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ORIGINAL PAPER

Influence of local site conditions on strong ground motion characteristics at Tarai region of Uttarakhand, India

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Abstract Local site conditions strongly influence the characteristics of strong ground motion. In this study, influence of local site conditions on characteristics of strong ground motion records and their further effects on hazard studies were investigated for the Tarai region of Uttarakhand, India, where the thickness of soil cover varies significantly from few meters to several hundreds of meters. Another importance of these sites is that these sites have strong motion recording stations. Site characterization of each of the strong ground motion station is conducted using MASW tests to obtain shear wave velocity profiles of the sites. Further, site-specific ground response analysis is carried out using SHAKE2000 to investigate local site effects on strong ground motion records. Results clearly show the differences in IS 1893:2002 (Part-1) suggested 5 % damping response spectrum and the one obtained from ground response analyses. For sites having V_{s30} around 200 m/s, constant acceleration frequency band is significantly widened in comparison with 5 % damping response spectrum of IS-1893:2002 (Part-1). This study further suggests the importance of thorough site characterization of strong motion instrumentation sites.

Keywords Site characterization · Response spectra · Microzonation · Shear wave velocity · Site response

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1 Introduction

Large modifications in seismic waves can occur due to change in variation in soil properties near to the surface of earth. These modifications, known as "local site effects," are the main cause due to which large amplitudes are observed in soil sites in comparison with rock sites. The oldest account of such modifications was reported by MacMurdo (1824) regarding earthquake in Cutch, India. He observed that the buildings situated on rock were not affected as much as the buildings whose foundations were on soft soil. Later, these findings are being continuously supported by many other earthquakes (e.g., "The September 19, 1985 Michoacán Earthquake" (Stone et al. 1987), "The October 19, 1989 Loma Pieta earthquake" (Seed et al. 1990), "The January 26, 2001 Bhuj Earthquake" (Sitharam and Govindraju 2004a, b), etc.) and through the works of many researchers worldwide (Seed et al. 1976; Silva 1988; Aki 1988; Boore 2004, etc.).

The September 19, 1985 Michoacán ($M_s = 8.1$) earthquake is very often referred whenever there are discussions over influence of local site conditions on strong ground motion. This earthquake caused only moderate damage in the vicinity of its epicenter, but caused extensive damage 350 km away in Mexico City. The peak accelerations observed in this earthquake at rock sites of Mexico City were only in the range of 0.03–0.04 g. However, in soft soil sites the peak accelerations were up to five times greater than those at rock site. Hence, the damage was negligible in the rock sites, but damages were very high at sites underlain by 38–50 m of soft soil (Stone et al. 1987). Similarly, on October 19, 1989, a $M_s = 7.1$ earthquake occurred near Mt. Loma Prieta located about 100 km south of San Francisco and Oakland, California. The earthquake produced MMI VII shaking in the epicentral region, while the intensities were found to be higher, MMI IX, in portions of San Francisco and Oakland. The damages were found to be very selective of site conditions (Seed et al. 1990). A study was conducted by Sitharam and Govindraju (2004a, b), for medium- to high-rise residential buildings collapsed in Ahmadabad in 2001 Bhuj Earthquake. Even though Ahmedabad city was 300 km away from the epicenter, high degree of damage is occurred due to the consequence of large amplification of shear waves by the thick layer of sandy soil deposit, resulting in differential settlements. This soil amplification has caused large accelerations to some buildings in particular to the buildings above four storeys and up to ten storeys.

Himalayan region is one of the most seismically active zones of world and also close to the Indo-Gangetic plain which is also most densely populated region of India. Indo-Gangetic plain has deep alluvium deposits, which would have significant effect on strong ground motion records as well as seismic hazard as noted from the literature (Jakka et al. 2013, 2015). Many strong motion recording stations, equipped with accelerographs and seismographs, are installed in this region by various agencies. Hence, the study of local site conditions becomes important for these station locations so that the accurate seismic hazard assessment can be carried out. Site characterization of all these stations needs lots of time and resources. For this study 12 towns (Fig. 1) in Tarai region (Plains of Himalayas) of Uttarakhand were considered. All these stations have strong motion recording stations under a Government of India project entitled "National Strong Motion Instrumentation Network."

2 Details of study locations

Towns that were selected for the study are Roorkee, Haridwar, Rishikesh, Dehradun, Vikasnagar, Kotdwar, Laksar, Kashipur, Haldwani, Udham Singh Nagar, Khatima and Tanakpur. The strong motion sensors installed at these sites are managed by Department of

Fig. 1 Site locations for study

Earthquake Engineering, IIT, Roorkee, under the "National Strong Motion Instrumentation Network." www.pesmos.in PESMOS is the website which provides records and other information about the "National Strong Motion Instrumentation Network," a project of Ministry of Earth Science, Government of India. Under this project, 294 strong motion accelerographs have been installed in north and NE India covering seismic zones V and IV and some thickly populated cities of seismic zone III. Installations have been done in states of Himachal Pradesh, Punjab, Haryana, Rajasthan, Uttarakhand, Uttar Pradesh, Bihar, Sikkim, West Bengal, Meghalaya, Arunachal Pradesh, Mizoram, Assam and Andaman and Nicobar Islands. The same network is referred as PESMOS in the later portions of this paper. The site classification provided in PESMOS is based on the study of Mittal et al. (2012) who modified the Borcherdt (1994) classification to suit to local conditions. Classification of sites by Mittal et al. (2012) (PESMOS site classification) was carried out by studying physical description of near surface materials and local geology. The physical description of near surface materials and local geology was gathered from Seismotectonic Atlas of India and its Environs (GSI 2000), Geological Maps of India (GSI 1998) and different books and research papers, but no actual testing was done at the strong motion recording stations (Mittal et al. 2012). Hence, the classification was mainly based on soil/rock types. Sites were divided into three categories: class A, class B and class C. The site classification of PESMOS is as follows:

- $V_{s,30} > 700$ m/s is defined as class A which means firm/hard rock site.
- 375 m/s $< V_{s,30} <$ 700 m/s is defined as class B which means soft to firm rock site.
- $V_{s,30} < 375$ m/s is defined as class C which means soil sites.

The site class for all the stations considered for this study lies in class C (soil sites), except Kotdwar which is class B as per PESMOS.

The objective of this paper is to provide site characterization of all the 12 sites up to 30 m depth and evaluate the local site effects due to top 30 m soil strata providing amplification functions for each site. Further expected 5 % damping response spectra were plotted by conducting ground response analysis (GRA) using SHAKE2000. For input motion in SHAKE2000, spectrum-compatible motions, compatible with 5 % damping response spectrum provided in IS 1893:2002 (Part-1) for rock sites, are generated using program developed by Kumar (2006), and used at the top of half space.

3 Site characterization

In general, site characterization can be defined as the process of defining the subsurface material properties. The site characterization is one of the most important aspects of geotechnical earthquake engineering, as strong motion recordings cannot be properly interpreted until and unless the geotechnical and geophysical properties of material, through which seismic waves are travelling, are known. The material properties can be defined with various parameters such as, shear modulus, density, index properties and shear wave velocity. Lots of different kinds of field and laboratory tests are available to identify these properties. As already discussed, for PESMOS classification, no geophysical and geotechnical site investigations were conducted at these stations and the site classes were assigned on the physical description and local geology of that area.

For this study, shear wave velocity profiles were obtained by conducting MASW test at all the twelve selected locations, nearest to the installed strong motion instrument. Information regarding soil strata of all the stations was obtained from various geotechnical investigating agencies and tube-well boring agencies.

For conducting MASW testing, equipment known as McSeis-SXW, manufactured by OYO Corporation Japan, was used. The geophones used were of 2 Hz frequency and 80-kg drop weight hammer was used as source. To start the test, a location was identified nearest to the installed strong motion instrument. After finalizing the location, an array of 24 geophones of 2 Hz frequency was laid out at the spacing of 2 m. The geophones are connected to the data acquisition device. The “2-D surface wave method” was opted in data acquisition device for conducting the required survey. The drop weight hammer was placed at 2 m intervals for each shot. The starting location was 1 m prior to the first sensor in the line of sensors. The last location was 1 m away from the last sensor in the line of sensors. Hence, a total of 25 shots were recorded for each station.

The data recorded in 25 shots were than analyzed using the software SeisImager/SW. The SeisImager/SW software has three more tools, i.e., PickWin95, WaveEq and GeoPlot which are used for further analysis.

The first step of the analysis is making the file list of all the waveform files, from all the 25 shots gathered, in which source receiver configuration is mentioned. In the next step, all pairs that have common midpoint (CMP) from all traces were extracted and cross correlation of CMP gather files was calculated. Cross-correlated CMP gather files were then saved as pseudo shot gather files for each CMP location. Next step is generation of dispersion curves by converting it into frequency domain for each cross-correlated CMP gather. Dispersion curve generation is one of the most critical steps in the calculation of shear wave velocity profiles. If there is any error in generation of inversion curves, then the shear wave velocity profile will also be erroneous.

The dispersion curves are generally displayed as phase velocity versus frequency. In the next step, inversion of dispersion curves is conducted and shear wave velocity profiles were generated using GeoPlot.

3.1 Shear wave velocity profiles

The results obtained from MASW field tests are shown in Fig. 2 as 1D shear wave velocity profile. The details of soil stratification and soil types are also provided in Table 1.

Summary of the results in the form of V_{s30} is presented in Table 2. After analyzing the results, based on measured V_{s30}, it was observed that Haldwani, Tanakpur and Vikasnagar should lie on class B in PESMOS and not in class C. Classification of these sites as per NEHRP was also carried out and presented in Table 3.

4 Ground response analysis

Ground response studies are very helpful in estimating the acceleration time history at surface level for input time history at base, amplification functions and 5 % damping response spectrum at each site. For conducting ground response analysis, we need acceleration time histories at bedrock level and soil properties of the soil strata. Due to scarcity of recorded motions at these locations, a methodology similar to Govindaraju and Bhattacharya (2012) was used for getting suitable time history for the analysis. This methodology involves, (a) selection of time histories with peak acceleration, at bedrock level, which represents the seismic hazard (b) development of synthetic acceleration time histories which matches with the 5 % damping response spectrum, given for rock sites, provided by IS 1893:2002 (Part-1).

According to seismic zoning map of India, Bureau of Indian Standards (IS 1893:2002 Part-1), these sites lie in severe seismic zone (Zone IV) with a zone factor of 0.24. Also, Global Seismic Hazard Assessment Program (GSHAP) map, which is based on 10 % probability of exceedance in 50 years, specifies the maximum peak ground acceleration (PGA) of 2.4 m/s^2 (0.24 g) for this region. Hence, in the present study, the maximum peak ground acceleration (PGA) of 0.24 g has been selected for these sites.

For ground response analyses, synthetic earthquake ground motions were used as input motion. These synthetic earthquake ground motions, compatible to 5 % damping response spectrum provided in IS 1893:2002 (Part-1), were generated using the program developed by Kumar (2006).

For generating synthetic ground motions, one of the steps is to select suitable ground motions from historical earthquake records. The records were selected, from Kik-NET or K-NET (http://www.kyoshin.bosai.go.jp/), on the basis that they must be recorded on rock sites and also the PGA of the records must be around 0.24 g. Also the records selected are in the range of magnitude 5–8. The details of strong motion records used are provided in Table 4. Using these strong motion records, the synthetic acceleration time histories were generated for the target 5 % damping response spectrum given for rock sites in IS 1893:2002 (Part-1). These synthetic acceleration time histories were then used as input motion at 30 m depth for conducting ground response analysis.

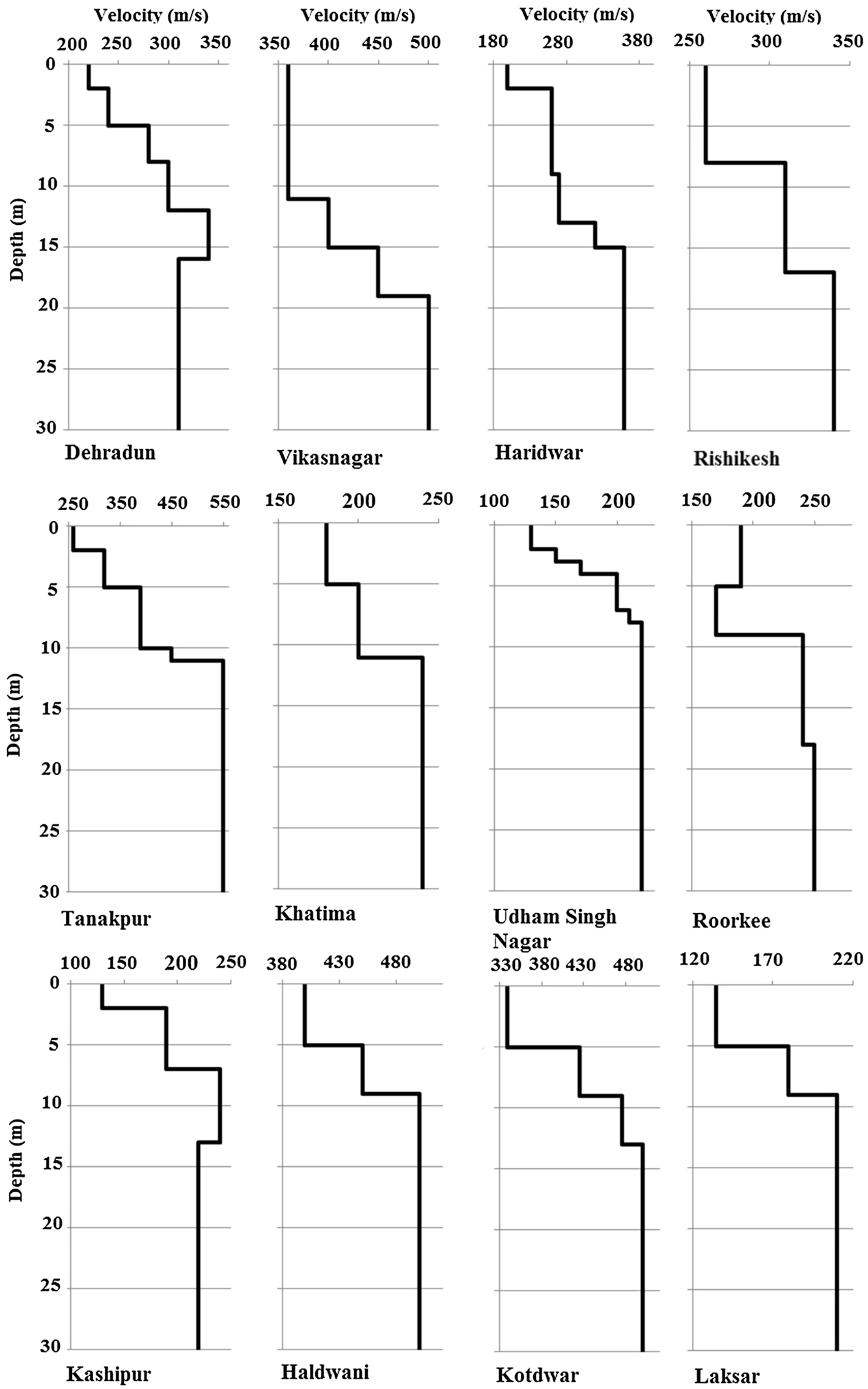

Fig. 2 1D shear wave velocity profiles of 12 stations

Table 1 Information regarding soil strata collected from various sources

<table>
<tr><th rowspan="2">S. No.</th><th rowspan="2">Location</th><th colspan="8">Soil Strata (m)</th></tr>
<tr><th>1-1.5</th><th>1.5-3.0</th><th>3.0-6.0</th><th>6.0-10.0</th><th>10.0-20.0</th><th>20.0-25.0</th><th>25.0-30.0</th><th>Water Table Depth (m)</th></tr>
<tr><td>1</td><td>Haldwani</td><td>Clay, Sand, Boulders</td><td colspan="6">Boulders, Pebbles, Sand</td><td>160</td></tr>
<tr><td>2</td><td>Tanakpur</td><td colspan="2">Clay, Sand, Boulders</td><td colspan="2">Boulders, Pebbles, Sand</td><td colspan="3">Boulders, Fine sand</td><td>12</td></tr>
<tr><td>3</td><td>Khatima</td><td>Clay, Sand</td><td colspan="3">Clay, Sand, Boulders</td><td colspan="3">Loose boulders, Fine sand</td><td>3</td></tr>
<tr><td>4</td><td>Udham Singh Nagar</td><td colspan="2">Clay</td><td colspan="2">Pebbles, Clay, Soft Boulders</td><td colspan="3">Sand, Clay</td><td>3</td></tr>
<tr><td>5</td><td>Kashipur</td><td colspan="2">Clay</td><td colspan="2">Pebbles, Clay, Soft Boulders</td><td colspan="3">Fine Sand, Clay</td><td>3</td></tr>
<tr><td>6</td><td>Kotdwar</td><td>Clay, Sand, Boulders</td><td colspan="6">Boulders, Pebbles, Sand</td><td>160</td></tr>
<tr><td>7</td><td>Roorkee</td><td colspan="4">Silty Sand</td><td colspan="3">Sand</td><td>6</td></tr>
<tr><td>8</td><td>Laksar</td><td>Clay</td><td colspan="3">Clay, Loose Boulders, Pebbles.</td><td colspan="3">Clay, Sand, Pebbles</td><td>10</td></tr>
<tr><td>9</td><td>Haridwar</td><td>Clay</td><td colspan="5">Clay, Boulders, Pebbles</td><td>Clay</td><td>50</td></tr>
<tr><td>10</td><td>Rishikesh</td><td colspan="2">Clay, Sand, Boulders</td><td colspan="2">Boulders, Pebbles, Sand</td><td colspan="3">Boulders, Fine sand</td><td>12</td></tr>
<tr><td>11</td><td>Vikasnagar</td><td>Clay</td><td colspan="3">Clay, Boulders</td><td colspan="3">Pebbles, Boulders, Sand</td><td>25</td></tr>
<tr><td>12</td><td>Dehradun</td><td>Clay</td><td colspan="2">Clay, Soft Boulders</td><td colspan="2">Soft Boulders, Pebbles, Sand, Clay</td><td colspan="2">Boulders, Pebbles</td><td>50</td></tr>
</table>

Predefined curves from SHAKE2000 were used as input for dynamic soil properties like G/Gmax and damping curves. Soil type for selection of curves is taken from Table 1. Also shear wave velocity profiles are provided as input for different layers as shown in Fig. 2. These shear wave velocity profiles were obtained from MASW testing at different locations as explained earlier in this paper.

For the sake of convenience of analysis and comparison of results, sites were grouped into the following three groups:

- Group 1: sites having $V_{s30} < 250$ m/s.
- Group 2: sites having V_{s30} between 250 m/s and 375 m/s.
- Group 3: sites having $V_{s30} > 375$ m/s.

Sites corresponding to Group 1 and Group 2 come under site class C (as per PESMOS) and sites corresponding to Group 3 come under site class B (as per PESMOS). These groupings were done for the ease of interpretation and understanding the results.

Output of the ground response analysis was obtained as two important results: One is amplification function for each site and other is 5 % damping response spectrum. The average amplification function, taking average of five ground response analyses for five spectral compatible motions corresponding to different earthquakes, is calculated. These results were used as follows:

Table 2 Summary of shear wave velocity profiles and corresponding site class as per PESMOS

S. no.	Location	Vs30 (m/s)	Site class	
			Given in PESMOS	Actual site class (PESMOS) based on V_{s30} obtained from site investigation
1	Tanakpur	434	C	B
2	Khatima	218	C	C
3	Udham Singh Nagar	198	C	C
4	Kashipur	208	C	C
5	Haldwani	472	C	B
6	Kotdwar	448	B	B
7	Roorkee	218	C	C
8	Haridwar	294	C	C
9	Rishikesh	305	C	C
10	Vikasnagar	425	C	B
11	Dehradun	289	C	C
12	Laksar	187	C	C

Table 3 Site classes as per NEHRP

S. no.	Location	Vs30 (m/s)	NEHRP site class	Definition
1	Tanakpur	434	C	Dense soil
2	Khatima	218	D	Stiff soil
3	Udham Singh Nagar	198	D	Stiff soil
4	Kashipur	208	D	Stiff soil
5	Haldwani	472	C	Dense soil
6	Kotdwar	448	C	Dense soil
7	Roorkee	218	D	Stiff soil
8	Haridwar	294	D	Stiff soil
9	Rishikesh	305	D	Stiff soil
10	Vikasnagar	425	C	Dense soil
11	Dehradun	289	D	Stiff soil
12	Laksar	187	D	Stiff soil

a. The calculated amplification functions of different sites were compared.
b. Average response spectrum was also obtained for all the sites and compared with response spectrum given in IS 1893:2002 (Part-1).
c. The response spectrum was also compared with the spectrum obtained from earthquake records recorded at these stations.

Summary of amplification at fundamental mode and corresponding fundamental frequencies at each site for each record are provided in Table 5. Last column of Table 5 shows maximum amplification and corresponding frequency for the curve obtained after taking average of all the figures obtained from ground response analysis of different

Table 4 List of strong ground motion records used for generating spectral compatible synthetic time histories

S. no.	Name	Date and time	Lat (E)	Long (N)	Depth (km)	Magnitude	Record	PGA (cm/s^2)	Duration (s)
1	The Iwate-Miyagi Nairiku Earthquake	6/14/08 8:43 AM	39.03	140.88	8	7.2	AKTH040806140843	255.5	300
2	The Tokachi-Oki Earthquake 2003	9/26/03 4:50 AM	41.78	144.07	42	8	HKD1130309260450	204.9	297
3	–	3/28/11 7:24 AM	38.79	141.33	31	6.5	MYGH041103280724	143	132
4	–	8/30/12 4:05 AM	38.407	141.913	60	5.6	MYG0121208300405	184	85
5	–	2/12/01 10:02 PM	39.398	141.263	122	6.4	MYG0110112022202	204.83	170

records. Amplification functions for each site are provided in Figs. 3, 4 and 5. Amplification for Group 1 sites ranges between 2.5 and 4.8 over frequency band of 0.8–1.0 Hz. For Group 2 sites, amplification was found to be varying from 3.6 to 4.0 over frequency band of 1.1–1.4 Hz. Similarly, for Group 3 sites, amplification was found to be varying from 4.3 to 4.9 over 2.0–2.1 Hz frequency.

Figures 6, 7 and 8 show the comparison of average normalized 5 % damping response spectrum for different sites, with the 5 % damping response spectrum of IS 1893:2002 (Part-1). The comparison clearly shows that the response spectrum, obtained after theoretical ground response analysis, has high variation than the response spectrum provided in IS 1893:2002 (Part-1). Figure 9 shows the comparison of 5 % damping response spectrum obtained from theoretical ground response analysis, 5 % damping response spectrum obtained using actual recorded ground motion and 5 % damping response spectrum provided in IS 1893:2002 (Part-1) for the study region.

5 Discussions

It was found that most of the places have soil strata consisting of mixture of boulders and sand except Roorkee, Kashipur and Udham Singh Nagar, where the soil strata primarily consist of sand and clay. In towns such as Haldwani, Tanakpur, Kotdwar and Rishikesh, the boulders are predominant from the top layer of soil strata. The depth of water table is found to be shallow for most of the sites except Haldwani and Kotdwar where it is more than 150 m. For five other sites, viz. Khatima, Udham Singh Nagar, Kashipur, Roorkee and Laksar, it was <10 m. The shear wave velocity profiles were obtained by conducting MASW tests. The V_{s30} values calculated from these results vary from 187 to 472 m/s. As per measured $V_{s,30}$ values, four sites are falling under site class B and eight are falling under site class C (Table 2). It was found that three sites, viz. Haldwani, Tanakpur and Vikasnagar, were originally defined as site class C based on surface geology (PESMOS), which are now coming under site class B according to the measured shear wave velocity profiles ($V_{s,30}$).

Ground response analyses for these sites were carried out using SHAKE2000, and the outputs were taken as amplification functions and response spectra. Fundamental frequency for Group 1 sites is observed to be <1 Hz. Group 2 sites showed max response at the fundamental frequency just above 1 Hz. Fundamental frequency for Group 3 sites was observed to be at around 2 Hz. The amplification ratios, for average amplification function (Table 5), for all the sites were found to be almost similar except for Khatima and Kashipur, where it was below 3 at fundamental frequency. The maximum average amplification ratio is observed for Tanakpur at around 4.9 at fundamental frequency of 2.1 Hz, while minimum was for Khatima at 2.5 at fundamental frequency of 0.8 Hz.

The comparison of normalized spectrum, obtained after ground response analysis, with response spectrum provided in IS 1893:2002 (Part-1), does not match (Figs. 6, 7, 8). With decreasing $V_{s,30}$ values, widening in the frequency band, at constant acceleration band, can be clearly seen from the Figs. 6, 7 and 8. The response spectrum obtained from ground response analysis was also compared with response spectrum obtained from recorded motion. The response spectrum of all the sites obtained from the actual recorded motions is toward left (Fig. 9) in comparison with the response spectrum obtained from ground response analysis. This could be due to two reasons:

Table 5 Amplification ratios at fundamental mode and corresponding fundamental frequencies at each site for each synthetic time history

Site	AKTH040806_EW		HKD113030_EW		MYG011011_EW		MYG0121208_EW		MYGH041103_EW		Average amplification function	
	Amplification	Frequency	Amplification	Frequency	Amplification	Frequency	Amplification	Frequency	Ampli fication	Frequency	Ampli fication	Frequency
DDN	4.37	1.38	4.38	1.38	4.41	1.5	4	1.25	3.5	1	3.7	1.4
HDW	4.7	2.13	4.2	2	4.62	2.13	4.12	1.88	4.5	2	4.3	2
HW	4.3	1.38	4.3	1.5	4.25	1.5	3.9	1.25	3.75	1.25	4	1.4
KDW	4.72	2.13	4.25	1.88	4.53	2	4.15	1.88	4.5	2	4.3	2
KPR	4.85	1	4.71	1	3.7	1.63	3.37	1.63	3.43	1.63	2.9	1
KTM	2.6	0.38	3.5	0.75	3.5	0.75	3	0.63	3	0.63	2.5	0.8
LSR	5	1	5	1	4.7	0.88	4.4	1	4.25	1	4.6	1
RKSH	3.93	1.25	3.8	1.25	4.17	1.25	3.4	1.13	3.8	1.13	3.6	1.1
ROO	3.6	1	3.53	1.13	3.5	1	3	0.88	3.55	1	3.4	1
TNK	5.5	2.25	4.9	2.13	5.5	2.25	4.74	2	5.1	2.13	4.9	2.1
USN	5	1	5.1	1	5	1	4.5	1	4.6	1	4.8	1
VKN	5.1	2	4.52	1.88	4.6	2	4.21	2.25	4.83	2	4.4	2

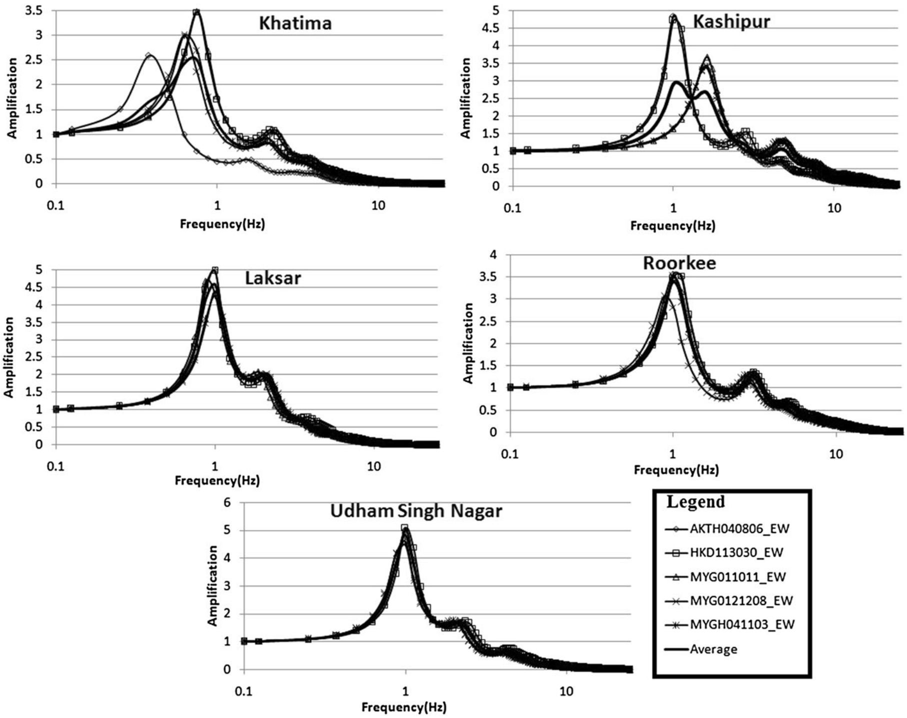

Fig. 3 Amplification function for Group 1 sites having Vs30 < 250 m/s

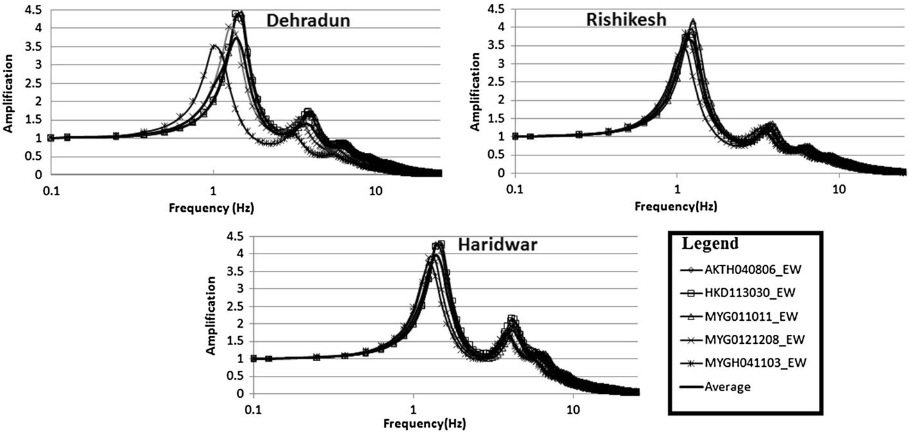

Fig. 4 Amplification function for Group 2 sites having 250 m/s < Vs30 < 375 m/s

a. Actual earthquake records, taken into consideration for analyses, were short-distance earthquakes. Short-distance earthquakes usually consist of high-frequency content, which results in shift of response spectrum toward left.

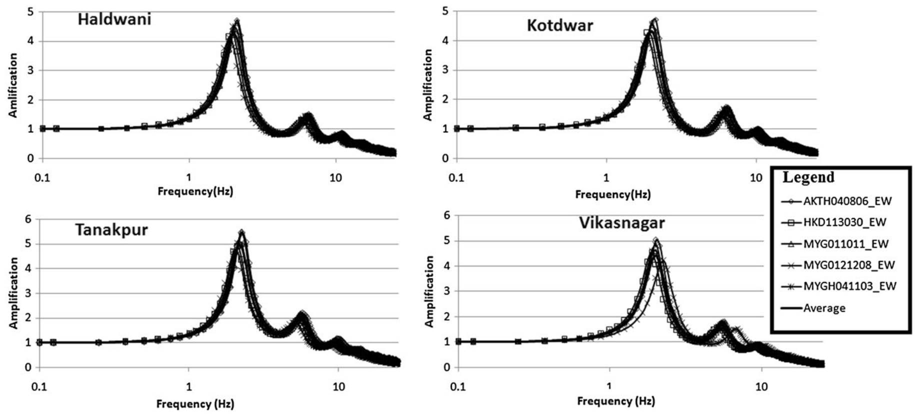

Fig. 5 Amplification function for Group 3 sites having Vs30 > 375 m/s

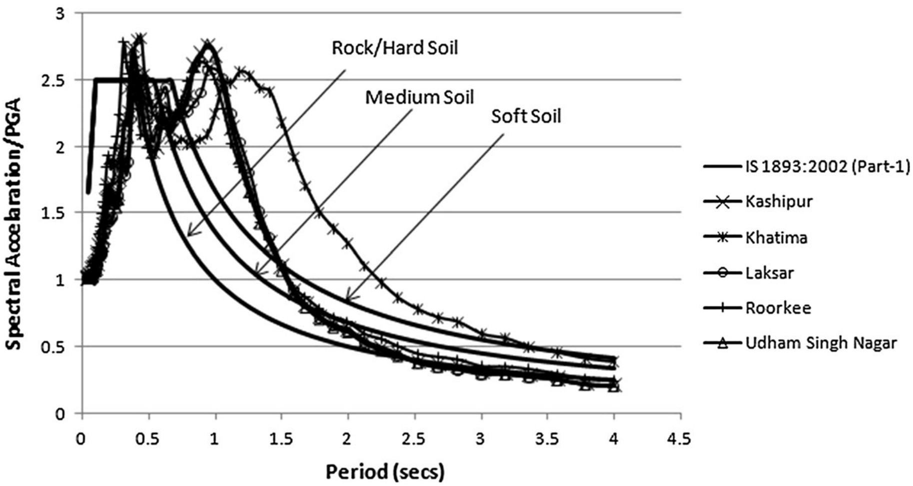

Fig. 6 Comparison of normalized response spectrum, for Group 1 sites having Vs30 < 250 m/s, with response spectrum of IS 1893:2002 (Part-1)

b. All the spectrum-compatible ground motions considered for ground response analyses were high-intensity motions in comparison with the actual recorded earthquakes. High intensity of shaking induces higher strains in the medium. It is a well-known phenomenon that shear stiffness of soil decreases with increase in strain in the layer (i.e., modulus reduction with strain, usually represented by modulus reduction (G/Gmax v/s strain) curve). This decrease in the shear modulus, in turn, causes increase in fundamental period of the site.

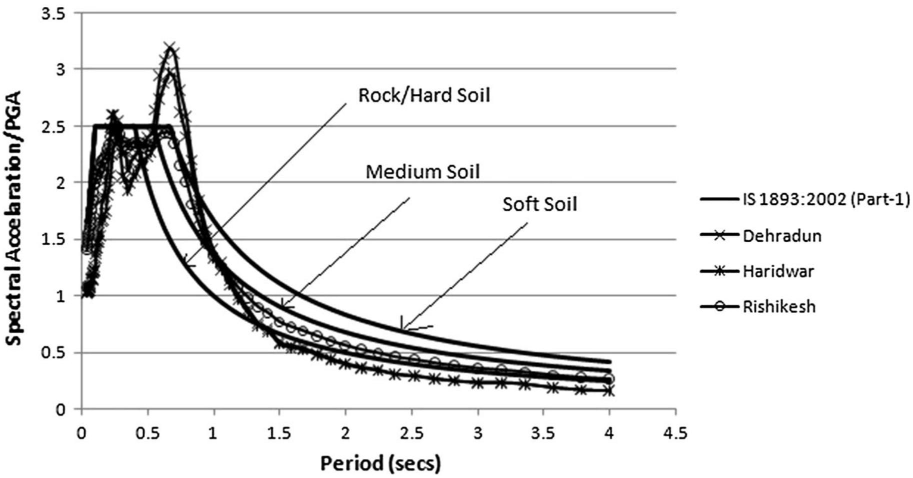

Fig. 7 Comparison of normalized response spectrum, for Group 2 sites having 250 m/s < Vs30 < 375 m/s, with response spectrum of IS 1893:2002 (Part-1)

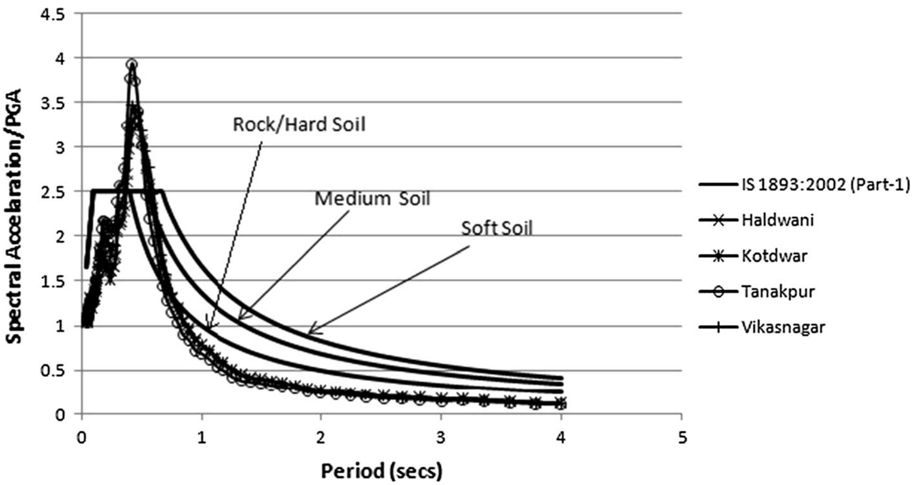

Fig. 8 Comparison of normalized response spectrum, for Group 3 sites having Vs30 > 375 m/s, with response spectrum of IS 1893:2002 (Part-1)

6 Conclusions

Site characterization by using measured $V_{s,30}$, obtained from MASW field test conducted at each station, clearly identifies the problems in existing site classes (in PESMOS), which are based on surface geology. Three sites, viz. Haldwani, Tanakpur and Vikasnagar, which were originally cited as class C sites (in PESMOS), were found to be in class B after conducting MASW tests.

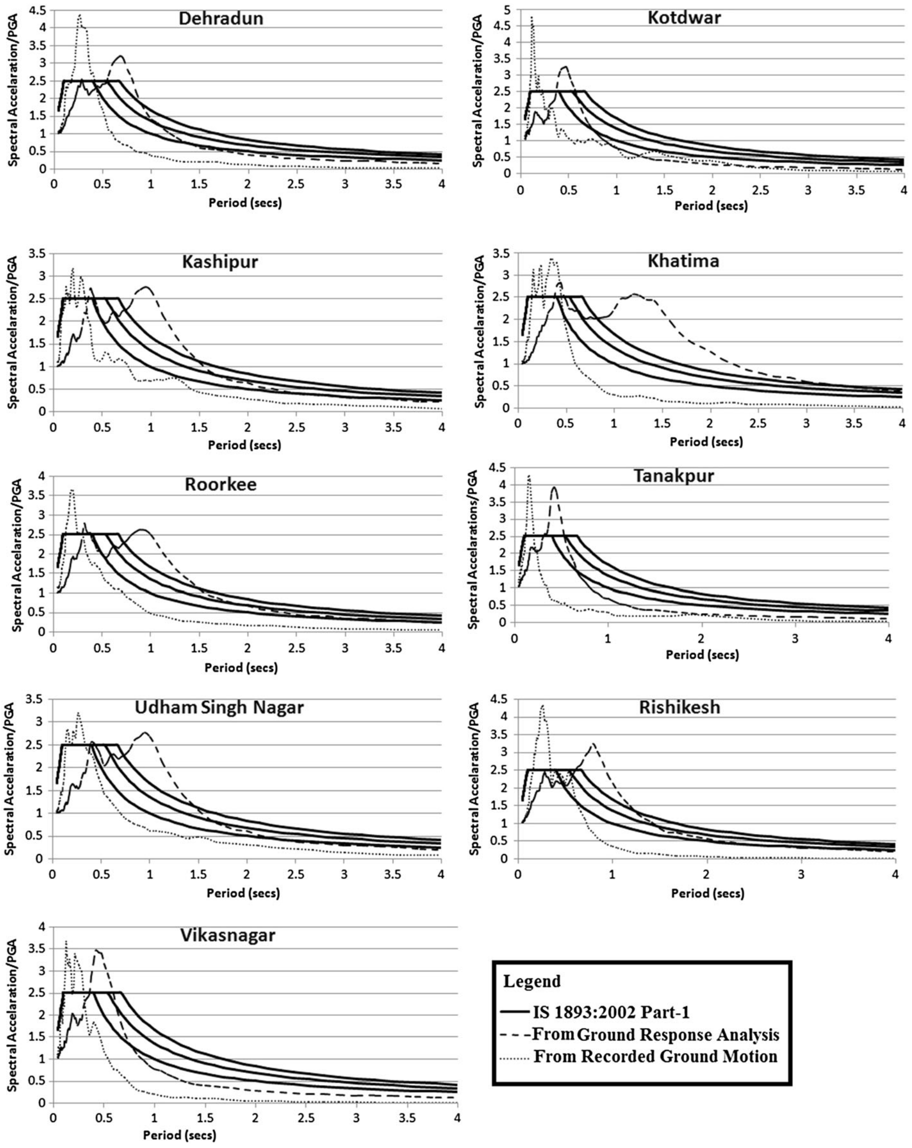

Fig. 9 Comparison of response spectra obtained by ground response analysis, response spectra obtained from recorded motion and response spectrum provided in IS 1893:2002 (Part-1)

Site amplification ratios from ground response analysis were found to be varying from 2.5 to 4.9 for different sites. Fundamental frequency was found to be similar for sites in a particular group. Fundamental frequency for Group 1 sites was found to be lowest (below 1 Hz).

The normalized response spectrum obtained from ground response analysis found to be not matching with response spectrum provided in IS 1893:2002 Part-1. For sites in Group 3, large amplifications were observed around 0.6 s period in response spectrum in comparison with response spectrum given in IS 1893:2001 (Part-1). For sites having lower average shear wave velocity (Group 1 and Group 2 sites), no such amplification is observed. Particularly Group 1 sites showed significant widening of constant spectral acceleration band. Thus, results of Group 1 and Group 2 sites clearly show major differences especially in response spectrum even though these two groups fall under same site class, i.e., class C of PESMOS and site class D of NEHRP. This clearly indicates the need for further division of site classes given in PESMOS as well as NEHRP. These differences in response to Group 1 and 2 clearly reflect that precautions must be observed while designing buildings/structures in such areas particularly those having high period. In particular, design of tall buildings for sites under Group 1 requires considering site-specific spectrum rather than using IS spectra.

The following recommendations are made based on outcomes of the current study.

a. Site characterization study for all the locations, wherever strong motion recording stations are situated, must be carried out.
b. Studies to evaluate site effects for all the strong motion stations must be conducted.

These studies will provide necessary data required for different important research works like the development of region-specific ground motion prediction models (attenuation laws), preparation of appropriate codal provisions, carrying out the accurate site-specific seismic hazard studies, which further helps in microzonation studies.

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