Subsurface site characterization of Donga Fan, Northwest Himalaya using multichannel analysis of surface waves and response analysis

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The characterization of sediments in a tectonically complex region is important from the seismological point of view to study possible earthquake effects due to the presence of soft sediments. Multichannel analysis of surface waves (MASW) method was used to acquire seismic data from 87 sites for estimating shear wave velocity ($V_s$) of near-surface materials beneath the Donga Fan. The majority of the Donga Fan is underlain either by alluvial fan or river terrace deposit. About 80% of the Donga Fan has an average shear wave velocity ranging from 180 to 360 m/s, whereas 20% of the area has high stiffness values ($V_s > 360$ m/s). The estimated $V_s$ values are higher in the northern part of the study area due to thin sediment (<30 m) cover compared to the central, south and southwestern parts which have thick sedimentation (>150 m) above bedrock. The response analysis suggests that peak spectral acceleration varies from 0.49 g at 1.61 Hz to 1.69 g at 3.22 Hz with variation in amplification ratio from 4 to 11 times. The spectral acceleration computed for two-storey buildings also varies from 0.10 to 0.40 g (at 5% damping), whereas in the case of single-storey buildings it varies from 0.12 to 0.22 g (at 5% damping). The predominant frequency estimated using ambient noise measurements varies from 0.84 to 5 Hz, indicating variation in the thickness of sediments and is in good agreement with the $V_s$ values estimated using the MASW technique.

**Keywords:** Bedrock response analysis, multichannel analysis of surface waves, site response, shear wave velocity.

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study area is bounded by high hazard potential seismogenic zones, i.e. Kangra seismogenic zone to the west, and Uttarakashi and Chamoli seismogenic zones to the northeast and eastern regions respectively (Figure 2). Active tectonics, seismic hazards and palaeo-seismic studies have also indicated that the area is situated in a region with high seismic 46 hazard potential.\textsuperscript{5,6,9}

The area immediately to the west of Doon Valley is the southeastern Himachal Pradesh (Shimla) region, which has been considered as the seismic gap region as it has a very low seismicity rate since the last 100 and 500 years. Considering the seismic gaps of Eastern Himalach\textsuperscript{10} and other seismic gap regions all along the Himalayan arc, it may not be equally seismogenic to generate great earthquakes\textsuperscript{11,12}. Thus the Himalayan arc is found to be segmented in nature and there are significant variations in the strain values of different segments based on seismicity for the last 500 years\textsuperscript{13}. Further analysis indicated that the southeastern Himachal Pradesh (Shimla) region has a clear deficit in seismic energy release even after considering the last 100 years of earthquake data. Although this region does not fulfil the criteria for generating great earthquakes, large or moderate earthquakes cannot be ruled out. If this region gets activated any time, the Donga Fan which is close to it will experience a much larger effect due to strong excitation from the southeastern Himachal Pradesh, Uttarakashi and Chamoli regions. Thus, the Donga Fan falls under high hazard zone due to the presence of difference seismogenic zones around it.

Under such conditions the study of site amplification is significant because the southern part of the Fan has a thick sedimentary cover with soft soil or very thin soft soil above bedrock in the northern part. Considering the high hazard potential, increasing asset value and population growth unconstrained by building codes requires characterizing each site in terms of site amplification, which is currently an important tool for assessing seismic hazard at regional and local scale\textsuperscript{14}. The presence of active faults in and around the Donga Fan can also increase the seismic hazard potential of the region\textsuperscript{15}. The Donga Fan area had a scanty population with poorly built earthquake non-resistant structures (adobe and burnt brick houses) before the formation of Uttarakhand state (November 2000). Later, the area was earmarked for setting up educational institutions and industries. The extent and spate of damage observed during the 2015 Nepal earthquake (7.6 Ms) to the poorly constructed structure and buildings raised challenging questions about risk management and the responsibility of disaster managers to reduce the ensuing disaster from future earthquakes. The development for economic growth of the country, the Donga Fan which is contributing towards the development of the nation requires an estimation of site amplification parameters.

Shear wave velocity ($V_s$) along with density of the material are key parameters in estimating the site response of any sedimentary basin soil\textsuperscript{16}. Presently, the engineering community is using the shear wave velocity for designing structures\textsuperscript{17}.

In India we are still in a process of measuring shear wave velocity of the earthquake-prone regions. Although some cities have been covered under seismic microzonation studies, like Dehradun, Sikkim, Jammu and NCR Delhi, several urban centres of the frontal Himalayan region need to be studied for collecting such data, which are located in a very high hazard zones and fall under seismic zones V and IV (ref. 2). In this study, a newly coming up urban centre of Doon Valley (Donga Fan) has been considered. The Ministry of Earth Sciences, Government of India (GoI) is encouraging seismic microzonation studies of major urban centres in the near future. The estimation of hazard of any urban centre requires rapid and inexpensive measurements of shear wave velocity over large sedimentary cover for accurate estimation of future hazard maps. Traditionally, standard penetration test is used for the estimation of $V_s$ parameters, especially for site-specific projects. However, for the estimation of $V_s$ parameters over large sedimentary cover, a multichannel analysis of surface waves (MASW) method has been used which has also been validated with the results obtained through microtremor measurements carried out in open and heavily urbanized areas\textsuperscript{18,19}. Although the ambient noise measurements have limited spatio-temporal resolution for the near-surface materials, the MASW method has been used for high resolution of the near-surface materials\textsuperscript{17}. The MASW method has been developed more recently for determining shallow $V_s$ (ref. 18) and is extensively used in major urban centres of the NW Himalaya\textsuperscript{19,20}.

In complex geological settings like that of the present study area where there are irregular variations in stiffness and high impedance contrast between the bedrock and unconsolidated sediments, the data acquired using the
Figure 3. Different litho-units of post-Siwalik Doon gravels under the Donga Fan. a, Section exposed along Nuni Nadi from Kandoli site at the northern part of the Fan showing different units of Doon Gravels. b, Section exposed in Majhaun site. Above this section, shear wave velocity profiles have been taken to validate the shear wave velocity profiles with depth. c, Section showing different litho-units of Doon Gravels located close to Majhaun site (site no. 40) river section. d, Close view of unit C exposed at the southern part of the Fan (site no. 81). The classification proposed by Thakur and Pandey has been adopted.

MASW method require attention during processing and inversion.

Geological and geomorphic setting

Tectonically, the Doon Valley is sandwiched between two major thrusts, i.e. the Main Boundary Thrust (MBT) to the north and the Main Frontal Thrust (locally named as Mohand Thrust) to the south, and comprises mainly Doon Gravels. Litho-stratigraphically, the Doon Gravels are the resultant of post-Siwalik depositions, and the active tectonic activity coupled with tropical climate and monsoon rainfall control the deposition and erosion of Fan sediments. In the piedmont area, the Donga Fan is unconformably deposited over eroded and steeply dipping Middle Siwalik rocks having very thin alluvial cover (20–30 m). The Middle Siwalik rocks (sandstone) are also exposed in the central part of the Fan along stream sections (Figure 1). The Doon Gravels are massive, thickly bedded and poorly consolidated to unconsolidated conglomerates (comprising pebbles and boulders in a fine-grained matrix; Figure 3a and c).

The northern part of the Fan is also characterized by dissecting Doon Gravels with lime-enriched materials, which acted as the cementing material in gravel beds thus increasing the stiffness of the sediments. The Doon Gravels can be divided into three major units: A–C. Unit A lies over the steeply dipping sandstone of Middle Siwalik rocks and comprise sub-angular to sub-rounded granule to pebble-sized clasts set in fine-grained matrix, thus forming a very stiff soil, whereas unit B unconformably overlies on unit A, and at some places it directly overlies on the Middle and Upper Siwalik Formations. These relationships have been observed under Donga Fan area (Figure 3b). Unit B consists of unconsolidated massive gravels with predominance of rounded to sub-rounded boulders, which unconformably overlie on the Upper Siwalik Conglomerates. The gravels are poorly sorted and clast-supported in the northern part, whereas these are matrix-supported in the southern part of the Fan (Figures 3a, c and d). Unit C is a younger Fan surface which has unconformable contact with both units A and B and the Siwalik Formation (Figure 3a and c) in the northern part of the Fan area. This unit predominantly comprises poorly sorted angular to sub-angular granules and pebbles that are interspersed with boulders (Figure 3d). The clasts are supported by a gritty matrix, whereas boulders and pebbles are set in with finer clast matrix. The distal part of the Fan area is rich in clay content with the decrease in clast size, mud and silt, thereby making the topsoil usable for brick kiln industry.
**Figure 4.** Schematic diagram showing field configuration of Multichannel Analysis of Surface Waves (MASW). a. Different components used in the MASW survey. b. Layout of geophones on a survey line with 40 kg accelerated weight drop hammer as an impact source. c. Shot gathered and combined in one single trace using walkaway method. d. Extraction of dispersion curve for 1D shear wave velocity inversion.

**Data acquisition and analysis**

The shear wave velocity of the Donga Fan was estimated using MASW method. This is a non-destructive seismic method that inverts $V_s$ profiles of the subsurface from the dispersive property of Rayleigh waves\textsuperscript{18,19,22,23}. The Rayleigh waves, normally known as ground roll, have low velocity, low frequency but high amplification in soft sediments\textsuperscript{22,23}. Continuous acquisition of multichannel surface wave data along a linear transect generates two-dimensional (2D) $V_s$ profiles having a total spread length of ~72–100 m that contains information about the horizontal and vertical continuity of materials as shallow as 30–100 m. The data have been acquired from 87 sites using 24-channel seismograph with 4.5 Hz spike-based vertical geophones. The seismic source used is a propelled energy generator (PEG-40 kg), which is an elastometer aided weight drop hammer (EAWDH). The shear wave velocity data have been retrieved using geophone interspacing of 1 m (Figure 4 a and b).

The receiver spacing and offset distance were decided after optimizing the field parameters by experimenting at different sites over the Donga Fan, which vary from 1 m (near shot) to 25 m (far shot). The data were collected by moving both source and receiver in an incremental manner using roll along method for conducting 2D shear wave velocity profiling, thus covers total spread of 73–97 m. At each shooting location, multiple stacks (10–15) were made to enhance the signal and obtain good resolution of the dispersion image in active MASW survey\textsuperscript{22–24}. The depth of investigation in this technique depends on various parameters, i.e. elastic properties, density of the soil/rock, seismic source, frequency of the geophone and spread length\textsuperscript{22,23,25}. The available equipment in combination with the used parameters eventually produced sections with an investigation depth ranging from 30 to 60 m. A record length of 1.024 sec with a sampling rate of 0.5 ms was found to provide good quality records\textsuperscript{19,20}. On the other hand, in order to cover maximum areas, one-dimensional (1D) profiling was also done along a linear transect using the source at different offset distances (20, 40 and 60 m) having geophone interspacing of 1 m (Figure 4 b).

The data processing was performed using SurfSeis 3.0 software, which includes conversion of SEG-2 data to KGS format, assigning the field geometry to the acquired data. Shots gathered from the near (1 m), middle (13 m), and far offset (25 m) of the survey line were configured with field parameters to generate seismic records for each shot using the walkaway method (Figure 4 c). Each seismic record was then processed using preliminary parameters to obtain overtone image in order to select reference phase velocity and phase frequency. The amplitude of the signal is represented by colour variation in the overtone image, which otherwise demonstrates whether the mode considered is correctly selected for the specific type of
inversion applied or not. The dispersion analysis was then performed using each overtone image by normalization of complex numbers with Fourier transform\(^1\)\(^9\),\(^2\)\(^2\),\(^2\)\(^3\) (Figure 4d). In order to increase the confidence level in our dataset, a number of dispersion curves were plotted with their corresponding signal-to-noise ratio (SNR) using different shooting locations from the same site. Figure 5 shows the reliability and consistency of the results. As observed from Figure 5, SNR remains above 0.8. The reason for forming the 2D analysis is to determine the vertical and lateral variabilities under the Donga Fan.

In the present analysis, phase velocity of 850–1000 m/s were observed at frequencies as low as 3–4 Hz, and phase velocity of 200 m/s at frequencies of 10–15 Hz, thus indicating the depth of investigation achieved. Since wavelength (\( \lambda \)) is a function of phase velocity (\( c \)) as well as frequency (\( f \)), it is possible to obtain information at depth down to 10–100 m (Figure 5). However, the 1D shear wave velocity profile shows an investigation depth >100 m when the shooting offset distance is 40–60 m and accelerated weight drop as an impact source is being used.

Results and discussion

Validation of shear wave velocity profiles

In order to constraint the shear wave velocity profile, independent information is needed. The stratigraphic information obtained from geotechnical studies carried out in Doon Valley\(^2\)\(^6\) and lithological information from borehole data provided by the Ground Water Board, GoI have been used. Most of the borehole information was drilled through Doon Gravels and the corresponding lithology is shown in Figure 6 for three sites along with a description of the materials mapped in the litholog profile.

The sites considered for validation in the present study are Chhorba (site no. 63), Baluwala (site no. 76) and Institute of Chartered Financial Analysts of India (ICFAI) University, Campus (site no. 81) from the western, central and southeastern parts of the Fans respectively (Figure 7). The Chhorba site is famous for brick kiln industry, and the top 15 m soil shows clay and sand. The shear wave velocity of the top 15 m soil cover is 160–200 m/s from the 2D profiles, indicating a very soft soil according to the National Earthquake Hazard Reduction Programme (NEHRP) soil class (Figure 7a). Below 15 m depth the soil is marked by the presence of plastic and sticky clay with gravels, thus increasing the shear wave velocity to 300–400 m/s up to 40 m depth. Below 40 m depth, the soil column shows alternating layers of coarse sand with clay and gravel and plastic sticky clay with gravel, thus representing a shear wave velocity of 550–600 m/s and can be classified as unit C (ref. 1).

The second site reveals that the top 20 m of soil has the same velocity as the top 12 m of Chhorba site followed
by a second layer of 40–45 m thickness with $V_s$ of 300–400 m/s. The last layer shows alternating coarse sand and clay with gravel at a depth of 60 m with a shear wave velocity of 550–700 m/s, thus representing lateral variation in stiffness (Figure 7b). The last site validated was the ICFAI University Campus where a funnel-shaped feature with depth suggested that there is a decrease in velocity in the central part compared to the extreme ends of the profile indicating attenuation of shear wave velocity, thus inferred as presence of water-bearing beds. The first layer of this site also have very low shear wave velocity (160–200 m/s), but the thickness of this layer goes up to ~30–40 m with lateral variation (Figure 7c). The second layer (~30–70 m) shows presence of coarse sand, clay and gravel, thus representing the same shear wave velocity as of Baluwala and Chhorba site (site no. 63). The shear wave velocity variation with depth at different sites may indicate depositional environment.

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The 2D shear wave velocity profiles derived from the northern part of the Fan using the MASW technique have also been validated using litho-sections of the Donga site (site no. 5) and Majahun site (site no. 40) located within the Donga Fan20, where bedrock (sandstone) is exposed at very shallow depth along the river section. It is important to mention that the shear wave velocity is not an analogy to the lithology, as it depends on the volumetric fracture density, rock fabrics (e.g. shear wave splitting), overburden thickness and water content, among others and is therefore not uniquely correlative with lithology, but provides stiffness of the soil. Based on the NEHRP Classification27, materials having $V_s > 760$ m/s are considered as rocks for engineering applications. Thus running seismic profile directly over the exposed litho-sections will provide shear wave velocity values of bedrock and other lithologies, which enable us to correlate them for the unexposed section (Figure 3).

The shear wave velocity estimation was conducted covering 87 sites from the Donga Fan. The average shear wave velocity of the northern part of the Fan area was higher than the central and southern parts. The shear wave velocity of sites nos 1, 3, 5, 8, 24 and 39 (Tauli Langa, Pipalsar, Donga, Bidholi, Kandoli and Gadaria sites respectively; Figure 1) varied from 300 m/s at the top few metres to about 500 m/s up to 15–20 m, and increased up to 850 m/s below 30 m depth. The high $V_s$ values at a depth of 30 m reflect the velocity of engineering bedrock level which may represent shear wave velocity of the underlying Siwalik rocks (Figure 8a).

The low root mean square error (RMSE) values suggest a high level of confidence (Figure 8b). The RMSE is calculated based on the $V_s$ profile of a layer whose theoretical dispersion curve shows the best match with 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 confidence18.

Sites like Badowala (site no. 33), Chandpur Khurd (site no. 45), Bhagwanpur (site no. 38), Mandovala (site no. 52), Dhakoliwala (site no. 53), Silver Heights (site no. 56), Kedarwala (site no. 60) and Bahadarpur (site no. 69) show low shear wave velocity (200–300 m/s) for the top 15–20 m soil cover, followed by $V_s$ of 400–500 m/s for the next 10–15 m soil column, indicating stiff soil behaviour of the top 30 m soil column. The shear wave velocity increased to >700 m/s below 40–45 m depth (Figure 9). In general, the shear wave velocity increases with depth with slight variation in the surrounding may be due to presence of water bearing bodies.

On the other hand, sites like Badowala and Chandpur Khurd located adjacent to the river beds show very low velocity in the top 15–20 m soil cover which varies from 160 to 200 m/s, followed by 300–400 m/s for next 20 m depth (Figure 9). Further below at 40 m depth, $V_s$ increases to 800 m/s. However, at the eastern end of the section below, the station location 122–126, the shear wave velocity drops to 450–500 m/s compared to the surrounding sediments. Thus, it may indicate the presence of dissolution features or moisture content below 40 m depth.

The southern part of the Fan shows a very thick layer of clay (Figure 10). The clay is found to be much stiffer if it is dry; however, it has very less stiffness under moist conditions. Most of these sites are used for making burnt bricks. The top 20 m soil column has low shear wave velocity (350–400 m/s) and below the location of stations 135–140, the same velocity is extended up to 60 m depth. Thus, it may indicate the presence of moisture or water content at Rajawala site (site no. 49). Similarly, the shear wave velocity profile of Dholkot site (site no. 72) up to 40 m depth is between 350 and 400 m/s (Figure 10). The shear wave velocity derived for different sites of the Fan shows that the topsoil has velocity ranging from 300 to 400 m/s (5–12 m only) in the northern part, 200–250 m/s (10 m) in the central part and <200 m/s (10–20 m) in the distal part of the Fan. The second layer has a shear wave velocity of 500–600 m/s (12–18 m depth) in the northern part of the fan, 300–400 m/s (10–22 m depth) in the central part and 250–350 m/s (20–25 m depth) in the distal part. The third layer has a shear wave velocity of >760 m/s (below 18–20 m depth) in the northern part of the Fan, 500–600 m/s (22–40 m depth) in the central part of the Fan and 400–550 m/s below 25 m depth. The isolated high below the location of station 112 is stiffer (may be due to gravels) compared to its surrounding profile. The study carried out for Dehradun Fan sediments complements the observations made in the Donga Fan area28.

Based on the information from 2D shear wave velocity profiles and SHAKE 2000 (ref. 29) analysis the average shear wave velocity along with other parameters like natural frequency of the soil column, response spectra and amplification spectra have been derived. The average shear wave velocity, depth to bedrock and response parameters and amplification ratios have been tabulated.
in attribute table along with site location maps for visualization. All point information was then interpolated considering average distance between points and the survey profile line. The interpolation of all spatial data was performed in Arc View and Arc GIS software with a grid spacing of 25 × 25 m. The interpolated values were classified based on the natural grouping of data to produce a number of classes. According to NEHRP classification, different classes have been defined for the shear wave velocity map. The shear wave velocity values were then contoured using krigging method to generate a $V_s$ map. Figures 8–10 show the variation of shear wave velocity with depth, indicating that the northern part of the Fan has stiffer soil compared to central and distal parts. Based on the NEHRP classification, the Donga Fan has been classified into three soil classes, i.e. C ($V_s = 360–760$ m/s), D ($V_s = 180–360$ m/s) and E ($V_s = 180$ m/s). Of this, 80% of the area fall under class D (Figure 11).

Response analysis

According to the shear wave velocity estimation, it can be concluded that the thickness of sediments above engineering bedrock in the northern side of the Fan is about 10–20 m; however, near the MBT, the engineering bedrock ($V_s > 760$ m/s) is exposed at the surface. All along the river section downstream, several river terraces have been developed by these streams, and the thickness of sediments in these terraces above engineering bedrock was found to be within 20–25 m. The total thickness of the sediments was found to be >50–100 m in the middle of the Fan area and >150–200 m in the distal part of the Fan (Figure 12).

The thickness of sediments and shear wave velocity are the main parameters which affect the amplitude, frequency and duration of vibration that in turn determine the severity of hazard in any area. More importantly, seismic methods are dependent upon stress and strain behaviour; so the subsurface deposits with large contrast in density and velocity can bring spatial variability of the damaging pattern under fan deposits. However, the Donga Fan deposits do not have much variation in density of the material as all the sediments have been derived from the same source (adjoining Lesser Himalayan and Outer Himalayan rocks). However, the near-surface material properties, i.e. stiffness, damping of the material and impedance contrast play a major role in site amplification of different sites in the Donga Fan. Shear wave velocity is one the key parameters in controlling the damage pattern of any region, and is assumed to propagate vertically upwards from the bedrock and their motion will be different for outcrop and at near surface; so their transfer function has been approximated using linear computer algorithm SHAKE2000 (ref. 29). Since the shear wave velocity was acquired using low strain source, strong ground motion {Chamoli earthquake (6.4 mb) with PGA as 0.054 g for bedrock} from the region was taken as the

Figure 11. Average shear wave velocity map of the Donga Fan.

Figure 12. Thickness of sediments above engineering bedrock beneath the Donga Fan.

Figure 13. Computed acceleration time history for Kandoli site using SHAKE2000 from horizontal component strong motion data of the Chamoli earthquake. (Source: Department of Earthquake Engineering, Indian Institute of Technology, Roorkee.)
input parameter to obtain the response spectra for different sites of the Donga Fan, as no other strong motion data are available from the Himalayan region for any major or great earthquake. Therefore, the strong motion data of Chamoli earthquake recorded at Tehri at bedrock level was considered as the reference input motion, and the acceleration-time history has been derived at each reference site (Kandoli site; Figure 13). If needed, the shear wave velocity data can be used by other researchers for simulating the strong motion data for great earthquakes and calculate the response.

Three to four soil layers model, such as surface clay, rock fill (pebble, cobble, sticky clay sand mixed with lime) gravel, and compact gravel and boulder equivalent of rock has been considered up to 30 m, based on the exposed litho-sections and litholog information. The damping and modulus curve values were obtained from SHAKE2000 using standard values of these layers30–34.

The SHAKE2000 software was used to calculate response analysis using various parameters like $G_{\text{max}}$, $\gamma_{\text{Max}}$, unit weight, sub-layer thickness, damping, shear modulus curves to derive shear strain, $G_{\text{max}}$, sub-layer thickness and damping ratios using shear wave velocity from experimental data30–34. The amplification spectra, response spectra along with natural frequency, average shear wave velocity of the top 30 m soil columns were 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. All response parameters were added to the attribute table to process the data in GIS format.

All point-source information was interpolated using a grid spacing of $25 \times 25$ m by considering average distance between points and the survey profile line. The interpolation technique has been used with natural grouping of data to produce several classes randomly.

**Output of site response analyses**

Figure 14a shows the response spectrum from stiffer soils, i.e. Kandoli site (site no. 39) and Figure 14b shows its corresponding amplification spectrum.

The maximum peak spectral acceleration was found to be 0.8g at frequency of 4.9 Hz. The corresponding amplification spectrum for the same site showed peak amplification at 4.9 Hz with typically hard-rock amplification spectrum for the next two layers. Similarly, after examining the near-surface characteristics of Rajewala site (site no. 49), the peak response was observed at 1.8 Hz with peak spectral acceleration of 0.75 g (Figure 14c). Its corresponding amplification spectrum shows peak amplification at 1.8 Hz (Figure 14d).
Thus, it can be inferred that under thick sedimentary cover, one can have site amplification at lower frequency compared to hard-rock sites, where the site amplification was observed at >4 Hz. Since the study area is mainly occupied by either single or two-storey buildings, spectral analysis is shown only for these types of building. The spectral acceleration computed for two-storey buildings also varied from 0.19 to 0.40 g (at 5 Hz with 5% damping, Figure 15a). Whereas, in case of single-storey buildings, spectral acceleration varied from 0.12 to 0.22 g (at 10 Hz with 5% damping, Figure 15b). The corresponding amplification ratio varied from 6 to 15 times in the entire Donga Fan. The characteristic site periods for 30 m soil column showed variation from 0.82 to >1.00 s (1.22–1 Hz) in the south-western part of the Fan, to 0.20–0.57 s (1.75–5 Hz) in the northern part of the Fan (Figure 16 and Table 1).

The central part of the Fan showed a variation in site characteristics from 0.60 to 0.70 s (1.66–1.42 Hz). According to the horizontal to vertical spectral ratio (HVSR) studies from Doon Valley, the predominant frequency obtained in the Fan ranged from 0.13 to 2 Hz in the southern part, 2.5 to 4 Hz in the central part, and 5 to 8 Hz in the northern part, which is in good agreement with the peak spectral frequency obtained in the present study (Table 1).

**Conclusion**

Given the lack of knowledge on the recurrence interval for major or great earthquakes in the Himalayan region, the reconciliation of site amplification using geotechnical properties of the near surface is of utmost importance. Further, the construction of any engineering site is dependent on the understanding of the subsurface information, i.e. stiffness parameters of the soil column and their effect on the buildings during strong excitation. $V_s$ profile is one of the key parameters in this respect and can provide a relative means of determining environmental effect of the subsurface. The assessment of site-effect studies at micro-scale or urban-level scale requires knowledge of elastic properties of subsoil down to bedrock level to estimate bedrock motion expected at the site.

As the construction of any engineering site is dependent on the understanding of the near-surface properties of the material, therefore stiffness parameters of the soil column and their effect on the buildings during strong excitation have been estimated. In the present study, variation of shear wave velocity in the top 30 m soil column has been derived using MASW method. The study reveals that majority of the Donga Fan area comes under soil class D ($V_s$ 180–360 m/s) according to NEHRP classification. The spatial distribution of $V_s$ has provided valuable information on the stiffness of the soil in different parts of the Fan area. The characteristic site period of each site computed using response analysis is in good agreement with the fundamental frequencies derived using the HVSR technique. The northern part of the...
Table 1. Various response parameters using SHAKE2000 analysis

<table>
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<th>Site no.</th>
<th>Site name</th>
<th>Bedrock depth</th>
<th>Period (T)</th>
<th>PGA (g)</th>
<th>$V_s$ Bedrock (F/s)</th>
<th>$V_s$ Bedrock (mt/s)</th>
<th>Accel.</th>
<th>Freq.</th>
<th>5 Hz</th>
<th>1 Hz</th>
<th>10 Hz</th>
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<th>Freq.</th>
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<td>Kotra Kalyanpur</td>
<td>25</td>
<td>0.24</td>
<td>0.187</td>
<td>1377</td>
<td>417</td>
<td>1.09</td>
<td>4.34</td>
<td>0.698</td>
<td>0.040</td>
<td>0.248</td>
<td>18.00</td>
<td>4.62</td>
</tr>
<tr>
<td>5</td>
<td>Donga</td>
<td>42</td>
<td>0.67</td>
<td>0.109</td>
<td>826</td>
<td>250</td>
<td>0.490</td>
<td>1.61</td>
<td>0.200</td>
<td>0.088</td>
<td>0.119</td>
<td>8.58</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>NT40</td>
<td>50</td>
<td>0.49</td>
<td>0.144</td>
<td>1355</td>
<td>411</td>
<td>0.787</td>
<td>1.81</td>
<td>0.197</td>
<td>0.080</td>
<td>0.168</td>
<td>8.56</td>
<td>1.75</td>
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<tr>
<td>7</td>
<td>NT56</td>
<td>50</td>
<td>0.67</td>
<td>0.220</td>
<td>986</td>
<td>299</td>
<td>0.864</td>
<td>1.78</td>
<td>0.387</td>
<td>0.094</td>
<td>0.251</td>
<td>9.39</td>
<td>1.62</td>
</tr>
<tr>
<td>8</td>
<td>Bidholi</td>
<td>23</td>
<td>0.25</td>
<td>0.231</td>
<td>1219</td>
<td>369</td>
<td>1.10</td>
<td>4.16</td>
<td>0.550</td>
<td>0.041</td>
<td>0.266</td>
<td>10.69</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>NT14</td>
<td>30</td>
<td>0.45</td>
<td>0.197</td>
<td>876</td>
<td>265</td>
<td>1.07</td>
<td>2.38</td>
<td>0.293</td>
<td>0.079</td>
<td>0.212</td>
<td>7.40</td>
<td>2.25</td>
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(Contd)
Donga Fan area reflects the effect of impedance contrast because of the high $V_s$ variation between the top soft soil and the stiffer material below, whereas the southern part of the Fan shows high amplification due to greater thickness of sediments above engineering bedrock level.

The Donga Fan is characterized by long-term weathering and erosion history with unknown sediment thickness that may lead to large variation in site amplification. The present study shows variation in the stiffness of the sediments with depth, spectral acceleration and characteristic site period at different sites of the Donga Fan based on actual shear wave velocity measurements and response analysis following few assumptions. Considering the intensity variations from the past earthquakes (1905 Kangra, 1991 Uttarakashi and 1999 Chamoli), the present study will be helpful in land-use planning of the upcoming urban centre and to reduce disaster risk in the future. The present methodology will be useful for researchers studying other such valleys or duns.

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