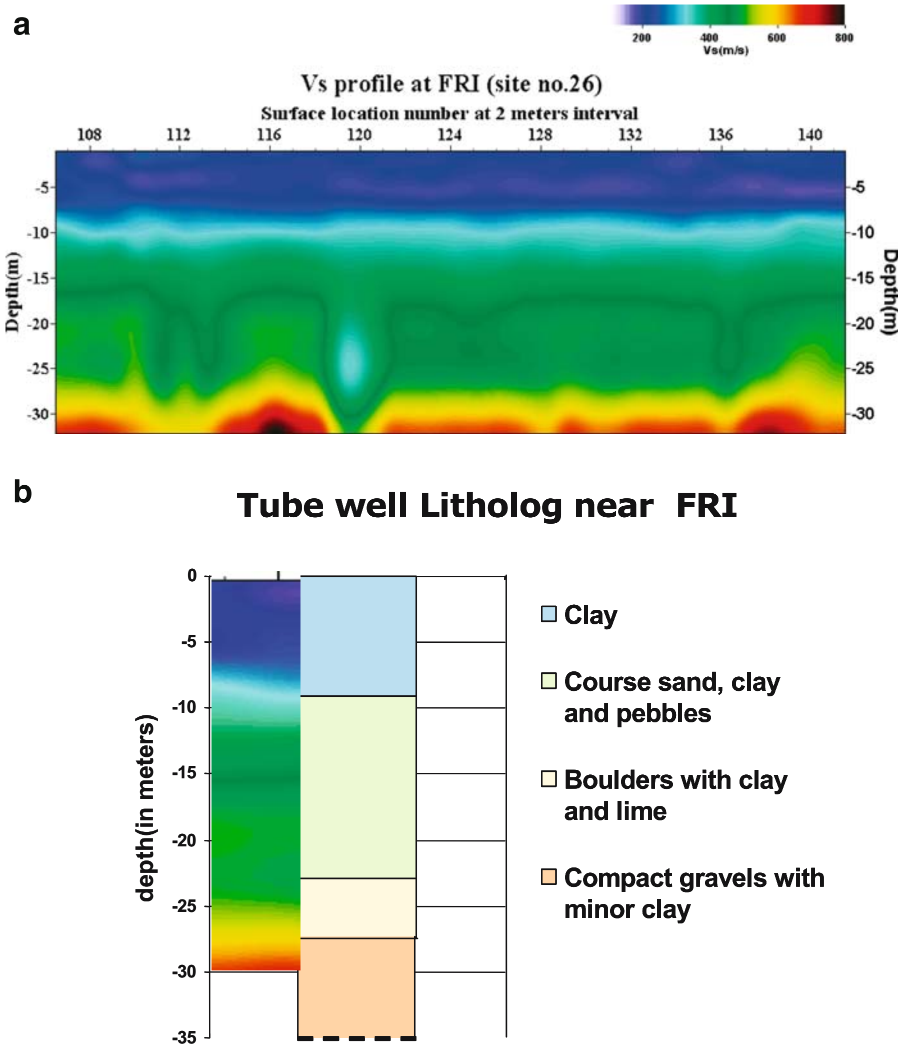


Fig. 5 **a** Vs profile at in the FRI site no. 26. The profile shows 10 m of the upper layer having Vs of about 200 m/s that increases to 500 m/s at a depth of 30 m. The second layer is very thick in this section as compared to site no. 2. **b** Tubewell litholog of a site close to FRI site no. 26 and corresponding Vs profile

cementation of alluvium (caliche) raises Vs 30 values to 500–600 m/s (Scott et al. 2006). Inference on material composition is also confirmed by the litholog of a site very close to FRI (Fig. 5b). The field photograph (Fig. 6) from the nearby site of FRI shows the nature of rock fills (gravels, pebbles mixed with clay, sand, and lime), which are exposed almost 15 m below the surface and correlated well with the Vs section of Birpur site no.14. Similar lithology has been observed at Anarwala site no. 4, which is very much comparable to the Vs profile of the FRI site.

The Chiala site no. 47 located towards further southwest of the city shows very thick sedimentation as the velocity varies from 180 to 400 m/s up to a depth of 30 m (Fig. 7). Dehradun City, as described before, is comprised mainly of fan deposits with increasing thickness from the north to the southern part of the city. The southern part of the city lies at the trough of the synclinal valley, accumulating finer sediments from northern Lesser Himalayan ranges and southern Siwalik ranges. The south-southwestern area of the city is under paddy cultivation and the soil is also used for brick manufacturing, thus suggesting presence of thick clay/finer sediment horizon at the distal portion of the alluvial fan. This has been revealed in our survey by the presence of a thick layer with lower Vs. The mean Vs of this part of the city is around 180–360 m/s; at some sites, Vs is around 174 m/s (e.g., site no. 43 and 49). The change in Vs value at a depth of 22 m at station location 141 up to a depth of almost 35 m may indicate erosional features.

Fig. 6 Photograph near FRI site no. 26 showing the lithology below 10 m from the surface, which gives rise to Vs more than 350 m/s. At a depth of 30 m, the Doon gravels cemented with sandy calcareous materials show velocity more than 500 m/s

The Vs profile at Badripur site located in the southeast part of Dehradun City (site no. 46) shows horizontal layers of different composition (Fig. 8). The surface wave data collected from this site have a frequency range of 10 to 24 Hz with phase velocities of 600 to 650 m/s at the 10-Hz component. The maximum investigation depth of 35 m has been achieved with an RMSE error value of about one. High SNR indicates high confidence in the obtained phase velocity–frequency curve. The top layer of the profile (8–9 m) has an average Vs of about 300 m/s, which may represent the velocity of terrace deposit as the site is located near the river. The second layer goes down to a depth of almost 16 m, showing an average Vs of 500 m/s, and the third layer extends to a depth of around 30–34 m with a Vs of 700 m/s. The deepest layer has Vs more than 900 m/s and may represent the bedrock level (Fig. 8). Thus, the variation of Vs with depth in different parts of the city indicates heterogeneity in layer composition and thickness.

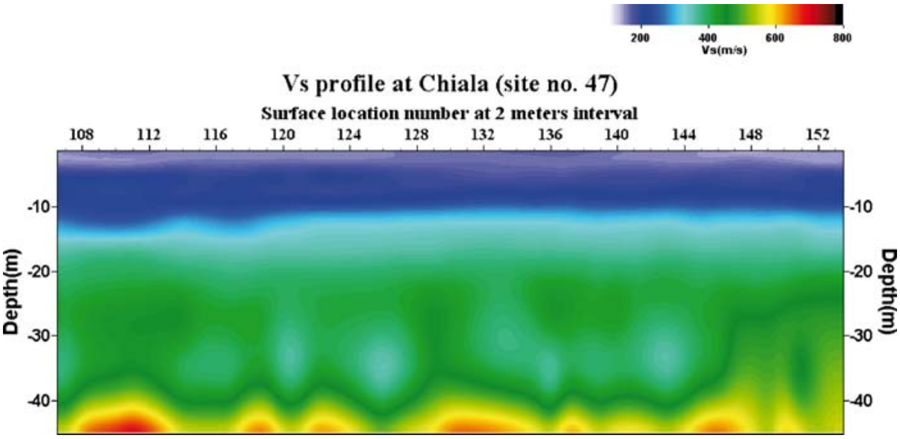
6 Ground response analysis

6.1 Input parameters

SHAKE2000, based on the SHAKE method developed by Schnabel et al. (1972) dealing with 1-D ground response analysis, has been used for determination of surface response and amplification with respect to reference input earthquake motion. The dynamic and static soil properties (i.e., Vs or maximum shear strength and unit weight) are essential for the ground motion response analysis. Because the analysis accounts for the nonlinear behavior of the soil using an iterative procedure, dynamic soil properties play an important role. As the variation in geotechnical properties of the individual soil layers could not be modeled due to lack of data, dynamic properties such as modulus reduction and damping ratio have been taken from the database of materials properties provided with SHAKE2000 for corresponding materials as observed in tube well lithologs and Vs data (Seed and Idriss 1970; Schnabel 1973; Seed et al. 1986; Sun et al. 1988; Vucetic and Dobry 1991; Gazetas and Dakoulas 1992).

For a given earthquake, the response of an elastic site depends both on the thickness of the deposit and Vs. In engineering site investigations, 30 m is a typical depth of boring and detailed site character-

Fig. 7 Shears wave velocity profile from southwestern part of the city at Chiala site no. 47 shows a 12-m-thick upper layer with a velocity of 150–200 m/s. The second layer with an average velocity of about 400 m/s goes up to a depth of 40 m at locations 100–144 and up to 20 m depth at locations 144–152



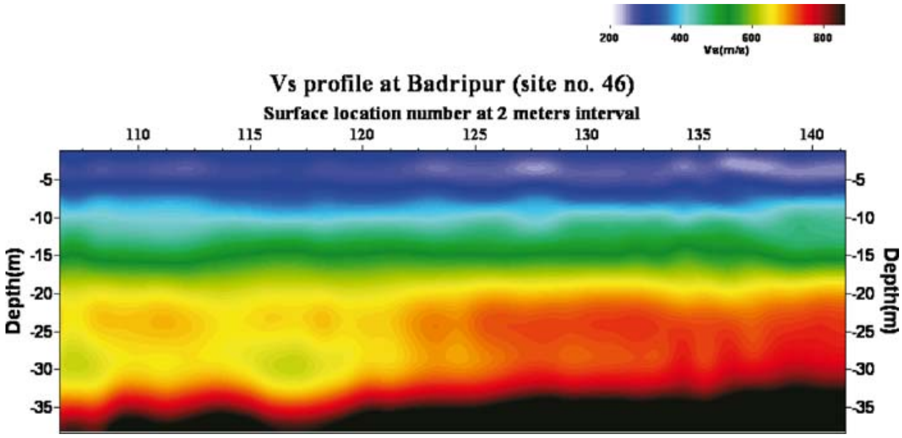


Fig. 8 Shears wave velocity profile from southeastern part of the city (site no. 46) shows sharp changes in Vs at about 5-, 15-, and 30-m depths. It indicates the presence of horizontal layers, and the presence of upper Siwalik boulder beds further towards the southeast is also confirmed by field investigation

izations. Therefore, most of the site effect studies in earthquake ground motion are based on the geotechnical properties in the upper 30 m (Finn 1991; Anderson et al. 1996; Boore et al. 1993). According to Borcherdt (1994), the upper 30-m soil column is considered to be responsible for site amplification. The National Earthquake Hazard Reduction Program (NEHRP) has incorporated this for classification of sites on the basis of average Vs (Street et al. 2001). Anderson et al. (1996) have also used the upper 30 m of soil column for ground motion analysis. Recently, a comprehensive study carried out by Romero and Rix (2001) to identify soil deposits susceptible to ground motion amplification in the central US demonstrates that the 30-m assumption may be adequate to estimate the site response if little or no information is available for larger depths. In the present study area, at depths more than 30 m, Doon fan gravel deposits mainly consist of compact boulders with minor clay equivalent of upper Siwalik boulder bed. Therefore, the upper 30 m of soil/alluvium has been considered to define the variation in site amplification at different locations of the city.

In Dehradun City, mainly three to four soil layers have been observed in the upper 30 m, such as clay on the top followed by rock fill (pebbles, cobble, clay, sand mixed with lime) and gravel, and the last layer consists of compact gravels and boulders equivalent of rock. Assuming lateral continuity, layers have been defined based on borehole data, lithology exposed

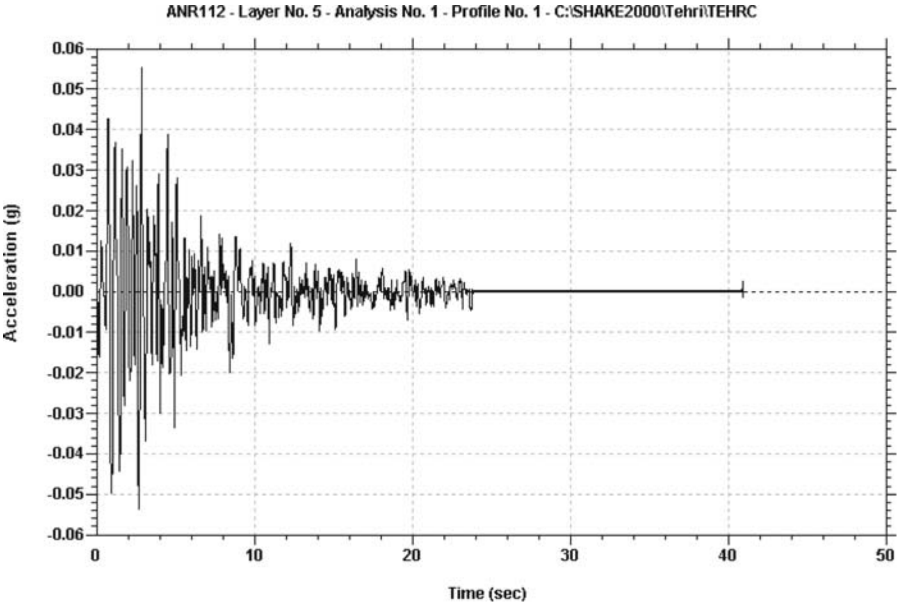
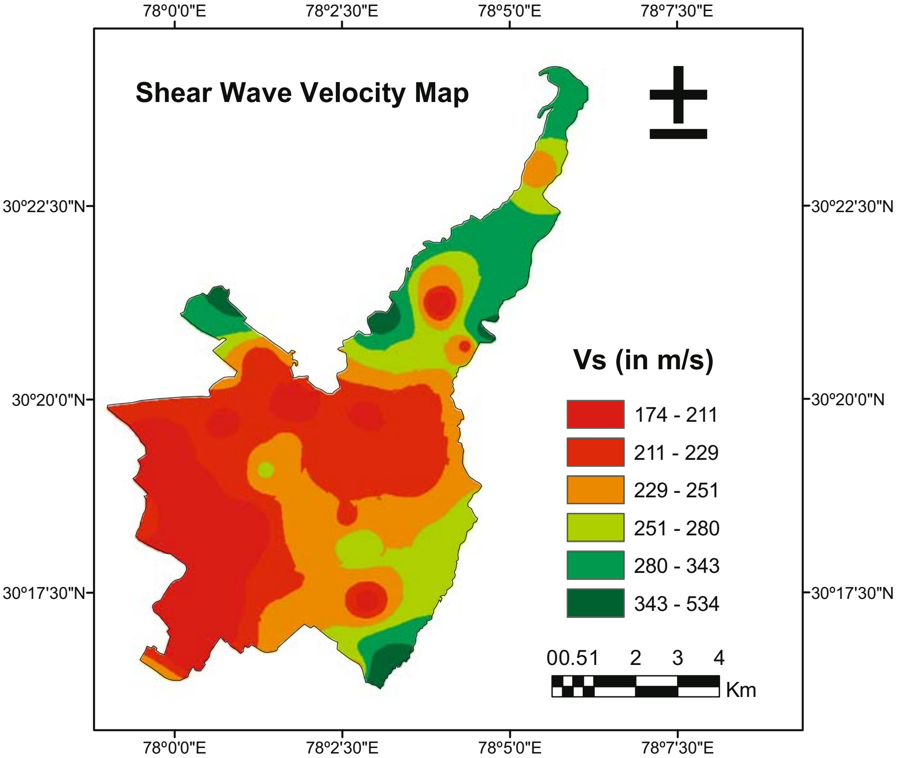


Fig. 9 Computed acceleration time history for Anarwala site using SHAKE2000 from horizontal component strong motion data of the Chamoli earthquake (source: Department of Earthquake Engineering, Indian Institute of Technology Rorkee)

Fig. 10 Mean Vs map of Dehradun City



along river sections, and Vs profiles (Figs. 5b and 6). As soil profile input to SHAKE2000, number of soil layers, thickness, damping, unit weight, and Vs have been provided based on the present analysis at specific locations. In the next step, reference input motion was provided from the Chamoli earthquake (6.8 mb) data recorded at Tehri at a distance of 85 km from the epicenter. Tehri town, located at a distance of 40 km from the study area, is the nearest place where actual earthquake strong motion data have been recorded. Therefore, the strong motion data recorded at bedrock level have been considered as reference input motion, and the acceleration-time history is derived at each reference site (Fig. 9). In SHAKE2000, the summary of first output gives information about natural period and average Vs of the soil column besides other parameters such as shear modulus, maximum stress, maximum strain, peak acceleration, damping, and unit weight for each specified layer.

6.2 Output of site response analyses

The response and amplification spectrum along with shear modulus, average Vs, and natural periods have been derived between the free surface and the lowermost layer with infinite depth (half-space) for different damping ratios, i.e., 0.03, 0.05, 0.1, and 0.2 at each site. The average Vs, natural period, and response spectra of different sites have been added to the attribute table of the site location map to prepare different maps for visualization. All point information were interpolated by considering average distance between points and the survey profile line. Interpolation and all other spatial analyses have been carried out in Arc View and Arc GIS software with a grid spacing of 50×50 m. The interpolated values have been classified based on the natural grouping of data values to produce the number of classes.

In Vs map, six major zones have been identified in the city (Fig. 10). However, according to the NEHRP classification scheme, these can be regrouped into three major zones. Zone 1 represents areas that come under class E of NEHRP (<180 m/s). Zone 2 represents the majority of the city area, especially the southwestern and central part where velocity varies from 180 to 360 m/s (class D). The northern and southeastern parts of the city show velocity higher than 360 m/s; thus, they can be classified as class C. The average Vs of the soil column is slightly higher in the northern and southeastern parts of the

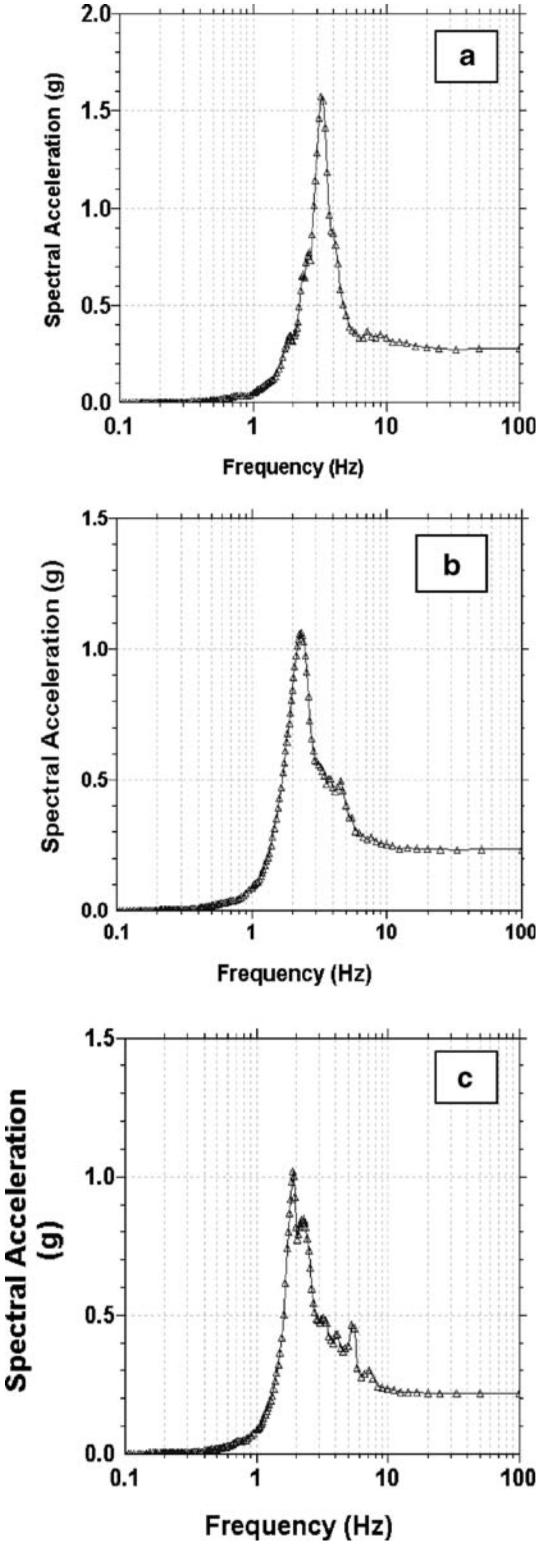


Fig. 11 Response spectrum of **a** Surya Prasth Ashram, **b** FRI, and **c** Chiala site at 5% damping for two-story structures (5 Hz)

city compared to the southwestern part, where it shows very low Vs (i.e., less than 256 m/s) mainly due to the presence of thick clay/silt deposits (up to 30 m), e.g., at Chiala site no. 47. In the same region at Majra (site no. 43) and Clement town (site no. 49), the mean Vs varies from 174 to 184 m/s. The northern and the southeastern parts of the city are represented by high Vs values at 20-m depth (site no. 2 and 19). The northern part of Dehradun shows higher Vs values due to presence of thin fan deposits at the proximal part underlain by bedrock or consolidated gravels with higher stiffness than the piedmont terrace deposits of the central and southern parts of the city. 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 (Fig. 11). Spectral acceleration maps have been produced in Arc GIS by interpolating values at 5 and 10 Hz (Figs. 12 and 13).

The characteristic site periods computed by SHAKE2000 show variation from 0.24 s (4.2 Hz) in the northern part of the city to 0.75 s (1.3 Hz) in the south-southwestern part of the city, which were in agreement with the Vs map (Fig. 10). The amplification functions derived between free surface and the lowermost layer show peak amplification at 3–4 Hz in the northern part of the city, 2–2.5 Hz in the middle of the city, and 1.5 Hz in the south and southwestern parts of the city (Fig. 14). This suggests the presence of thin layers of alluvium in the northern part of the city compared to the south and southwestern parts. Observation of microtremors study also reveals amplification in frequency ranges such as 0.8 to 2 Hz in the south and southwest zones, 2–3 Hz in the central zone and 4–8 Hz in the northern zone (Mundepi and Kamal 2006).

The seismic hazard assessment carried out using the probabilistic technique for the northwest Himalayan region shows peak ground acceleration of the order of 0.2 g for Dehradun City (Mahajan et al. 2002). The input motion derived from the strong motion data shows 0.05 g at the bedrock for the horizontal component of Chamoli earthquake (6.8 mb) data recorded at Tehri. The spectral acceleration shows the acceleration value in the range of 0.14 to 0.36 g for single-story building (10 Hz natural frequency) and 0.24 to 0.74 g for two-story buildings (5 Hz natural frequency) (Figs. 12 and 13). In India, most tall buildings have flexible steel-framed structures, whereas single-

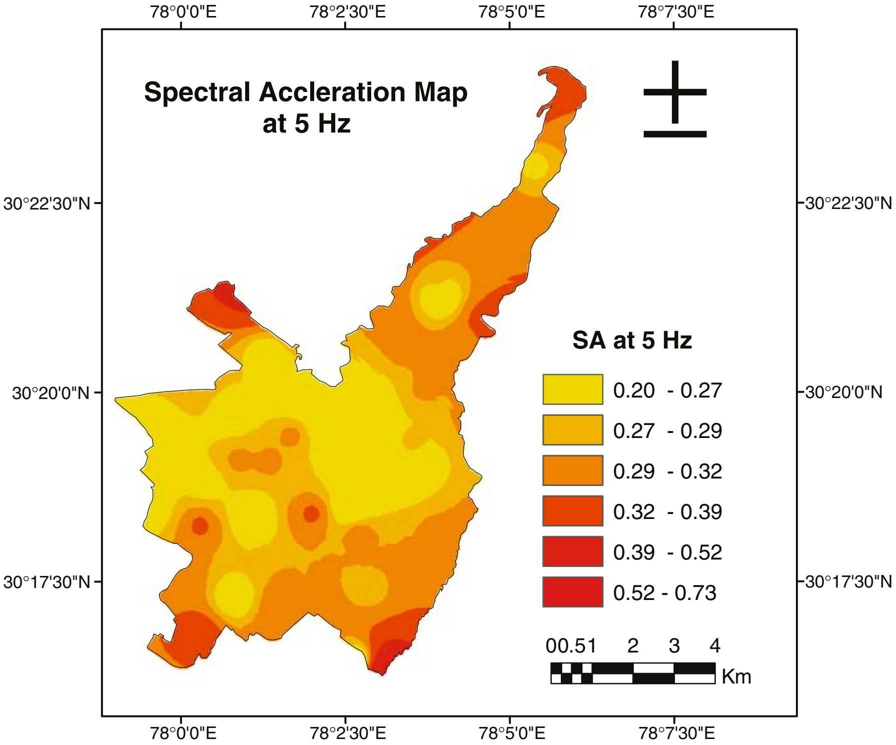


Fig. 12 Seismic microzonation map in terms of spectral acceleration at 5% damping for two-story structures (5 Hz)

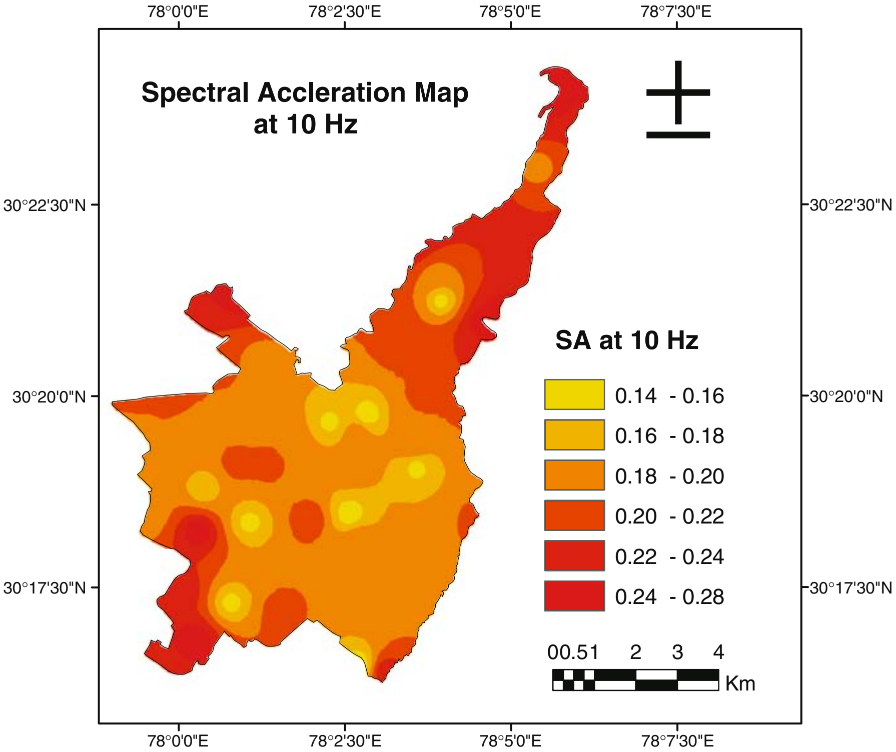


Fig. 13 Seismic microzonation map in terms of spectral acceleration at 5% damping for single-story structures (10 Hz)

and double-story buildings in India are mostly made up of bricks and concrete yielding high frequency. The natural period can be calculated as $T=0.1N$, where N is the number of stories. This yields values of 1, 2, 5, and 10 Hz for 10-, 5-, 2-, and 1-story buildings (Celebi et al. 2003). In case of one- and two-storied buildings, the structure is stiffer with low mass, thereby yielding high natural frequency (Kramer 1996). Because Dehradun City has mostly one- or two-story buildings, the spectral acceleration has been thus calculated for only these two types of buildings.

If the magnitude of the earthquake increases to 8.0, the acceleration could be different for single- and two-story buildings. However, in the present analysis, a scenario is presented on variability in amplification and spectral accelerations at different sites of Dehradun City for an earthquake of a magnitude of 6.8 mb.

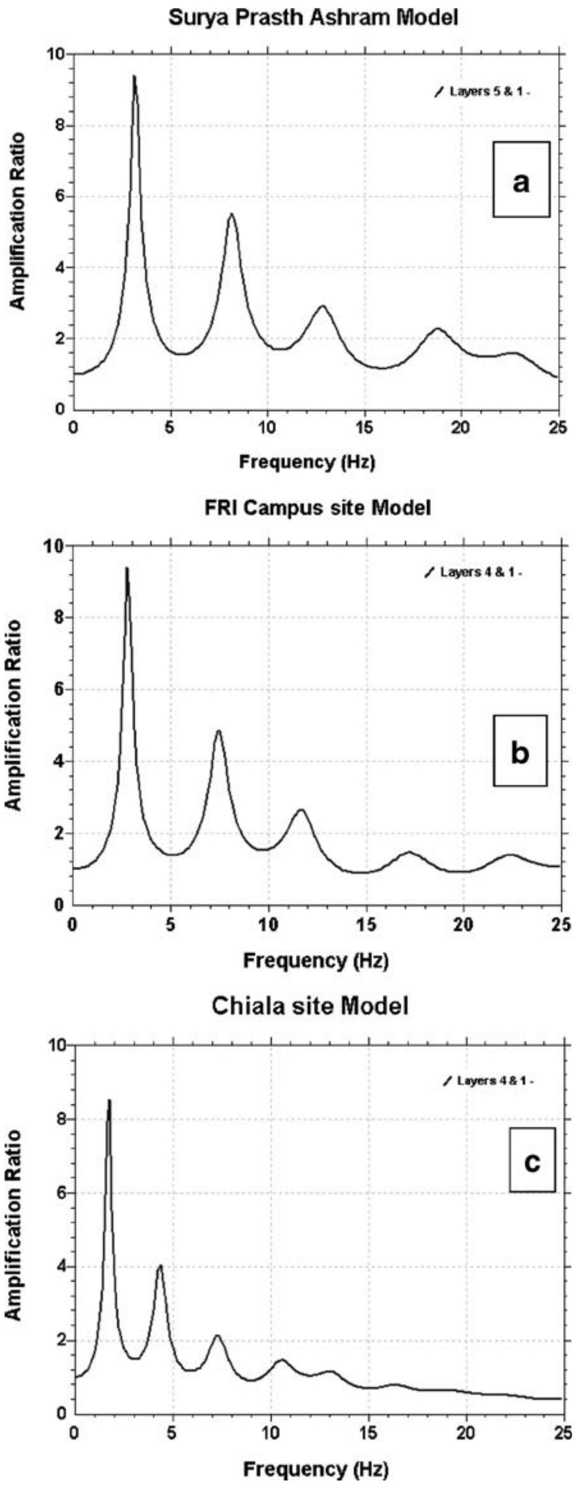


Fig. 14 Amplification functions for sites **a** Surya Prasth Ashram (SPRR), **b** FRI, and **c** Chiala. Note that the softer soil at Chiala site will amplify low-frequency input motion (1.5 Hz) much more strongly than the stiffer soil at SPRR. At higher frequencies, the opposite behavior is expected

7 Conclusion

The present study revealed the variation of Vs in the upper 30–40 m of soil horizon using MASW technique. This information was critical in analyzing surface response and local amplification using SHAKE2000. In the present study, the emphasis is laid on the first 30–40 m of soil column that shows an average Vs ranging from 150 to 350 m/s, and at a few locations of the city, the velocity was in the range of 360–760 m/s. The spatial distribution of Vs has provided valuable information on the scenario of site amplification in different parts of the city. The study has helped us to understand that 14-Hz geophones can record frequencies as low as 7 Hz in Dehradun City. In a broad sense, the average Vs and the characteristic site period of the soil column help to identify areas of high amplification within the city and provide information on site response for each location. The peak ground motion response is in good agreement with the characteristic site period of each site. The northern part of the Dehradun City may reflect the effect of impedance contrast because of the presence of high Vs variation between the top layer and the lowermost layer, which is reflected in the characteristic site period of these sites. However, in rest of the city, the depth of low-velocity layers is more pronounced, as the MDS and LDS fan deposits largely cover them. The study has revealed the presence of high-Vs layers (>500 m/s) at varying depths, suggesting the presence of boulder horizon cemented with calcareous material. The compactness of the deposits increases with depth, and so do the Vs. The velocity horizon showing more than 750 m/s may represent the bedrock, which is equivalent to upper Siwalik boulder beds in Doon valley. The present study demonstrated a methodology for seismic microzonation of Dehradun City located at the foothill belt of Himalaya. It shows the possibility of incorporating additional borehole data and input ground motion when available to further generate additional scenarios for better assessment of seismic hazards. Thus, the result provides city planners with better understanding of spatial variation of seismic hazard, which will be of immense value in planning and disaster management in the Dehradun region, one of the fastest growing cities of northern India.

Acknowledgement The present work is the result of a collaborative effort between the Wadia Institute of Himalayan Geology (WIHG), Dehradun; the International Institute for Geo-information Science and Earth Observations (ITC), The Netherlands; and the Indian Institute of Remote Sensing (IIRS), Dehradun. The authors are thankful for constant support from the director of the WIHG, the dean of the IIRS, and the rector of the ITC for carrying out this work. Useful discussion and valuable suggestions during the course of the investigation, analysis, and writing of this manuscript by Prof. B.R. Arora, Director, WIHG; Prof. R.C. Lakhera, In-Charge, Geosciences; and Prof. V.K. Jha, IIRS, are duly acknowledged.

References

Aki K, Richards PG (1980) Quantitative seismology. Freeman, San Francisco

Anderson JG, Lee Y, Zeng Y, Day S (1996) Control of strong motion by the upper 30 meters. Bull Seismol Soc Am 86:1749–1759

Arya AS (2000) Recent developments towards earthquake risk reduction in India. Curr Sci 79:1270–1277

Auden JB (1936) The structures of the Himalaya in Garhwal. Rec Geol Surv India 71:409–433

Bilham R, Gaur VK, Molnar P (2001) Himalayan seismic risk. Science 293:1442–1444

Boore DM, Joyner WB, Fumal TE (1993) Estimation of response spectra and peak acceleration from western North American earthquakes, an interim report. Open file report 93-509. United States Geological Survey, Menlo Park

Borcherdt RD (1970) Effects of local geology on ground motion near San Francisco Bay. Bull Seismol Soc Am 60:29–61

Borcherdt RD (1994) Estimation of site-dependant response spectra for design (methodology and justification). Earthq Spectra 10:617–653

Bullen KE (1963) An introduction to the theory of seismology, 3rd edn. Cambridge University Press, London

Celebi M, Prescott W, Stein R, Hudnut K, Behr J, Wilson S (2003) GPS monitoring of structures: recent advances. In: Kueppers AN, Zschau J (eds) Early warning systems for natural disaster reduction. Springer, Berlin Heidelberg New York, p 710

Dziewonski A, Blosch S, Landisman M (1969) A technique for the analysis of transient seismic signals. Bull Seismol Soc Am 59:427–444

Finn, WDL (1991) Geotechnical engineering aspects of seismic microzonation. In: Proceedings of the 4th international conference on seismic zonation, vol 1. Earthquake Engineering Research Institute, Oakland, pp 199–250, 25–29 August 1991

Gazetas G, Dakoulas P (1992) Seismic analysis and design of rockfill dams: state-of-the-art. Soil Dyn Earthq Eng 11:27–61

Herrmann RB (1973) Some aspects of band pass filtering of surface waves. Bull Seismol Soc Am 63:663–671

Ivanov J, Park CB, Miller RD, Xia J (2000) Mapping poison's ratio of unconsolidated materials from a joint analysis of surface-wave and refraction events. In: Proceedings of the symposium on the applications of geophysics to engineering and environmental problems, Arlington, 20–24 February 2000

Kramer SL (1996) Geotechnical earthquake engineering. Prentice Hall, Englewood Cliffs

Kumar S, Mahajan AK (1993) The Uttarkashi earthquake of 20th October 1991: field observations. Terra Nova 6:95–99

Mahajan AK, Virdi NS (2001) Macroseismic field generated by 29 March, 1999 Chamoli earthquake and its seismotectonics. J Asian Earth Sci 19:507–516

Mahajan AK, Mihilov V, Dojcinovski D (2002) A preliminary probabilistic seismic hazard assessment of northwest Himalaya. In: Paul DK, Kumar A, Sharma ML (eds) Proceedings of the 12th symposium on earthquake engineering. Phonix, New Delhi, pp 277–286

Mahajan AK, Sporry, R, Chabak SK (2005) Shear wave velocity survey for seismic hazard zonation studies in Dehradun, India. In: Near Surface 2005, Palermo, 5–8 September 2005

Middlemiss CS (1910) The Kangra earthquake of 4th April, 1905. Mem Geol Surv India 38:1–409

Miller RD, Xia J, Park CB, Ivanov JM (1999) Multichannel analysis of surface waves to map bedrock. Lead Edge 18:1392–1396

Mitchell, B (1973) Radiation and attenuation of waves from the southeastern Missouri earthquake of October 21, 1965. J Geophys Res 78:886–899

Mooney HM, Bolt BA (1966) Dispersive characteristics of the first three modes for a single surface layer. Bull Seismol Soc Am 56:43–67

Mundepi AK, Kamal (2006) Effective soft sediment thickness in Dehradun City using ground ambient vibrations. Himal Geol 27:183–188

Nakata, T (1972) Geomorphic history and crustal movement of the foot-hills of the Himalayas, Sci. Report, Tohoku University, Japan, 7th Ser. Geography 22:39–177

Nazarian S, Stokoe KH, Hudson WR (1983) Use of spectral analysis of surface wave method for determination of moduli and thickness of pavement. Transp Res Rec 930:38–45

Nossin, JJ (1971) Outline of geomorphology of the Doon valley, northern UP. Z Geomorphol 12:18–50

Park CB, Brohammer M (2003) SurfSeis 1.5V software for multichannel analysis of surface waves. Kansas Geological Survey, Lawrence

Park, CB, Miller, RD, Xia J (1998) Imaging dispersion curves of surface waves on multichannel records. Technical programme with biographies, Society of Exploration Geophysicists, 68th Annual meeting, New Orleans

Park CB, Miller RD, Xia, J (1999) Multichannel analysis of surface waves. Geophysics 64:800–808

Park CB, Miller RD, Miura H (2002) Optimum field parameters of an MASW survey. Ext. Abstract, Society of Exploration Geophysicists of Japan, Tokyo, 22–23 May 2002

Phillip G (1995) Active tectonics of Doon valley. Himal Geol 6:55–62

Rautela P, Sati D (1996) Recent crustal adjustments in Dehradun valley, Western Uttar Pradesh, India. Curr Sci 71:776–780

Romero MS, Rix GJ (2001) Ground motion amplification of soil in the Upper Mississippi Embayment (GIT/CEE/GEO-01-1). Georgia Institute of Technology, School of Civil and Environmental Engineering, Atlanta, pp 493

Schnabel PB (1973) Effects of local geology and distance from source on earthquake ground motions. Ph.D. thesis, University of California, Berkeley

Schnabel PB, Lysmer J, Seed HB (1972) SHAKE: a computer program for earthquake response analysis of horizontally layered sites, report no. UCB/EERC-72/12. Earthquake Engineering Research Center, University of California, Berkeley

Scott JB, Rasmussen T, Luke B, Taylor WJ, Wagoner JL, Smith SB, Louie, JN (2006) Shallow shear velocity and seismic microzonation of the urban Las Vegas, Nevada Basin. Bull Seismol Soc Am 96:1068–1077

Seed HB, Idriss IM (1970) Soil moduli and damping factors for dynamic response analysis, report no. EERC 70-10. University of California, Berkeley

Seed HB, Wong RT, Idriss IM, Tokimatsu K (1986) Moduli and damping factors for dynamic analyses of cohesionless soils. J Geotech Eng 112:1016–1032

Singh AK, Prakash B, Manchanda M (2004) Tectonic geomorphology of the Dehradun valley using digital terrain model and optically stimulated luminescence dating. Himal Geol 25:59–78

Slob S, Hack R, Scarpas T, van Bemmelen B, Duque A (2002) A methodology for seismic microzonation using GIS and SHAKE—a case study from Armenia, Colombia. http://www.itc.nl/library/Papers/arti_conf_pr/slob_hack.pdf. Cited 1 June 2004

Street R, Wooley EW, Wang Z, Harris, JB (2001) NEHRP soil classification for estimating site dependant seismic coefficients in the Upper Mississippi Embayment. Eng Geol 62:123–135

Sun JI, Golesorkhi R, Seed HB (1988) Dynamic moduli and damping ratios for cohesive soils, report no. EERC 88–15. University of California, Berkeley

Thakur VC (1995) Geology of Dun Valley, Garhwal Himalaya: neotectonics and coeval deposition with fault—propagation folds. J Himal Geol 6(2):1–8

Thakur VC, Pandey AK (2004) Late quarternary tectonic evolution of Dun in fault bend/propagated fold system, Garhwal Sub-Himalaya. Curr Sci 87:1567–1576

Tian G, Steeples DW, Xia J, Miller RD (2003) Multichannel analysis of surface wave method with the autojuggie. Soil Dyn Earthqu Eng 23:243–247

Tsai YB, Aki K (1969) Simultaneous determination of the seismic moment and attenuation of seismic surface waves. Bull Seismol Soc Am 59:275–288

Vucetic M, Dobry R (1991) Effect of soil plasticity on cyclic response. J Geotech Eng 117:89–107

Xia J, Miller RD, Park CB (1999) Estimation of near surface shear wave velocity by inversion of wave. Geophysics 64:691–700

Xia J, Miller RD, Park CB, Ivanov J (2000) Construction of 2-D vertical shear wave velocity field by the multichannel analysis of surface wave technique. In: Proceedings of the symposium on the application of geophysics to engineering and environmental problems, Arlington, 20–24 February 2000

Xia J, Miller RD, Park CB, Hunter JA, Herris JB, Ivanov J (2002) Comparing shear wave velocity profiles inverted from multichannel surface waves with borehole measurement. Soil Dyn Earthq Eng 22:181–190