CrossMark

ORIGINAL PAPER

Evaluating the effects of ground motion parameters on response spectra in Uttarakhand Himalayas, India

Himanshu Mittal[1] · Yih-Min Wu[1] · Ashok Kumar[2] · Arjun Kumar[3] · Babita Sharma[4]

Abstract Uttarakhand, a state of India, is located in seismically active Himalayan region and in the proximity of plate boundaries. The effects of important ground motion parameters like magnitude, distance, and local geology and site conditions on acceleration response spectra are examined in Uttarakhand Himalayas in this work. A total of 447 strong ground motion histories (horizontal and vertical) from 42 earthquakes were selected. The results show that the shape of the acceleration response spectra is influenced by the local site conditions and regional geology. The studies are carried out for two categories of sites, i.e., rock sites and soft soil sites. The maximum average horizontal spectral amplification for rock sites is 2.7 at 0.1 s, while for soft soil sites, it is found to be 3.2 at 0.2 s. In the same way, the maximum average vertical spectral amplification for rock is found to be 2.7 at 0.1 s, while for soft soil, it is found to be 2.95 at 0.1 s. The average spectral amplification in vertical component also shifts from low period (rock) to high period (soft soil). The level of spectra increases with decrease in distance for rock sites as well as soft soil sites. When comparing different magnitude earthquakes in different geological conditions, the response spectra are found to follow each other up to 0.04 s, while for period greater than 0.04 s, the spectra of higher magnitude earthquake is observed on the higher side. For soft soil sites, spectra from different magnitude earthquakes are observed to follow each other up to 0.1 s, beyond which they get separated.

Keywords Uttarakhand · Response spectra · SA · Site conditions

Introduction

The Indian subcontinent is unique in the sense that it comprises of inter-plate and intra-plate regions and both regions are prone to bigger earthquakes. The inter-plate region comprises of the entire 2500-km Himalaya belt running from east to west. Himalayan plateau is known as one of the active seismic area in the world, which from time to time has experienced destructive earthquakes (e.g., 1803 Kumaon;1833 Kathmandu; 1897 Shillong, Mw 8.1; 1905 Kangra, Mw 7.8; 1934 Bihar-Nepal, Mw 8.4; and 1950 Assam, Mw 8.7), causing heavy loss of human lives and property. Albeit no major tremor happened till April 2015, yet late, two more remarkable extent quakes, i.e., April 2015 (Mw 7.8) and May 2015 (Mw 7.3), in Nepal locale raised vital issues about seismic hazard along Himalayan belt and its likelihood cannot be denied in the future also. Strong ground motion records are very sparse in India. However, strong motion network in India (www.pesmos.in) is providing useful data nowadays. The availability of strong motion data in Uttarakhand from this network has given an opportunity to study the impact of various strong motion parameters on shape and amplitude of response spectra.

The response of a structure to an earthquake motion is commonly evaluated using response spectra, which are defined as the graphic relationship between the maximum

✉ Himanshu Mittal
himanshumitt10@gmail.com

1 Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan

2 Department of Earthquake Engineering, Indian Institute of Technology, Roorkee 247667, India

3 Department of Civil Engineering, Arni University, Kathgarh (Indora), Himachal Pradesh, India

4 Seismology Division, Ministry of Earth Sciences, New Delhi, India

responses of single-degree-of-freedom (SDOF) systems and their natural periods. However, the individual response spectra of strong motion records have jagged shapes with significant peaks and valleys and differ remarkably; hence, they can only be used to evaluate the seismic forces during specific earthquakes at certain sites (Newmark and Hall 1969). As opposed to the response spectra, design response spectra (developed statistically from the response spectra of past strong motion earthquakes), as suggested by several building codes, are extremely effective in identifying the loads during the probable earthquake ground motions in the future. The idea of response spectra was put forward by Biot (1941, 1942) and Housner (1941). In early days, standard spectra of Housner (1959) and Newmark and Hall (1969) were popular and used in many applications. Various seismological techniques used in the estimation of strong ground motions at the site of interest consist of factors which represent effects of earthquake magnitude (source), medium through which the seismic waves propagate, and characteristics of site. Characteristics of local site conditions affect the ground motion and modify the amplitude, frequency, and duration content of the seismic waves. These aspects are studied in detail as more and more strong motion data become available in the world. Housner (1959) derived smooth normalized acceleration and velocity response spectra from the two horizontal components of ground acceleration recorded at four large earthquakes in the western USA. The earthquakes were (Biot 1941) 1934 Imperial Valley, California ($M = 6.5$); (Biot 1942) 1940 Imperial Valley, California ($M = 7.9$); (BIS 2002) 1952 Kern County, California ($M = 7.7$); and (Borcherdt 1994a) 1949 Puget Sound, Washington ($M = 7.1$). The recording sites were underlain by rock, stiff soil, and deep cohesion less soil. Newmark and Hall (1969) proposed a new technique for estimating site-independent spectra based on the fact that the response spectrum over certain frequency ranges is related by an amplification factor to the peak values of ground acceleration, velocity, and displacement. Hayashi et al. (1971) analyzed the number of records of strong ground motion recorded on different soil conditions in Japan and divided the spectra into three groups as per local site conditions like stiff soil, loose soil, and intermediate soil. Mohraz (1976) estimated the average spectral amplification (SA) for three types of geological conditions: rock sites, soft soil sites less than 30 ft, and more than 30-ft alluvium in California region. Seed et al. (1976) used the normalized shape characteristics of strong motion response spectra at a 5% damping ratio to explore site conditions. Su et al. (2006) studied the influence of different strong motion parameters like magnitude, path effect and site effects

on shape of acceleration response spectra using the strong motion data from different countries. The same type of studies has been carried out in India by Raghukanth and Iyengar (2007) for peninsular India and Chopra and Choudhury (2011) for Gujarat region. Thus, it can be seen that response spectra is one of the most important parameters required in earthquake engineering.

In the present work, the effect of geological conditions, magnitude, distance, and local site conditions on average horizontal and vertical spectra using 447 ground motion histories from 42 earthquakes is studied. Finally, these spectra are compared with existing spectra in Indian code for design of earthquake-resistant structures.

Geology and seismotectonics

The Himalaya was formed and is sustained by the northward-driving Indian plate that continues to push against the Asian plate. In the process, it has created several fault systems to the south of the Indus–Tsangpo collision suture, marked by distinct lithotectonic boundaries. The Himalaya is divided into a number of sequences; each bounded to the south by a major north-dipping fault, such as the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), and the Main Central Thrust (MCT). Uttarakhand Himalayas are probably one of the most seismic areas in the world and have experienced earthquakes since historical time. As per seismic zoning map of India, the entire state of Uttarakhand has been assigned to zone IV or V, the two most seismic active areas (BIS 2002). In the Kumaon–Garhwal Himalaya, the MCT is a zone bound by the Munsiari Thrust (MT) in the south and the Vaikrita Thrust (VT) in the north (see Fig. 1). Detailed geology of the region has been reviewed by Valdiya (1980), Yin (2006), and others.

The distribution of seismicity throughout the Himalaya appears to be centered around in a 50-km wide belt with moderate-sized events (ML < 6) located beneath the lesser Himalaya between the MCT and the MBT (Seeber and Armbruster 1981; Khattri et al. 1989; Khattri 1992). Most of these events are located to the south of the MCT. Medium-sized earthquakes with well-determined fault plane solutions and focal depths determined by Ni and Barazangi (1984) define a simple planar zone situated at 10–20-km depth, with an apparent dip of 15°. This planar zone defines the detachment that separates the underthrusting Indian plate from the lesser Himalaya crustal block and along which the great Himalayan earthquakes occurred during past 90 years (Seeber and Armbruster 1981). Recent investigations in other segments of the Himalaya show that apart from infrequent distributions, most of the seismicity in these segments is also clustered in a narrow zone, just south of the surface trace of the MCT (Kumar et al. 2009).

Fig. 1 Seismotectonic setup of region. Various faults contributing to seismicity in the region, namely MBT, MCT, MFT, Vartica Thrust (VT), Munsiari Thrust (MT), Malari Fault, Mahendragarh Dehradun Fault (MDF), Great Boundary Fault (GBF), and Moradabad Fault (MF) are shown. All the strong motion stations in Uttarakhand are shown as *triangles*. *White stars* are the epicenter of earthquakes used in the present study
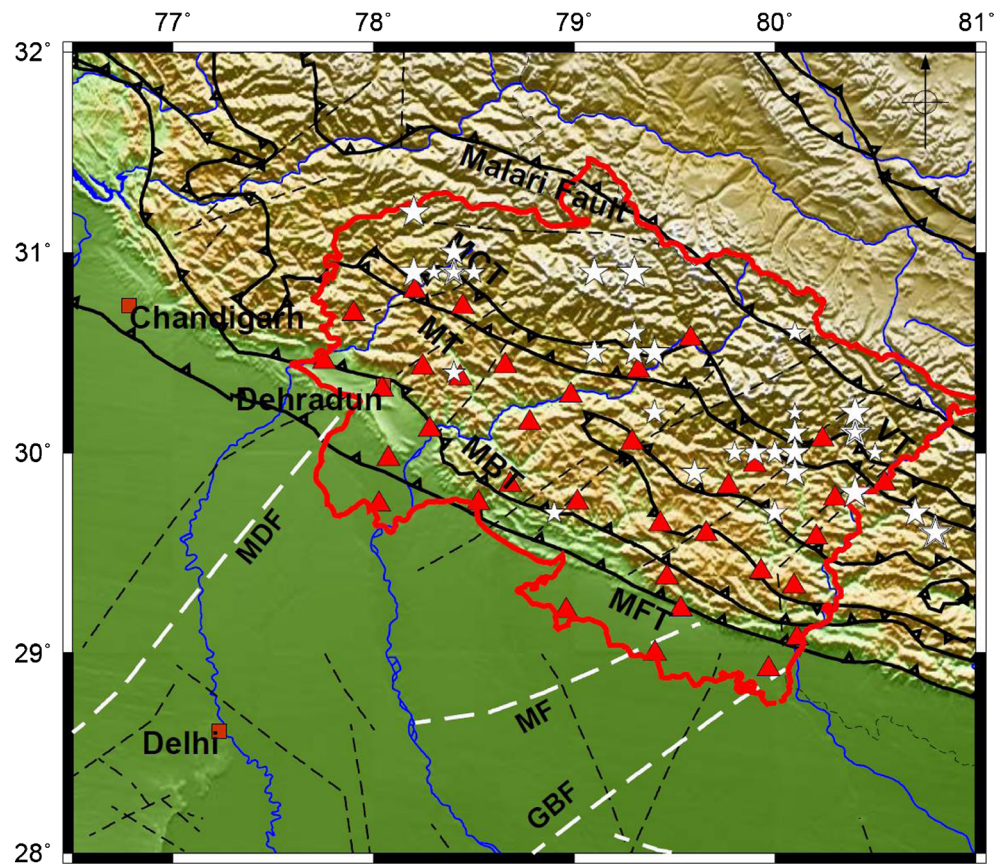
Data and network of India

The strong motion instrumentation network of India covers the Indian Himalayan range from Jammu and Kashmir to Meghalaya. The strong motion stations have been installed in the states of Himachal Pradesh, Punjab, Haryana, Delhi, Rajasthan, Uttarakhand, Uttar Pradesh, Bihar, Sikkim, West Bengal, Andman and Nicobar, Meghalaya, Arunachal Pradesh, Mizoram, and Assam. All 300 strong motion accelerographs consist of internal AC-63 GeoSIG triaxial force-balanced accelerometers and GSR-18 GeoSIG 18-bit digitizers with external GPS. The recording for all instruments is in trigger mode at a sampling frequency of 200 samples per second (Kumar et al. 2012). Numerous strong motion studies have been performed using data from this network (e.g., Mittal et al. 2013a,b; Mittal and Kumar 2015). The instruments are installed mainly in three geological conditions, i.e., rock sites, medium soil sites, and soft soil sites. The classification of these instruments based on geology was reported by Mittal et al. (2012). Out of these 300 stations, 35 instruments are installed in different parts of Uttarakhand, which is the study area for the present work. This network of digital SMA has recorded almost 50 earthquakes in Uttarakhand since its installation. Table 1 depicts the detail of stations, their geology, and number of earthquakes recorded by each station and magnitude range of earthquake magnitudes. The detail of site classification is also given.

Methodology

The acceleration response spectrum for 5% damping is estimated using 447 strong motion recordings from 42 earthquakes. The parameters of these events are given in Table 2. All the earthquakes used have magnitude >3. In Garhwal Himalayas, maximum earthquakes are recorded at six stations namely Chamoli, Barkot, Uttarkashi, Garsain, Tehri, and Roorkee, while in Kumaun Himalayas, maximum recording is found at five stations namely Bageshwar, Champawat, Kapkot, Munsiari, and Pithoragarh. Figure 2a depicts the available data from Uttarakhand as a function of peak ground acceleration (PGA) and hypocentral distance. It is seen that most of the records have PGA (the geometrical mean of two components) between 2 and 50 gal with hypocentral distance ranging between 20 and 170 km. Figure 2b gives the distribution of magnitude with

Table 1   Location of different stations in Uttarakhand (Mittal et al. 2012) along with local site conditions, recorded earthquakes, and magnitude range used in present work

Station name	Latitude (° N)	Longitude (° E)	Local site condition	Site class	No. of earthquakes	Magnitude range
Garhwal Himalayas						
Chamoli	30.412	79.320	Quartzite, dolomites	A	6	3.3–5.7
Dehradun	30.316	78.042	Soil (slope washed)	C	2	4.6–5.7
Pauri	30.150	78.777	Phyllites	A	2	3.6–5.2
Rudraprayag	30.287	78.983	Quartzite/slates	A	3	4.7–5.7
Tehri	30.374	78.430	Phyllites	A	5	3.5–5.7
Uttarkashi	30.730	78.445	Quartzite/slates	A	6	3.2–5.2
Barkot	30.809	78.205	Granite/phyllite/slates	A	6	3.5–5.7
Chakrata	30.694	77.901	Slitstones/slates	B	4	4.3–5.0
Dhanaulti	30.427	78.244	Slates/siltstones/limestones	B	4	3.5–5.7
Garsain	30.051	79.288	Schist, granodiorites, gneiss	A	5	3.9–5.7
Ghansali	30.434	78.656	Quartzite/slates	A	2	4.7–5.1
Joshimath	30.569	79.579	Granite/gneiss/quartzite	A	2	5.1–5.7
Kotdwar	29.748	78.523	Sandstones/shales	B	1	5.7
Lansdown	29.840	78.680	Schist, granodiorites, gneiss	A	1	5.7
Rishikesh	30.116	78.281	Soils (slope washed)	C	1	4.6
Roorkee	29.866	77.901	Soils (slope washed)	C	8	3.3–5.7
Vikasnagar	30.453	77.754	Soils (slope washed)	C	1	4.6
Kumaun Himalayas						
Almora	29.596	79.657	Schist, granodiorites, gneiss	A	2	4.6–5.7
Bageshwar	29.831	79.770	Quartzite, dolomites	A	8	3.9–5.7
Champawat	29.334	80.095	Granite	A	12	3.6–5.7
Dharchula	29.847	80.546	Phyllites/slates/limestones	A	3	3.2–5.7
Didihat	29.770	80.300	Schist, granodiorites, gneiss	A	1	5.7
Kapkot	29.941	79.899	Dolomite/limestones	A	10	3.9–4.9
Kashipur	29.211	78.960	Soils (slope washed)	C	1	5.7
Khatima	28.919	79.969	Soils (slope washed)	C	1	5.7
Munsiari	30.066	80.237	Schist, granodiorites, gneiss	A	6	3.9–5.7
Patti	29.407	79.931	Schist, granodiorites, gneiss	A	4	4.5–5.7
Pithoragarh	29.578	80.207	Phyllites/slates/limestone blue	A	9	3.2–5.7
US Nagar	28.997	79.403	Soil (slope washed)	C	3	4.6–5.7
Tanakpur	29.074	80.112	Alluvium	C	2	5.0–5.7

hypocentral distance. The magnitude of earthquakes used in the present study ranges from 3 to 5.7. Figure 2c shows the distribution of PGA with magnitude.

Before processing, all the records are baseline corrected. In the next step, the rotation of horizontal components is performed to get N–S and E–W component. Instrument correction of records is not done as the natural frequency of sensors is quite high (about 200 Hz), and thus, it will not make any difference. No frequency filter is applied during processing of data. Duhamel integral approach is used to estimate the acceleration response spectrum of 5% damping of each earthquake record at every site for two horizontal and a vertical components. The geometric mean of the two horizontal components of each record is taken

at every station. The mean is estimated to get average acceleration response spectrum for each station component wise.

The spectrum is normalized by dividing the spectral acceleration with PGA. After normalization, the stations with the same geology are grouped together and average response spectrum for particular geological formations is determined. All the stations rest on three kinds of sites namely rock, medium soil, and soft soil (Mittal et al. 2012). The effect of distance, geology, and magnitude on response spectra is also studied. The distance factor is studied by considering the stations at different distances from the same earthquake. Spectra of different stations on the same geology are compared to study

Table 2   Parameters of 42 events used in present study

| Date	Time	Lat.	Long	Dep.	ML	Region (IMD)	Records
14 December 2005	7:09:48	30.9° N	79.3° E	25.7	5.2	Chamoli	8
22 July 2007	23:02:12	31.2° N	78.2° E	33	5	Uttarkashi	2
19 August 2008	10:54:26	30.1° N	80.1° E	15	4.3	Pithoragarh	4
04 September 2008	12:53:21	30.1° N	80.4° E	10	5.1	(Uttarakhand)-Tibet	7
25 February 2009	4:04:21	30.6° N	79.3° E	10	3.7	Uttarakhand	1
18 March 2009	11:22:42	30.9° N	78.2° E	10	3.3	Uttarkashi	1
15 May 2009	18:39:22	30.5° N	79.3° E	15	4.1	Chamoli, Uttarakhand	1
27 August 2009	16:54:15	30.0° N	80.0° E	14	3.9	Uttarakhand, India	3
21 September 2009	9:43:47	30.9° N	79.1° E	13	4.7	Uttarkashi	9
03 October 2009	5:20:54	30.0° N	79.9° E	15	4.3	Bageshwar, Uttrakhand	3
11 January 2010	5:15:18	29.7° N	80.0° E	15	3.9	Pithoragarh	3
22 February 2010	17:23:43	30.0° N	80.1° E	2	4.7	Bageshwar, Uttarakhand	6
01 May 2010	22:36:25	29.9° N	80.1° E	10	4.6	Bageshwer, Uttarakhand	7
03 May 2010	17:15:08	30.4° N	78.4° E	8	3.5	Uttarakhand	4
31 May 2010	11:37:04	30.0° N	79.8° E	10	3.6	Almora, Uttarakhand	2
06 July 2010	19:08:20	29.8° N	80.4° E	10	5.1	India–Nepal Border	2
10 July 2010	3:16:20	29.9° N	79.6° E	10	4.1	Almora, Uttarakhand	4
14 March 2011	9:01:29	30.5° N	79.1° E	8	3.3	Chamoli, Uttarakhand	1
04 April 2011	11:31:40	29.6° N	80.8° E	10	5.7	Nepal–India Border Region	24
04 May 2011	20:57:15	30.2° N	80.4° E	10	5	India–Nepal Border Region	1
15 June 2011	0:59:28	30.6° N	80.1° E	10	3.4	Pithoragarh	2
20 June 2011	6:27:18	30.5° N	79.4° E	12	4.6	Chamoli, Uttarakhand	13
23 June 2011	22:13:46	30.0° N	80.5° E	5	3.2	Uttrakhand-Nepal	1
21 September 2011	2:24:36	30.9° N	78.3° E	10	3.1	Uttarkashi	1
24 September 2011	14:32:18	30.9° N	78.3° E	10	3	Uttarkashi	1
16 January 2012	5:01:00	29.7° N	78.9° E	10	3.6	Pauri, Uttarakhand	1
09 February 2012	19:17:29	30.9° N	78.2° E	10	5	Uttarkashi, Uttrakhand	6
26 February 2012	23:08:42	29.6° N	80.8° E	10	4.3	Western Nepal	2
10 May 2012	22:00:40	30.2° N	79.4° E	5	3.9	Chamoli, Uttrakhand	1
28 July 2012	5:48:06	29.7° N	80.7° E	10	4.5	Nepal–India Border	2
23 August 2012	16:30:19	28.4° N	82.7° E	10	5	Nepal	3
11 November 2012	18:39:19	29.2° N	81.5° E	10	5	Western Nepal	3
15 November 2012	6:46:07	30.2° N	80.1° E	5	3	Uttrakhand	1
27 November 2012	12:15:15	30.9° N	78.4° E	12	4.8	Uttarkashi, Uttarakhand	4
02 January 0213	17:42:15	29.4° N	81.1° E	10	4.8	Nepal	1
09 January 2013	7:44:20	29.7° N	81.7° E	34	5	Nepal	4
10 January 2013	15:16:13	30.1° N	80.4° E	5	3.2	Pithoragarh, Uttarakhand	1
29 January 2013	19:42:52	30.0° N	81.6° E	7	4	Nepal	1
11 February 2013	10:48:55	31.0° N	78.4° E	5	4.3	Uttarkashi, Uttarakhand	3
17 February 2013	16:27:07	30.9° N	78.4° E	10	3.2	Uttarkashi, Uttarakhand	1
06 April 2013	22:29:31	30.5° N	79.1° E	10	4.3	Rudraprayag	1
05 September 2013	18:35:42	30.9° N	78.5° E	11	3.5	Uttarkashi, Uttarakhand	1

All the locations are taken from Indian Meteorological Department website (www.imd.gov.in)

the effect of local geology. The magnitude effect is studied by considering the earthquakes with different magnitudes that have occurred in the same source region and recorded at the same station.

Results and discussions

The normalized acceleration response spectra are estimated for two horizontal and a vertical component for each

Fig. 2 A figure showing the relation of various strong ground motion parameters with each other used in the present study. **a** Peak ground acceleration-hypocentral distance distribution. **b** Magnitude-hypocentral distance distribution. **c** Magnitude-peak ground acceleration
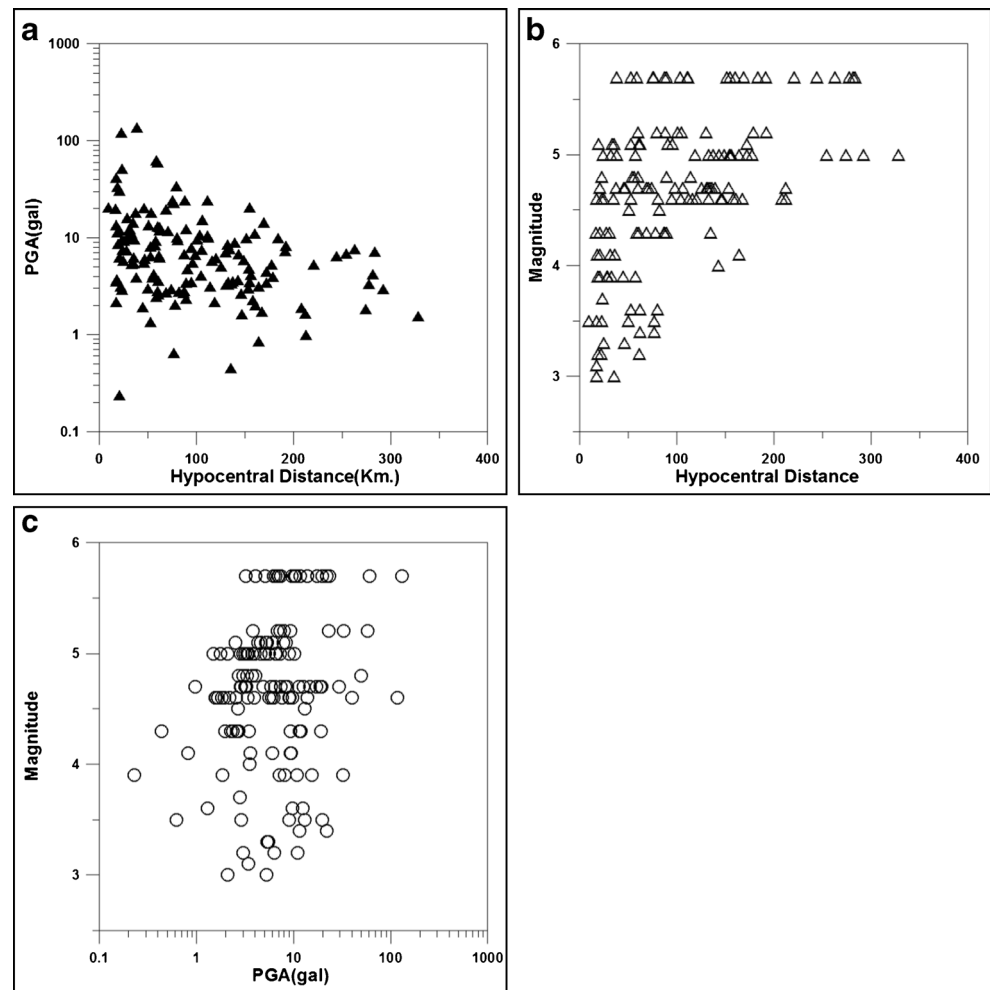
earthquake according to station. It has been observed that the sites located on rock show the highest value of SA between 0.05 and 0.15 s (7 and 20 Hz), while the sites located on medium/soft soil show the peak value above 0.15 s (below 7 Hz). From here, it can be concluded (as expected) that the rock sites experience ground motion amplification at higher frequencies, while medium/soft soil sites experience at lower frequencies.

(a)   Effect of geology:

To show the effect of geology, the geometrical mean of horizontal spectra and vertical spectrum for each station is grouped according to geology (Figs. 3, 4, and 5). Maximum sites in Uttarakhand fall under rock sites (Mittal et al. 2012). The response spectra of horizontal components for all these sites show the maximum normalized SA (will be referred as SA onwards) of 2.7 at 0.1 s (Fig. 3a). The vertical spectra for this class show the maximum SA 2.6–2.7 between period range of 0.07 and 0.1 s (Fig. 3b). Only three sites namely Chakrata, Dhanaulti, and Kotdwar fall under category of medium soil. The maximum SA for response spectra of

horizontal components for this class is observed to be 3.3 at 0.2 s (Fig. 4a), while vertical SA is found to be 2.7 at 0.1 s (Fig. 4b). Seven sites fall under soft soil sites, where earthquakes have been observed. The response spectra of horizontal components for all these sites show the maximum SA to be 3.2 at 0.2 s (Fig. 5a), while the vertical spectra for this class show the maximum SA 2.95 at 0.1 s (Fig. 5b). From Figs. 4 and 5, it is observed that maximum SA in horizontal and vertical components is the same for both medium as well as soft soil.

In order to study the effect of geology on the shape and amplitude of acceleration response spectra, the response spectra of horizontal components for all three classes are plotted and compared (Fig. 6a). In the same way, the response spectra of vertical component for all three site classes are also plotted (Fig. 6b). The effect of geology on horizontal spectra can be easily seen from Fig. 6a. The maximum average SA for rock sites is 2.7 at 0.1 s. The maximum average SA for medium soil sites and soft soil sites is found to be 3.1 and 3.2 at 0.2 s. The average SA for medium and soft soil is observed to be of the same order at the same period. So, the maximum SA observed for rock is less in low period range and is higher for medium

Fig. 3 Normalized acceleration response spectra for sites situated on rock formations. **a** Geometric mean of horizontal components and **b** vertical component. *Light black color lines* are the normalized spectra of individual earthquakes, while *dark black lines* are mean
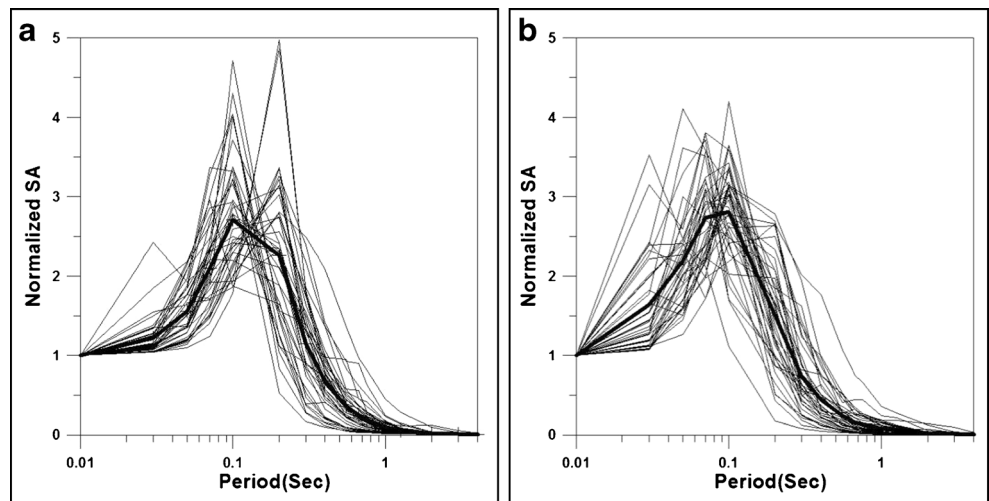
and soft soil sites in high period range. Almost the same observation is found from response spectra of vertical component (Fig. 6b). The maximum average vertical SA for rock is found to be 2.7 at 0.06 s. The maximum average vertical SA for medium and soft soil is found to be 2.6 and 2.95 at 0.09 s. The average SA in vertical component also shifts from low period (rock) to high period (medium and soft soil). Although the shape of response spectra of vertical component for medium and soft soil is the same, the average maximum SA is different for two types of sites.

The average horizontal SA falls below 1 at 0.3 s for rock sites. In the same way, it is observed to fall below 1 at 0.55 s for medium and soft soil sites. In the case of vertical response spectra, average SA falls below 1 at 0.25 s for rock sites and at 0.4 s for medium and soft soil sites.

The average horizontal SA for three types of sites is compared with normalized response spectra for three types of sites proposed in Indian design code for the entire country (Fig. 6). It is found that for period greater than 0.4 s, the SA is

overestimated in Indian code for all three site classes, i.e., soft soil, medium soil, and rock sites. SA is also underestimated at short periods, i.e., below 0.05 s for rock sites and below 0.1 s for medium and soft soil sites. It can be concluded that the seismic forces considered for design structures are overestimated for periods greater than 0.4 s. However, for vertical component, the average SA for three types of sites is underestimated below 0.1 s and overestimated above 0.25 s. The same type of studies has been performed previously by Raghukanth and Iyengar (2007) for peninsular India and Chopra and Choudhury (2011) for Gujarat region. According to Raghukanth and Iyengar (2007), the Indian code spectrum (BIS 2002) underestimates seismic forces on high-frequency structures for rock sites, while at soft soil sites, the Indian code overestimates forces on long period structures. According to Chopra and Choudhury (2011), for period greater than 0.4 s, the SAs are overestimated in Indian code for both soft soil and rock sites, while for periods below 0.1 s, the SAs are underestimated.

Fig. 4 Normalized acceleration response spectra for sites situated on medium soil formations. **a** Geometric mean of horizontal components and **b** vertical component. *Light black color lines* are the normalized spectra of individual earthquakes, while *dark black lines* are mean
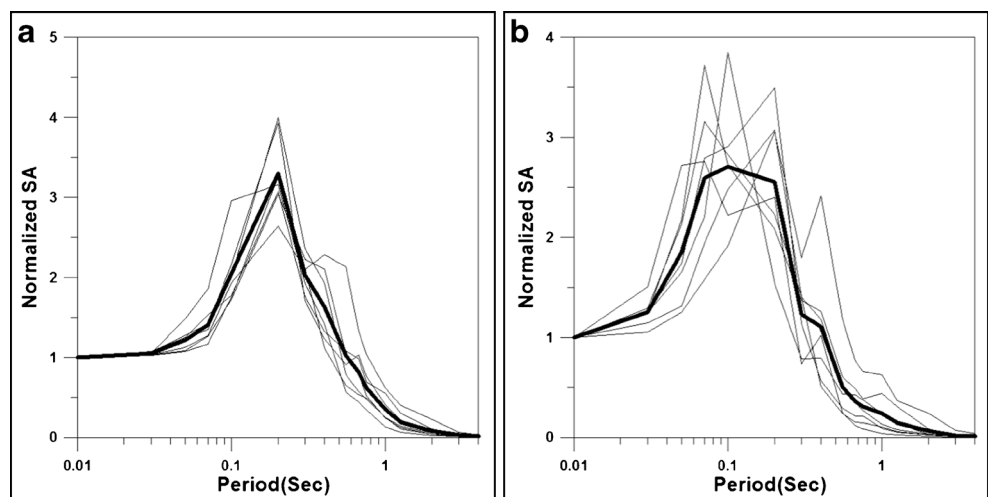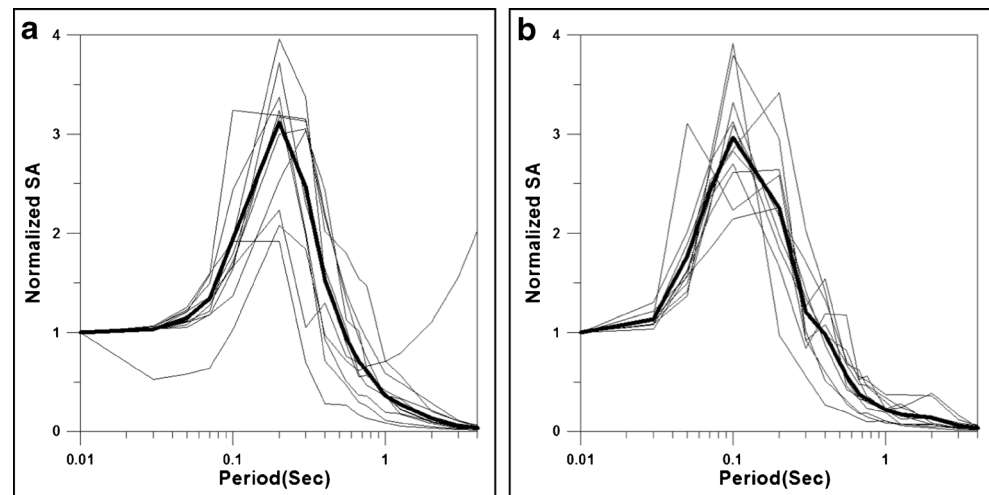
Fig. 5 Normalized acceleration response spectra for sites situated on soft soil formations. **a** Geometric mean of horizontal components and **b** vertical component. *Light black color lines* are the normalized spectra of individual earthquakes, while *dark black lines* are mean

The local geology plays an important factor in the recorded waveform of earthquake ground motions. Different site conditions can induce amplifications of different period ranges in the response spectra (Seed et al. 1976; Mohraz 1976). Such types of studies based on spectral acceleration have been carried out previously by many researchers in the world. Mohraz (1976) estimated the average SA for three types of geological conditions: rock sites, soft soil sites less than 30 ft, and more than 30-ft alluvium in California region. He observed average SA to be 2.1 for all components at rock sites. For soft sites with less than 30-ft alluvium, he found SA to be 2.6 for horizontal component and 2.2 for vertical component. Similarly for sites with more than 30-ft alluvium, he observed 2.3 for horizontal component and 2.1 for vertical component. Seed et al. (1976) used the normalized shape characteristics of strong motion response spectrum to explore site conditions. Hayashi et al. (1971) estimated average horizontal SA for three different kinds of sites in Japan. He estimated

maximum SA to be 3.3 for rock site, 2.5 for medium soil, and 2.6 for soft soil sites. Some researchers have combined the use of surface geology and shear wave velocity for site classification (e.g., Borcherdt 1994a,b). The classification of site conditions and an estimation of the site amplification ratio obtained by using surface geology and geomorphologic units have also been performed in Tokyo and Kanagawa, Japan (Yamazaki et al. 2000).

(b)   Effect of distance:

In order to study the effect of distance, the response spectra is plotted for rock as well as soft soil sites as shown in Fig. 7. There are several earthquakes which have been recorded at rock sites as well as soil sites. One such earthquake of magnitude 5.7 occurred in Kumaun Himalayas, which was recorded at soft soil as well as rock sites. It is observed that the level of spectra increases with decrease in distance for rock sites (Fig. 7a) as well as soft soil sites (Fig. 7b).

Fig. 6 Normalized acceleration response spectra for different geological conditions and its comparison with Indian code (*BIS* Bureau of Indian Standard) for **a** horizontal components and **b** vertical component
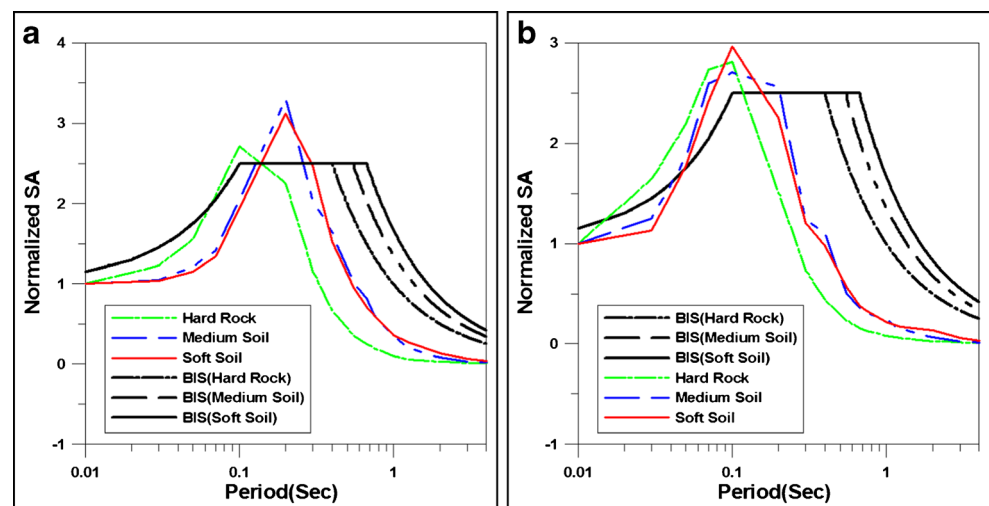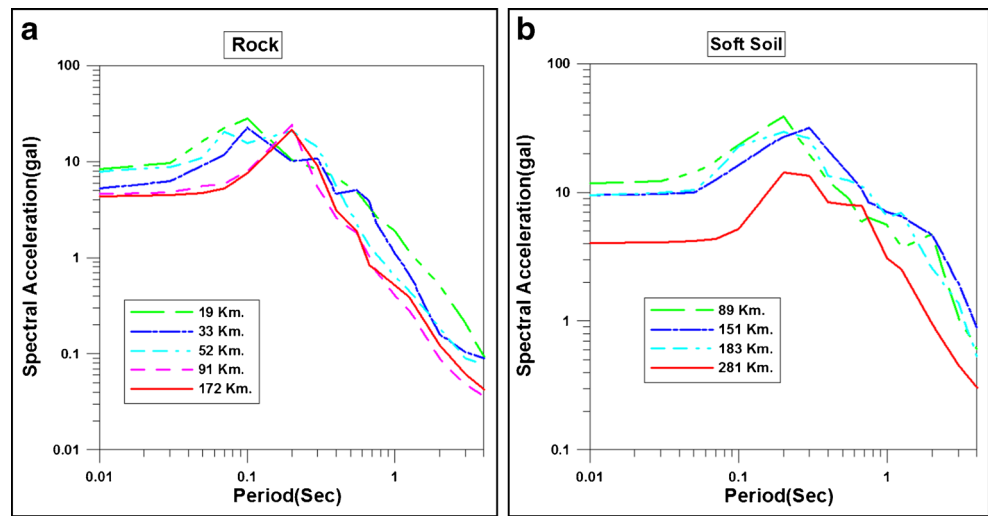
Fig. 7 Comparison of response spectra recorded at different distances for the same earthquake: (**a**) rock and **b** soft soil

(c) Effect of magnitude:

The effect of magnitude on response spectra is studied by considering three different stations that fall under different categories, i.e., rock, medium soil, and soft soil. At all these three stations, response spectra are plotted from different magnitude earthquakes that occurred in the same source region. At Champawat (rock site), the spectra are compared from five earthquakes between magnitude range of 3.9–5.1 (Fig. 8a). The response spectra are normalized with PGA to study the spectral shape. The response spectra are alike up to 0.04 s, while for period greater than 0.04 s, the spectra of higher magnitude earthquake is observed on the higher side. In the same way, the response spectra for medium soil site (Chakrata) are compared from four different earthquakes in magnitude range of 4.3–5.0 (Fig. 8b). The spectra are observed to be the same up to 0.08 s, beyond which higher magnitude spectra are observed on the higher side in the same way as that of rock. For Roorkee station situated on soft soil site, the response spectra are compared from four different earthquakes in magnitude range of 3.5–5.0 (Fig. 8c). Here, spectra from different magnitude earthquakes are observed to follow each other upto 0.1 s, beyond which they get separated. Higher magnitude earthquakes have spectra on the higher side. It can be said that the effect of magnitude on spectra is observed beyond 0.04 s for rock sites, 0.08 s for medium soil sites, and 0.1 s for soft soil sites.

(d) Effect of site conditions:

The local site conditions are an important factor in the recorded waveform of earthquake ground motions. A structure may attract substantial seismic force if the natural period of the structure matches with period of the ground. In view of this, the local site conditions become important in ground motion analysis and in earthquake-resistant designs. A response spectrum compatible with local site condition is a common input for structural dynamic analysis.

The effect of local site conditions is studied on shape and amplitude of response spectra for sites located in different geological conditions, i.e., rock and soft soil. The horizontal spectra are compared for different sites in a particular geological condition and the same distance range for each earthquake (Fig. 9). The spectra are normalized to study the shape. The horizontal spectra for rock sites are plotted and compared (Fig. 9a). These spectra are for magnitude 4.9–5.1 in distance range of 40–80 km. The maximum average SA for different sites is found to be 2.5–4.0 between period range of 0.09–0.3 s. In general, SA is around 2.5 for most of the sites except Pithoragarh, Patti, and Bageshwar. At Pithoragarh, a sharp peak with maximum SA of 4.0 is observed at 0.1 s. In the same way, the maximum SA for Patti is found to be 4.0 at 0.2 s. Both these sites are situated on rock sites as evident from their period of excitation but may experience more SA being situated on the hill side. Bageshwar experiences SA of the order of 4.0 at 0.3 s. Although this site falls under the category of rock, higher SA is observed because instrument is installed on recent-filled alluvium.

The horizontal response spectra are plotted and compared for six sites located in medium soil and soft soil formations (Fig. 9b). These spectra are plotted for earthquakes having magnitude range of 4.3–5.7 in distance range of 110–142 km. In general, value of SA ranges from 3.5 to 4.5 between period range of 0.2–0.6 s for all sites. A sharp peak with SA of 4.5 is observed at 0.2 s for Roorkee station. SA is found to be the same, i.e., 3.8 for both Chakrata and Dehradun stations. SA

Fig. 8 Comparison of normalized response spectra for different magnitude earthquakes at **a** rock site (Champawat), **b** medium soil site (Chakrata), and **c** soft soil site (Roorkee)
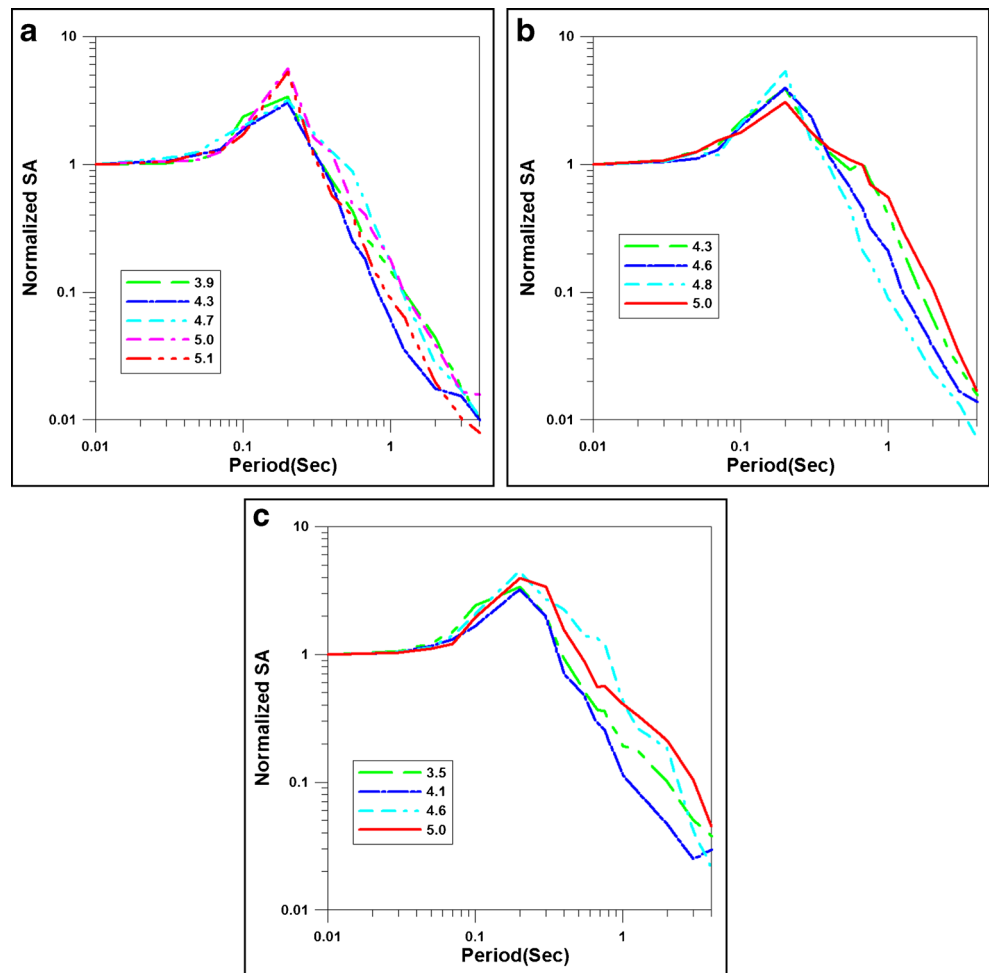
for Dehradun is observed in broad period range, i.e., 0.2–0.4 s. The maximum SA at different stations is observed depending upon the presence of soft soil material/alluvium at those sites. From here, it can be concluded that local site conditions plays an important role in modifying and amplifying the spectra at certain periods, though these sites are located on the same geological formations.

Fig. 9 Comparison of normalized response spectra recoded within the same distance range: **a** rock site and **b** soft soil site
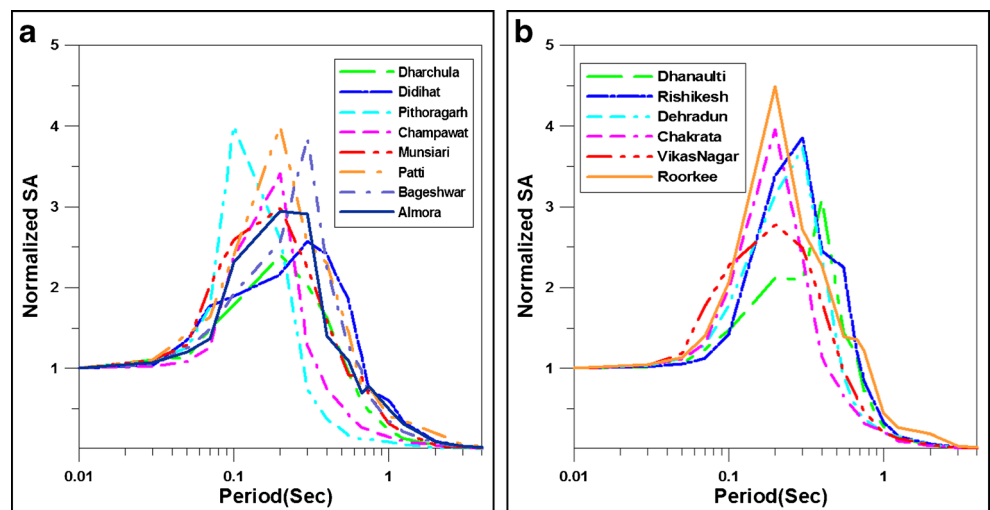
Conclusions

In the present work, the effects of important ground motion parameters on acceleration response spectra are worked out. These important strong ground motion parameters include magnitude, distance, local geology, and site conditions. A total of 447 strong ground motion histories (horizontal and vertical) from 42 earthquakes in Uttarakhand region were selected for the present work. The study shows that the shape of the acceleration response spectra is prejudiced by the regional geology and local site conditions. Initially, the sites were classified in three categories, i.e., rock, medium soil, and soft soil sites. But the shape of spectra is found to be the same for medium soil and soft soil sites in Uttarakhand. So, these sites are combined in one class only referred to as soft soil sites. The average maximum SA is found at lower period for rock sites, while for soft soil sites, it shifts toward higher periods. The maximum average horizontal SA for rock sites is 2.7 at 0.1 s. The maximum average SA for soft soil sites is found to be 3.2 at 0.2 s. The maximum average vertical SA for rock is found to be 2.7 at 0.1 s, while SA for soft soil is found to be 2.95 at 0.1 s. The average SA in vertical component also shifts from low period (rock) to high period (soft soil). Although the shape of average vertical response spectra for medium and soft soil is the same, the average maximum SA is different for two types of sites. The effect of distance and magnitude is also studied on the shape of response spectra. When comparing different magnitude earthquakes in different geological conditions, the response spectra are found to follow each other up to 0.04 s, while for period greater than 0.04 s, the spectra of higher magnitude earthquake are observed on the higher side. For soft soil sites, spectra from different magnitude earthquakes are observed to follow each other up to 0.1 s, beyond which they get separated. The site-specific response spectra developed using source to site distances, expected magnitudes, and actual local site conditions will be helpful in selecting earthquake-resistant designs in different geological conditions. Moreover, site-specific response spectra studies may be useful in terms of seismic hazard analysis. Presently, such studies are carried out for Uttarakhand region depending upon data. These studies will be carried out for other regions also once sufficient data are available.

References

Biot MA (1941) A mechanical analyzer for the prediction of earthquake stresses. Bull Seismol Soc Am 31:151–171

Biot MA (1942) Analytical and experimental methods in engineering seismology. Proc ASCE 68:49–69

BIS (2002) IS 1893–2002. Indian standard recommendations for earthquake resistant design of structures. Bureau of Indian Standards, New Delhi

Borcherdt RD (1994a) Estimates of site-dependent response spectra for design (methodology and justification). Earthquake Spectra 10:617–653

Borcherdt RD (1994b). An integrated methodology for estimates of site-dependent response spectra, seismic coefficients for site dependent building code provisions, and predictive GIS maps of strong ground shaking. Proceedings of Seminar on New Developments in Earthquake Ground Motion Estimation and Implications for Engineering Design Practice, Applied Technology Council ATC 35–1, 10–1 ~ 10–44

Chopra S, Choudhury P (2011) A study of response spectra for different geological conditions in Gujarat, India. Soil Dyn Earthq Eng 31: 1551–1564

Hayashi S, Tsuchida H, Kurata E (1971) Average response spectra for various subsoil conditions. Proceedings of third joint meeting, U.S. Japan panel on wind and seismic effects. UJNR, Tokyo

Housner, GW (1941). An investigation of the effects of earthquakes on buildings. Ph.D. thesis. California Institute of Technology, Pasadena, California

Housner GW (1959) Behavior of structures during earthquakes. J Eng Mech Div, Proc ASCE 85(EM4):109–129

Khattri KN (1992) Local seismic investigations in Garhwal–Kumaon Himalaya Geol Soc India Mem 23, 45–66.

Khattri KN, Chander R, Gaur VK, Sarkar I, Kumar S (1989) New seismological results on the tectonics of the Garhwal Himalaya. Proc Indian Acad Sci Earth Planet Sci 98:91–109

Kumar A, Mittal H, Sachdeva R, Kumar A (2012) Indian strong motion instrumentation network. Seismol Res Lett 83(1):59–66

Kumar N, Sharma J, Arora BR, Mukopadhyay S (2009) Seismotectonic model of the Kangra-Chamba sector of northwest Himalaya: constraints from joint hypocenter determination and focal mechanism. Bull Seismol Soc Am 99:95–109

Mittal H, Kumar A (2015) Stochastic finite-fault modeling of M w 5.4 earthquake along Uttarakhand–Nepal border. Nat Hazards 75(2): 1145–1166

Mittal H, Kumar A, Kamal (2013a) Ground motion estimation in Delhi from postulated regional and local earthquakes. J Seismol 17(2): 593–605

Mittal H, Kumar A, Ramhmachhuani R (2012) Indian national strong motion instrumentation network and site characterization of its stations. Int J Geosci 3(6):1151–1167

Mittal H, Kamal, Kumar A, Singh SK (2013b) Estimation of site effects in Delhi using standard spectral ratio. Soil Dyn Earthq Eng 50:53–61

Mohraz B (1976) A study of earthquake response spectra for different geological conditions. Bull. Seism. Soc. Am. 66:915–935

Newmark NM, Hall WJ (1969) Seismic design criteria for nuclear reactor facilities. Proceedings of fourth world conference earthquake engineering, B(4). Santiago, Chile, 37–50

Ni J, Barazangi M (1984) Seismotectonics of the himalayan collision zone: geometry of the underthrusting Indian plate beneath the Himalaya. J Geophys Res 89:1147–1163

Raghukanth STG, Iyengar RN (2007) Estimation of seismic spectral acceleration in peninsular India. J Earth Syst Sci 116:199–214

Seeber L, Armbruster JG (1981) Great detachment earthquakes along the Himalayan arc and long-term forecasting, in Earthquake Prediction:

An International Review. Maurice Ewing Series 4, American Geophysical Union, Washington, D.C., 259–277

Seed HB, Ugas C, Lysmer J (1976) Site-dependent spectra for earthquake-resistant design. Bull Seism Soc Am 66:221–243

Su F, Anderson JG, Zeng Y (2006) Characteristics of ground motion response spectra from recent large earthquakes and their comparison with IEEE standard 693. Proceedings of 100th anniversary earthquake conference, commemorating the 1906 San Francisco Earthquake. San Francisco, California; April 18–22, 2006

Valdiya KS (1980) Geology of Kumaun lesser Himalaya, interim record: Dehradun. Wadia Institute of Himalayan Geology, Dehradun, India 291 pp

Yamazaki F, Wakamatsu K, Onishi J, Shabestari KT (2000) Relationship between geomorphological land classification and site amplification ratio based on JMA strong motion records. Soil Dyn Earthq Eng 19: 41–53

Yin A (2006) Cenozoic tectonic evolution of the Himalayan orogen as constrain by along strike variation of structural geometry, exhumation history and foreland sedimentation. Earth Sci Rev 76:1–132