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Estimation of site amplification functions in Gujarat region, India

**Sumer Chopra · Dinesh Kumar · B. K. Rastogi · Pallabee Choudhury ·
R. B. S. Yadav**

Abstract Site response in the Gujarat region is studied using local earthquake data recorded at 32 sites spread all over Gujarat region, India. Out of these 32 sites, 15 sites are located in Kachchh region, 8 in Saurashtra and 9 in mainland Gujarat region. These sites are underlain by different types of rocks/sediments of different ages. Out of 32 stations, 7 stations are on Quaternary deposits, 6 on Tertiary, 11 on Deccan, 3 on Jurassic, 3 on Cretaceous and 2 on Proterozoic rocks. The predominant frequencies at these sites depend strongly on the local geology. The average predominant frequencies of the sites on Quaternary sediments are 2.4 Hz, 5.3 Hz on Tertiary, 7.5 Hz on Jurassic, 7.2 Hz on Deccan, 4.6 Hz on Cretaceous and 7.5 Hz on Proterozoic formations. The average site amplification values at predominant frequencies are 3.7 for the sites of Quaternary deposits, 3.3 for Tertiary, 3.3 for Cretaceous rock, 4.2 for Deccan trap, 4.1 for Jurassic sites and 4.6 for Proterozoic. The damage to the houses during 2001 Bhuj earthquake is compared with the amplification at predominant frequencies at those sites. The spatial variation of predominant frequencies and the site amplifications at different frequencies corresponding to the natural frequencies of different storey buildings are studied, which will be useful in the evaluation of seismic hazard in the region.

S. Chopra (✉)
Seismology Division, Ministry of Earth Sciences, Prithvi Bhavan, New Delhi 110003, India
e-mail: Sumer.chopra@gmail.com

D. Kumar
Department of Geophysics, Kurukshetra University, Kurukshetra 136119, Haryana, India
e-mail: dineshk5@rediffmail.com

B. K. Rastogi · P. Choudhury
Institute of Seismological Research, Raisan, Gandhinagar 382009, Gujarat, India
e-mail: brastogi@yahoo.com

P. Choudhury
e-mail: pallabee.ch@gmail.com

R. B. S. Yadav
Indian National Centre for Ocean Information Services, Ocean Valley, P.B. No. 21, IDA Jeedimetla
P.O., Hyderabad 500055, Andhara Pradesh, India
e-mail: rbsybhu@rediffmail.com

1 Introduction

It has now been well established that in addition to earthquake source process and propagation of seismic waves in a medium, the characteristics of the recording site are one of the important factor that causes earthquake ground motions to vary significantly from one location to another. The characteristics of the recording site include rock properties beneath the site, the local soil conditions and the topography of the site. The effect of local geological formations on ground motion also depends on the intensity, the frequency and the incidence angle of the incoming seismic waves. The earthquakes such as 1985 Mexico, 1988 Spitak, 1989 Loma Prieta and 2001 Bhuj have clearly demonstrated that the site conditions can have a significant influence on the amplitudes and response spectral characteristics of the earthquake ground motions as well as on damage pattern. The 2001 Bhuj earthquake caused severe damage to 4–5-storey buildings at Ahmedabad, situated in central Gujarat, and around 250 km from the epicentre. Various studies have shown the ability of surface geologic conditions to alter seismic motions (Borcherdt 1970; King and Tucker 1984; Aki 1988; Field et al. 1992). The effect of site conditions, known as site effect, is defined as the modification of the characteristics (amplitude, frequency content and duration) of the seismic waves due to specific characteristics and geometrical features of the soil deposits overlying the bedrock (Ansal 2004).

The soft soils that form low-velocity layers near the earth's surface trap energy amplify the frequencies due to the decrease in seismic impedance. It is common observation that the earthquake ground motions on sediments are larger than on hard rocks. The site characteristic is important from seismic hazard point of view, because the concentration of human population worldwide is in or near the sediment-filled valleys. The site amplification functions are required for the estimation of realistic earthquake ground motions and therefore for the estimation of seismic hazard of a region. The site response is one of the important factors required for the micro-zonation studies of a region. Most of the techniques used for the estimation of site response require a reference site, which is not available always. In one of the non-reference site techniques, originally proposed by Nakamura (1989) for micro-tremor measurements, the site response is obtained by dividing the horizontal-component noise spectrum by that of the vertical component. Nakamura (1989) opined that the vertical component of ambient noise is relatively uninfluenced by a soft sediment layer overlying a half space. It has been demonstrated that the Nakamura's technique predicts only the fundamental resonant frequency and finds discrepancies with the predicted amplitude (Field and Jacob 1995; Seekins et al. 1996). Lermo and Chávez-García (1993) extended the Nakamura (1989) approach by using earthquake records, instead of micro-tremors, recorded at single station. Their analysis is based on the observations during 1985 Michoacán earthquake that the vertical component was not subjected to site effects suffered by the horizontal components, and therefore, the horizontal-to-vertical ratio of the spectra can be used to evaluate site effects. They concluded that if the site effects are caused by simple geology, dominant period and local amplification level can be obtained using earthquake records of single station. This approach has been used widely on weak as well as strong-motion records (Chavez-Garcia et al. 1996; Castro et al. 1997; Riepl et al. 1998; Zare et al. 1999; Nath et al. 2000, 2002, 2005, 2008; Mandal et al. 2005).

The state of Gujarat in Western India comprises of three distinct geological regions, Kachchh, Saurashtra and mainland. The site amplification in different parts of Gujarat needs

to be estimated for assessing the seismic hazard of the region and getting first-hand information about the site response in different parts of Gujarat. Mandal et al. (2005, 2008) estimated the site amplification at stations located in the Kachchh region, mostly the 2001 aftershock zone using aftershock data and by spectral ratio and inversion method. Mandal et al. (2005) estimated the site response in the aftershock zone of 2001 Bhuj Mw 7.7 earthquake using the H/V spectral ratio method and 454 aftershocks (Mw 2.5–4.7) recorded at 12 three-component digital strong motion and 8 three-component digital seismograph sites. Mandal et al. (2005) prepared preliminary site response maps for 1–3 and 3–10 Hz frequency ranges for the area extending from 23–23.85°N to 69.65–70.85°E, the Kachchh aftershock zone. Mandal et al. (2008) determined the site response from the horizontal components of S-wave data from 38 aftershocks (Mw 3.0–5.6) of the 2001 Bhuj earthquake (Mw 7.7) recorded at 18 strong-motion sites in the Kachchh seismic zone, Gujarat, India, in the frequency range 0.2–10.0 Hz using the reference site generalized inversion technique. It is apparent that in both 0.2–1.8 and 3–7 Hz frequency bands, the presence of geological contacts and sediment thicknesses controls the site responses in the Kachchh seismic zone.
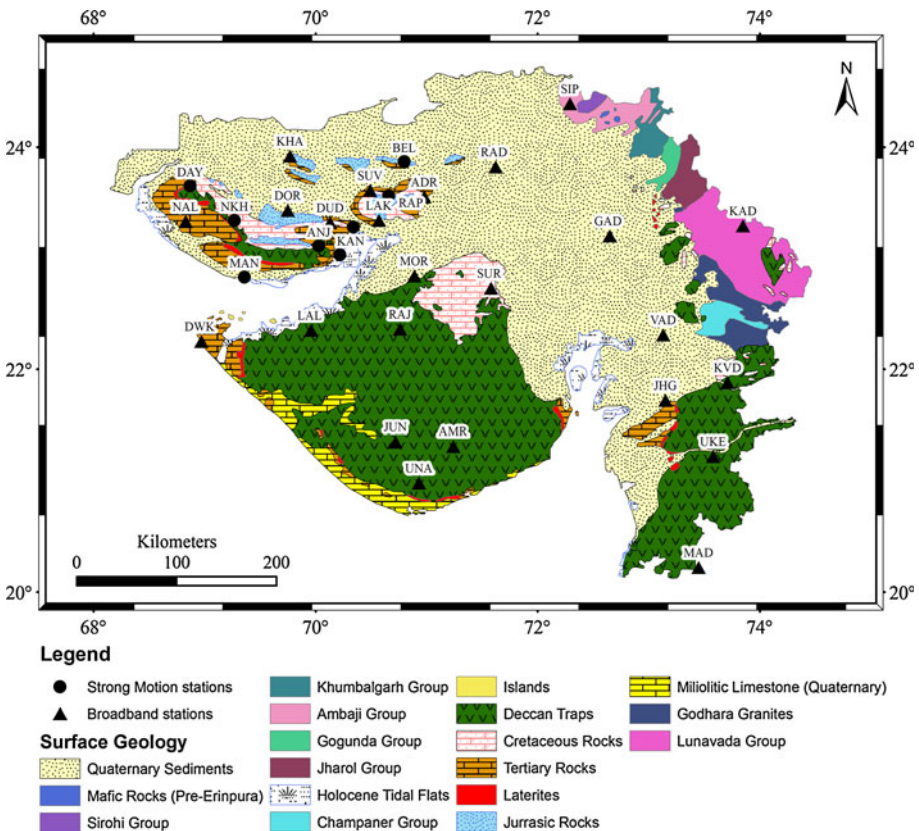

Fig. 1 Locations of the sites along with local geology used for the present analysis [*ADR* Adesar, *ANJ* Anjar, *BEL* Bela, *BCH* Bhachau, *DAY* Dayapar, *DOR* Dhori, *DUD* Dudhai, *KAN* Kandla, *KHA* Khavda, *LAK* Lakadia, *MAN* Mandvi, *NAK* Nakhatarana, *NAL* Naliya, *RAP* Rapar, *SUV* Suvai, *AMR* Amreli, *DWK* Dwarka, *JUN* Junagarh, *LAL* Lalpur, *MOR* Morbi, *RAJ* Rajkot, *SUR* Surendernagar, *UNA* Una, *GAD* Gandhinagar, *JHG* Jhagadia, *KAD* Kadana, *KVD* Kevadia, *RAD* Radhanpur, *SIP* Sipu, *UKE* Ukai, *VAD* Vadodara, *MAD* Madhuban(Valsad)]

In the present study, the site amplification functions have been estimated using horizontal-to-vertical spectral ratio (HVSR) technique at 32 sites distributed in the entire Gujarat region and located on varied geology (from Proterozoic to Jurassic, Cretaceous, Tertiary and Quaternary). The local earthquake data recorded on these stations spread all over Gujarat on different types of rocks and soils have been used for this purpose. The spatial distributions of predominant frequencies and amplifications at different frequencies corresponding to buildings of different storeys have also been discussed and presented.

2 Geology and seismotectonic setup of Gujarat

Gujarat State spreads over an area of around 1,96,000 sq. Km. It is bounded in the west by the Arabian Sea and in the north by the Rann of Kutch and Rajasthan desert, to the NE and east its limits are marked by the Aravali ranges, and the hills of Vindhya, Satpura and Western Ghats mark the Southern tip. Gujarat State is divided physiographically into three distinct geographical units, mainland Gujarat, Saurashtra and Kachchh. Figure 1 shows the geological map of Gujarat. The geology of Gujarat comprises a Precambrian basement over which younger rocks of Jurassic, Cretaceous, Tertiary and Quaternary are deposited. The rocks of Palaeozoic era are absent in Gujarat (Merh 1995). The sedimentary sequences are mainly Jurassic, Tertiary and Quaternary in age. About 60% of the area is covered by Deccan basalt covering major parts of Saurashtra, some portion in Kachchh and major portion of South Gujarat with intervening Cretaceous and Tertiary rocks at many places. Stratigraphically, mainland Gujarat comprises of Precambrian crystalline, sedimentary
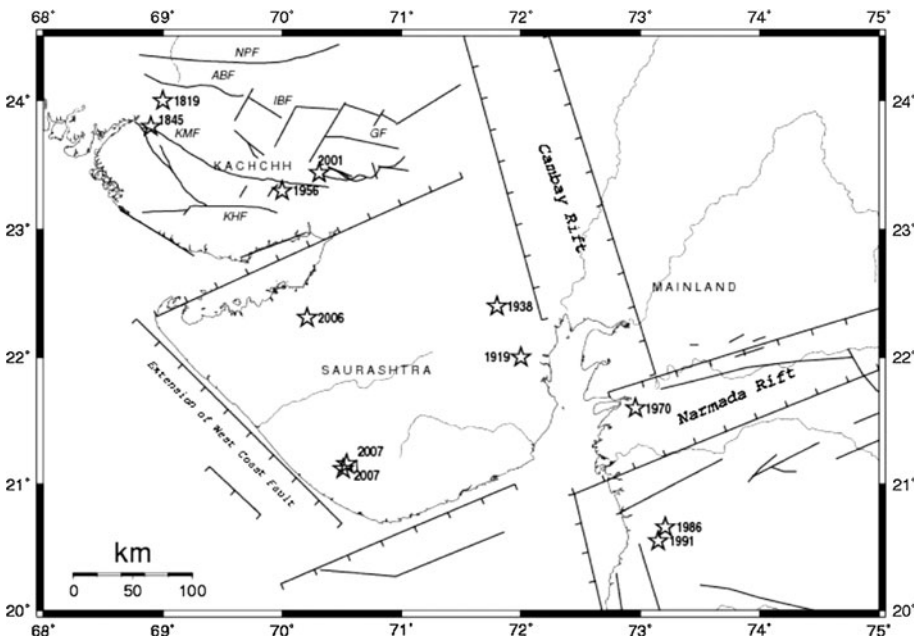

Fig. 2 The major tectonic features of the Gujarat region. The locations of major earthquakes in the region are also shown as *open stars* (1819:Kachchh; 1845:Lakhpat; 1919:Bhavnagar; 1938:Paliyad; 1956:Anjar; 1970:Bharuch; 1986, 1991:Valsad; 2001:Bhuj; 2006:Jamnagar; 2007:Talala)

rocks of Cretaceous, Tertiary and Quaternary periods, and the Deccan trap. The Saurashtra region shows sedimentary sequence as old as Upper Jurassic with the majority of area covered by basalts. Kachchh shows good development of Mesozoic and Tertiary sequence (Merh 1995).

The thickness of the sediment estimated is more than 3 km in the southern part of the Kachchh and 1.5 km in the northern part (Srinivasan and Khar 1995). The region is a

Table 1 Local surface geology of the sites used in the present study

Station and instrument type	Latitude °(N)	Longitude °(E)	No. of earthquakes	Magnitude range	Local geology
Kachchh region					
Adesar (BBS)	23.55	70.98	5	2.4–4.3	Tertiary
Anjar (SMA)	23.11	70.03	4	4.0–4.7	Deccan
Bela (SMA)	23.87	70.8	14	3.5–4.9	Jurassic
Bhachau (SMA)	23.28	70.34	15	3.0–4.9	Tertiary
Dayapar (SMA)	23.65	68.87	4	4.0–4.6	Deccan
Dhori (BBS)	23.43	69.75	14	2.4–3.4	Quaternary
Dudhai (BBS)	23.32	70.13	10	3.0–4.5	Tertiary
Kandla (SMA)	23.03	70.22	6	4.0–4.9	Quaternary
Khavda (BBS)	23.92	69.77	9	3.0–4.0	Jurassic
Lakadia (BBS)	23.34	70.57	10	3.1–4.1	Tertiary
Mandvi (SMA)	22.83	69.36	11	3.6–4.9	Quaternary
Nakhatrana (SMA)	23.34	69.27	9	4.0–4.9	Cretaceous
Naliya (BBS)	23.33	68.83	8	2.5–3.3	Tertiary
Rapar (SMA)	23.56	70.66	10	3.0–4.9	Jurassic
Suvai (BBS)	23.61	70.49	10	3.1–4.1	Cretaceous
Saurashtra region					
Amreli (BBS)	21.31	71.24	6	2.0–3.6	Deccan
Dwarka (BBS)	22.25	68.97	12	2.0–3.8	Tertiary
Junagarh (BBS)	21.35	70.72	10	2.0–4.7	Deccan
Lalpur (BBS)	22.35	69.96	15	2.0–4.5	Deccan
Morbi (BBS)	22.84	70.89	11	2.0–4.7	Deccan
Rajkot (BBS)	22.36	70.76	10	2.6–3.4	Deccan
Surendranagar (BBS)	22.73	71.58	10	2.5–4.7	Cretaceous
Una (BBS)	20.98	70.93	10	2.2–4.8	Deccan
Mainland Gujarat region					
Gandhinagar (BBS)	23.2	72.65	9	3.5–4.8	Quaternary
Jhagadia (BBS)	21.72	73.15	8	3.8–4.7	Quaternary
Kadana (BBS)	23.29	73.85	5	2.0–4.7	Proterozoic
Kevadia (BBS)	21.88	73.71	5	2.4–2.6	Deccan
Radhanpur (BBS)	23.82	71.62	4	3.6–4.1	Quaternary
Sipu (BBS)	24.39	72.29	4	4.1–4.7	Proterozoic
Ukai (BBS)	21.22	73.58	6	2.0–2.8	Deccan
Vadodara (BBS)	22.31	73.13	9	3.6–4.8	Quaternary
Valsad (BBS)	20.22	73.45	5	2.3–2.6	Deccan

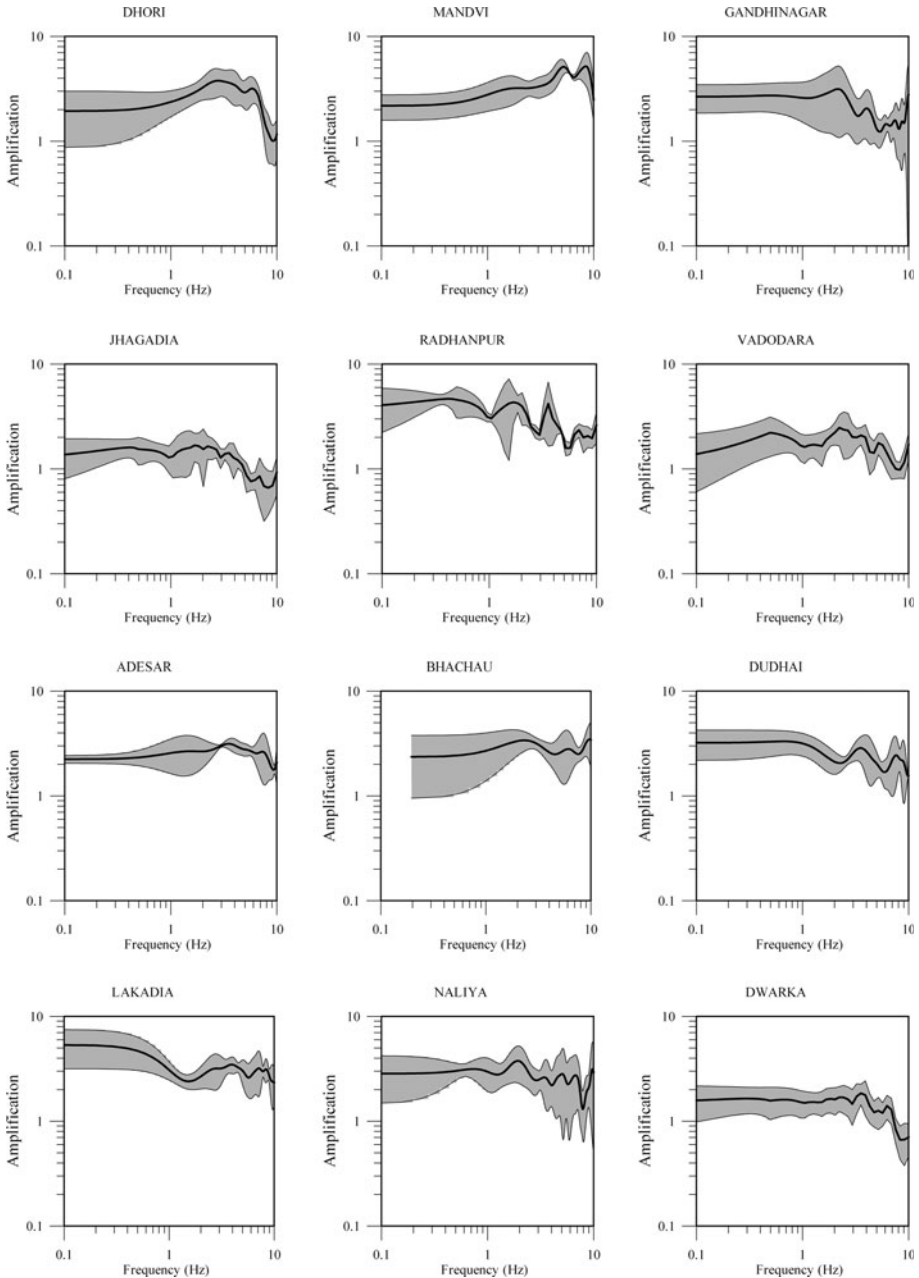*BBS* broadband site, *SMA* strong-motion accelerographs site

Fig. 3 Site amplification plots of various sites. The *shaded area* indicates the mean $\pm$ 1 standard deviation, and *dark line* is the mean

tri-junction of three failed rifts: Kachchh, Cambay and Narmada with several active faults (Biswas 1987, 2005; Talwani and Gangopadhyay 2001). These rifts were formed by the rifting along major Precambrian trends. The rifting developed around the Saurashtra horst.
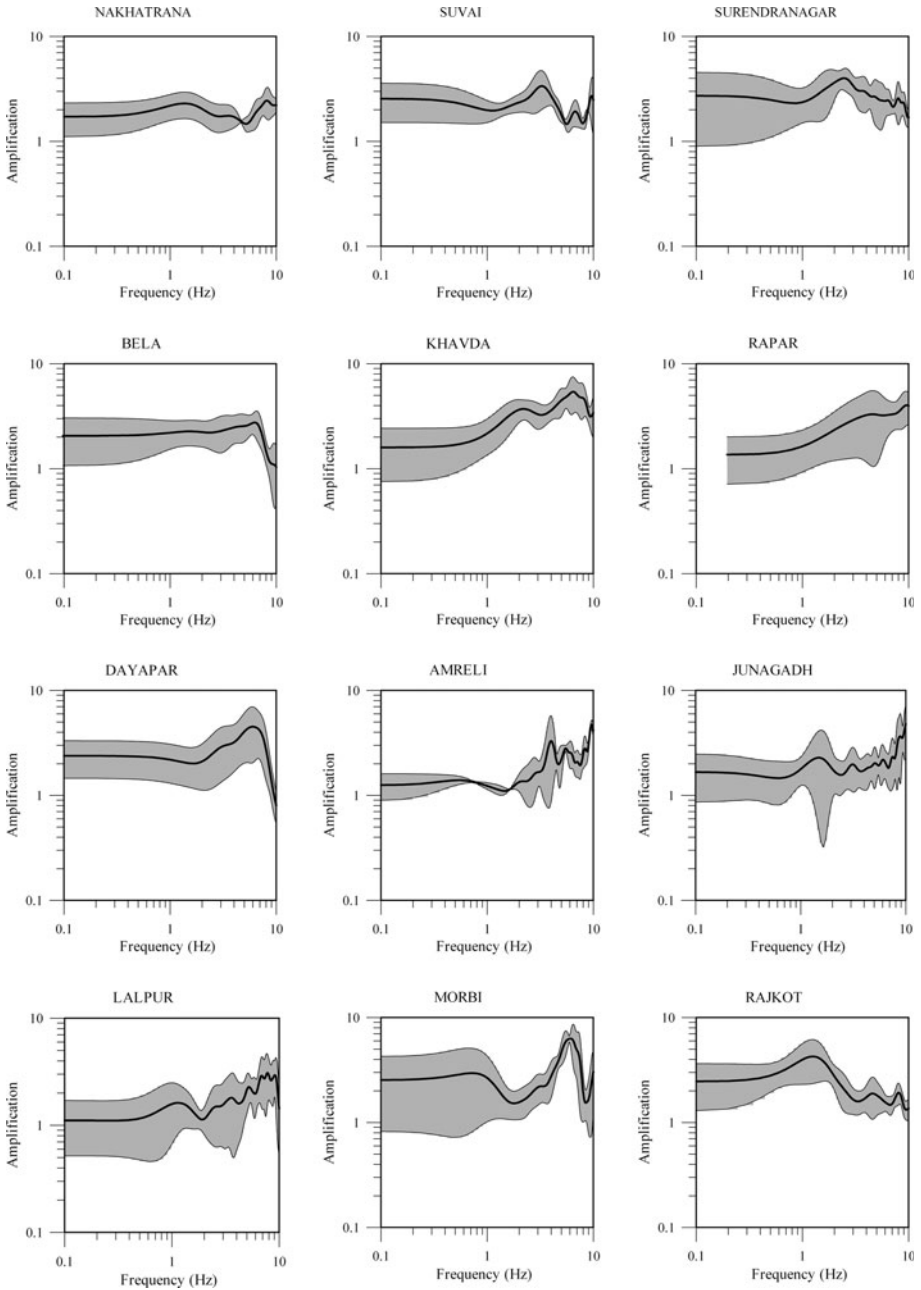
Fig. 3 continued

The major faults in Kachchh are Nagar Parkar fault (NPF), Allah Bund fault (ABF), Island Belt fault (IBF), Kachchh Mainland fault (KMF), South Wagad fault (SWF) and Katrol Hill fault (KHF) (Fig. 2). In addition, several NE and NW trending small faults/lineaments are observed (Biswas 1987). The Saurashtra region comprises of fractures
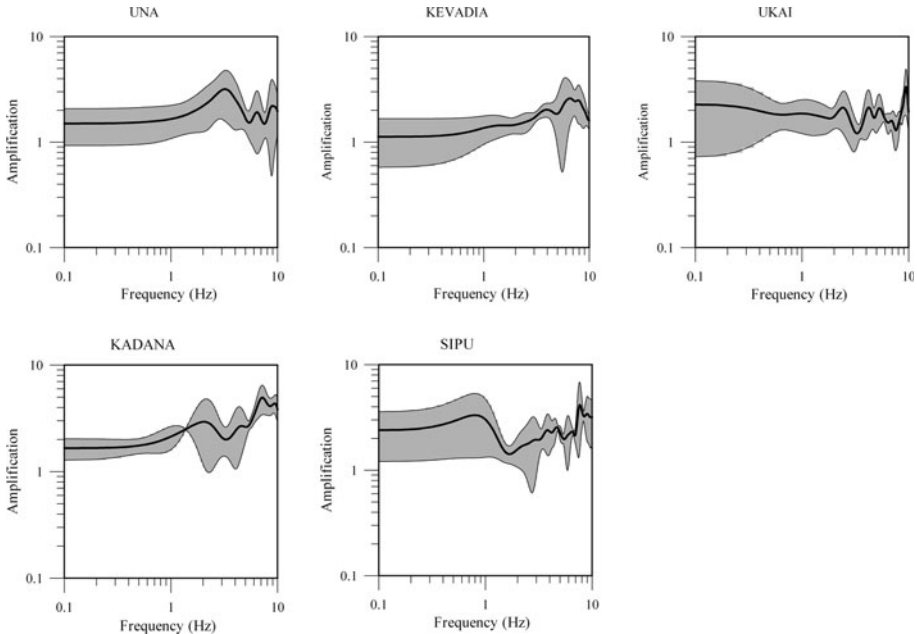
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related to three intersecting rift trends namely NE–SW Delhi trend, ENE–WSW Narmada trend and NNW–SSE Dharwar trend. The EW trending Narmada fault system is a zone of weakness following Narmada-Son Geo-fracture in the mainland Gujarat.

Gujarat region has witnessed many destructive earthquakes in the past. Most of these earthquakes occurred in the Kachchh region. Major earthquakes that occurred in the historical past in Kachchh are 1668 Indus delta (MM X), 1819 Kachchh (Mw 7.8) and 1845 Lakhpat (MM VIII) (Rajendran and Rajendran 2001). In the recent time, the region has been rocked by 1956 Anjar (Mw 6.0) and 2001 Bhuj (Mw 7.6) earthquakes. In the Saurashtra region, Paliyad sequence of 1938 with maximum magnitude of 5.7 was a significant seismic activity. Beside this, some swarm type of activity was reported from Jamnagar (Chopra et al. 2008) and Talala (Yadav et al. 2010). Moderate seismicity had been noticed in mainland Gujarat. Most of the activity is concentrated mainly along Narmada fault in southern portion of mainland. The Narmada region experienced seven major earthquakes of magnitudes varying between 4.2 and 6.5 (Senoi 1991).

3 Methodology and data processing

The horizontal-to-vertical (H/V) spectral ratio technique, proposed by Nakamura (1989) for the micro-tremors and extended successfully by Lermo and Garcia (1993) for the earthquake records, has been used here. Castro et al. (1997) tested the validity of the assumptions involved in using H/V ratios to estimate the site response of S-waves. They concluded that as long as vertical component of motion is not contaminated by surface waves, the source effect can be eliminated from S-wave spectra by calculating H/V ratios.

This technique assumes a half space with a horizontal sedimentary layer on top. Accordingly, the four components of ground motion are involved: horizontal and vertical component of the half space (base of soil column) and horizontal and vertical components at the surface. In the frequency domain, the vertical component of the transfer function, $hv(f)$, is defined as the ratio between the vertical component of motion on the surface, $V_S(f)$, and that on the base of the sediments, and $V_B(f)$ is given by (Castro et al. 1997):

Table 2 Estimated site amplifications, predominant frequencies and amplification at frequencies corresponding to the buildings of different heights

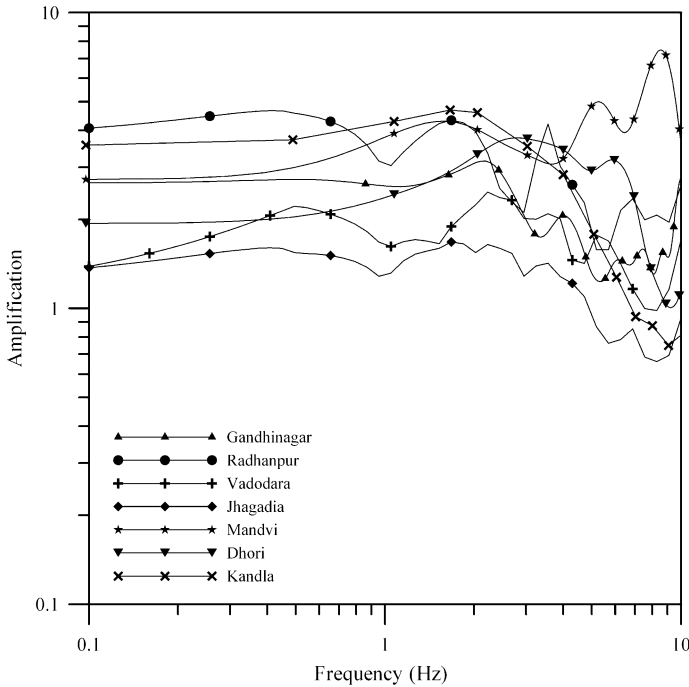| Station	Predominant frequency in Hz	Amplification at predominant frequency	Amplification at				
			10 Hz (0.1 s) (1 storey)	5 Hz (0.2 s) (2 storey)	2 Hz (0.5 s) (3–4 storey)	1 Hz (1 s) (tall buildings)	0.17 Hz (6 s) (high-rise buildings)
Nakhatarana	8.2	2.5	2.2	1.5	2	2.2	1.7
Surendernagar	2.4	4.0	1.7	2.6	3.6	2.3	2.7
Suvai	3.2	3.4	2.5	1.8	2.3	2	2.5
Amreli	9.5	4.7	4.2	2.2	1.3	1.2	1.3
Anjar	10	4.0	4.0	1.7	2.8	2.2	2.0
Dayapar	6	4.5	0.8	4.0	2.1	2.2	2.4
Junagarh	10	4.8	4.8	2.0	1.8	1.8	1.7
Kevadia	6.5	2.6	1.6	1.8	1.5	1.4	1.1
Lalpur	7.8	3.1	1.4	2.2	1.2	1.6	1.1
Morbi	6.2	6.3	3.0	4.7	1.6	2.6	2.5
Rajkot	1.3	4.3	1.4	1.8	2.9	3.9	2.5
Ukai	9.5	3.4	1.9	1.9	1.8	1.9	2.3
Una	3.2	3.2	2.0	1.7	2.2	1.6	1.5
Valsad	9	5.5	1.5	2.9	1.6	1.4	1.4
Bela	6.3	2.8	1.0	2.5	2.2	2.2	2.1
Khavda	6.5	5.4	3.4	4.5	3.6	2.1	1.6
Rapar	9.6	4.0	4.0	3.3	2.3	1.6	1.4
Kadana	7.2	5	3.9	2.6	2.9	2.1	1.7
Sipu	7.7	4.2	3.2	2.3	1.6	3	2.4
Dhori	2.8	3.8	1.1	2.9	3.2	2.3	1.9
Gandhinagar	2.2	3.2	2.8	1.3	3.1	2.7	2.7
Jhagadia	1.7	1.7	0.9	0.9	1.5	1.3	1.4
Kandla	2	5	0.8	1.8	4.6	4.3	3.6
Mandvi	5.3	5.1	2.6	5.0	3.2	2.8	2.2
Radhanpur	0.4	4.7	2.6	1.6	4.0	3.0	4.2
Vadodara	2.2	2.5	1.7	1.8	2.2	1.7	1.5
Adesar	3.5	3.2	2.1	2.8	2.7	2.6	2.2
Bhachau	10	3.5	3.4	2.6	3.3	2.7	2.4
Dudhai	8.9	4	1.5	1.8	2.9	3.5	2.8
Dwarka	3.6	1.9	0.7	1.3	1.6	1.5	1.6
Lakadia	4	3.5	2.3	3.1	1.8	2.7	3.2
Naliya	2	3.8	2.9	2.8	3.7	2.9	2.8

Fig. 4 Average site amplifications of the sites located on Quaternary sediments

$$hv(f) = V_S(f)/V_B(f) = Sv(f)P(f)Zv(f)/Sv(f)P(f) \tag{1}$$

where $Sv(f)$ contains the contribution of the source, $P(f)$ is the path effect from the origin to the base of sediments and $Z(f)$ represents the amplification induced by the sediments. Similarly, the horizontal component, $hu(f)$, can be defined as

$$hu(f) = H_S(f)/H_B(f) = Su(f)Zu(f)P(f)/Su(f)P(f) \tag{2}$$

where $H_S(f)$ and $H_B(f)$ are the horizontal components of the motion on the surface and on the base of the sediments, respectively. From Eqs. 1 and 2, the ratio can be written as:

$$hu(f)/hv(f) = Zu(f)/Zv(f) = H_S(f)V_B(f)/H_B(f)V_S(f) \tag{3}$$

$Zv(f) = 1$ for the S-waves under the assumption that the vertical component of the ground motion is amplification free. Also, if we assume that on the base of the sediments, the spectral amplitude of both components is same, that is,

$$H_B(f) = V_B(f). \tag{4}$$

Then the amplification factor of the horizontal component can be written as (from Eq. 3):

$$Zu(f) = H_S(f)/V_S(f) \tag{5}$$

Thus, the site effects can be estimated at single station using spectral ratios between horizontal and vertical components of the earthquakes without a reference station.
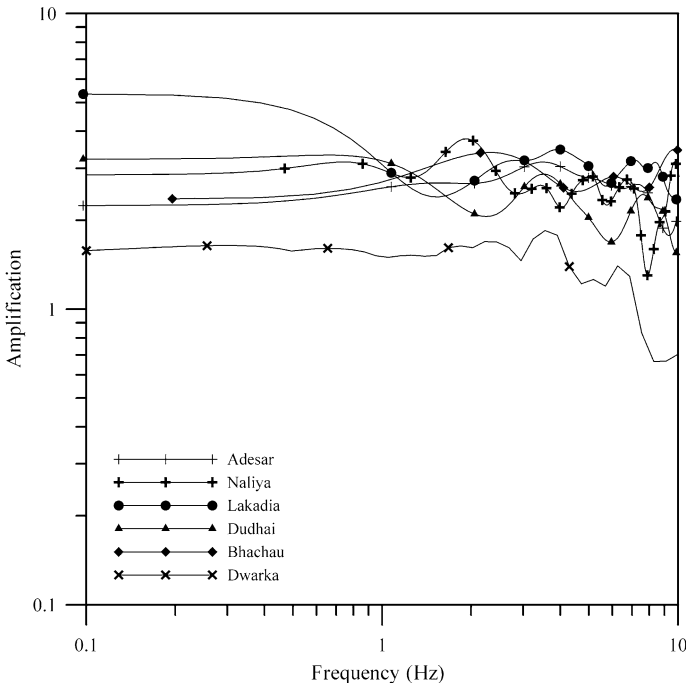
Fig. 5 Average site amplifications of the sites located on Tertiary deposits

The waveforms of local earthquakes with magnitudes 2.5–4.3 recorded at 32 sites in Gujarat region have been used in the present analysis. The recording sites are located in different regions with varying geology of Gujarat. These include 15 sites in Kachchh region, where the seismic network is dense due to intense seismic activity, 8 in Saurashtra and 9 in mainland Gujarat region. Figure 1 shows the locations of the sites used in the present analysis. Out of 32 stations, 7 stations are located on Quaternary deposits, 6 on Tertiary, 11 on Deccan, 3 on Jurassic, 3 on Cretaceous and 2 on Proterozoic rocks. Table 1 gives the local geology of the recording stations along with their locations. 24 sites are deployed with broadband seismographs and 8 sites with strong-motion accelerographs (Table 1, Fig. 1).

A time window of 5.0 s starting from 0.5 s before the S-wave arrival has been selected from all the three components at a recording site. The small window is chosen to avoid the contamination of S-waves by the surface waves. At each site, 5–10 earthquakes are carefully selected for the analysis depending on the signal-to-noise ratio. The H/V spectral ratio, $SR_{ij}(f_k)$, has been estimated at each jth site for ith event at central frequency f_k from the root mean square average of the amplitude spectra of horizontal components:

$$SR_{ij}(f_k) = \frac{\frac{1}{\sqrt{2}}\sqrt{\mathrm{abs}H_{ij}(f_k)|_{\mathrm{NS}}^2 + \mathrm{abs}H_{ij}(f_k)|_{\mathrm{EW}}^2}}{\mathrm{abs}V_{ij}(f_k)}$$

where $H_{ij}(f_k)|_{\mathrm{NS}}$, $H_{ij}(f_k)|_{\mathrm{EW}}$ and $V_{ij}(f_k)$ are, respectively, the Fourier spectra of the N–S, E–W and vertical components. The ratio is then smoothened using Hamming and Tuckey technique (Bath 1974) and plotted against frequency. The H/V ratios have been obtained
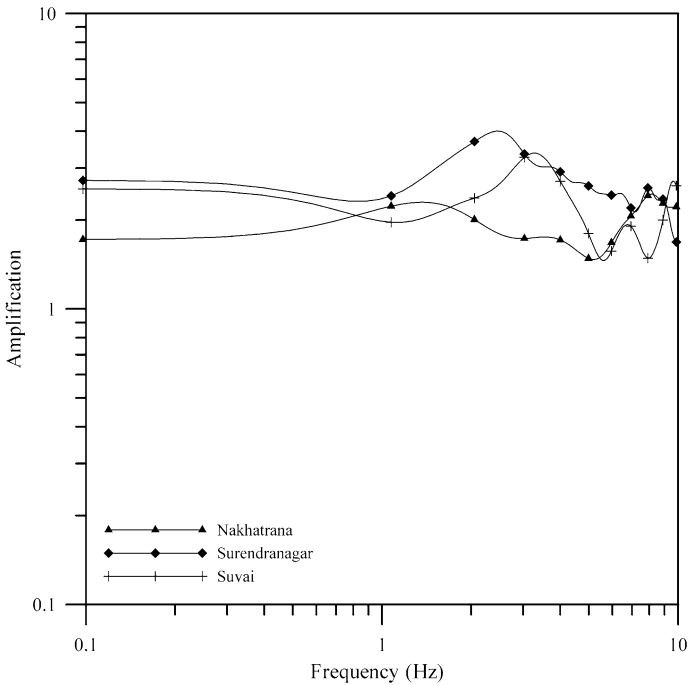
Fig. 6 Average site amplification of the sites located on Cretaceous rocks

for the frequencies up to 10 Hz, keeping in view the frequency range of engineering significance (1–10 Hz).

4 Results and discussions

The H/V ratio (amplification) estimated from the recorded earthquakes presented in our study is shown in Fig. 3. The thick lines in the plots show the average H/V ratios for that particular site. The shaded portion depicts the mean plus and minus one standard deviation. Table 2 summarizes the estimated site amplifications and corresponding predominant frequencies along with the local geology of 32 sites in Gujarat region. The average H/V ratios for the 7 sites (Gandhinagar, Radhanpur, Vadodara, Jhagadia, Kandla, Mandvi and Dhori) situated on Quaternary deposits are shown in Fig. 4. We note that these sites, except Mandvi and Radhanpur, show the predominant frequencies in the range 1.7–2.8 Hz. Mandvi shows the predominant frequency of 5.3 Hz, whereas Radhanpur does not have a clear peak instead has three peaks at 0.4, 1.7 and 3.5 Hz. The average site amplification estimated at predominant frequency for these 7 sites is 3.7 ± 1.3. For Gandhinagar and Vadodara, the predominant frequency is 2.2 Hz and maximum amplification is 3.2 and 2.5, respectively. These sites are located in Cambay Graben with thick Quaternary sediments. Mandvi, located on the coast, shows the maximum predominant frequency of 5.3 Hz among the Quaternary sites and maximum amplification of 5.1. Dhori shows maximum amplification of 3.8 at 2.8 Hz. This may be the one of the reasons that this village had experienced severe damage during 2001 Bhuj earthquake. The predominant frequency
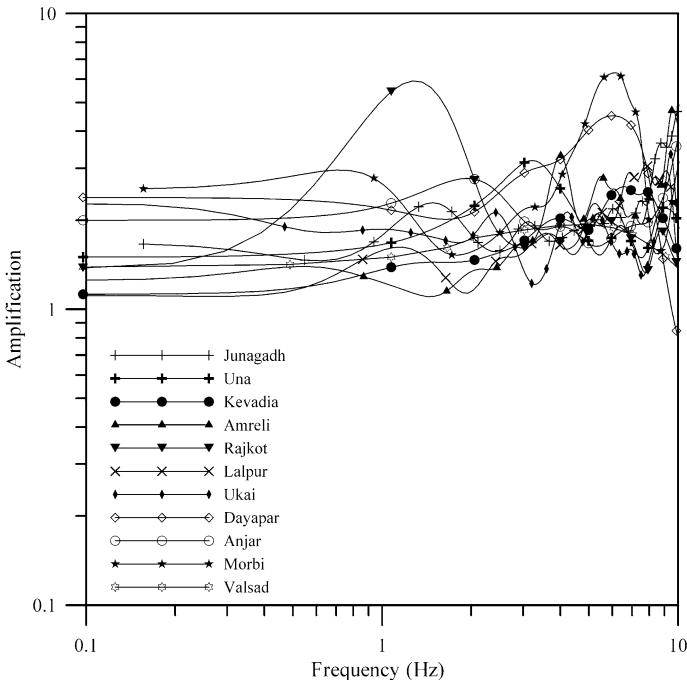
Fig. 7 Average site amplifications of the sites located on Deccan trap

range (1.7–2.8 Hz), except for Mandvi and Radhanpur, estimated for the sites of Quaternary deposits is corresponding to the natural frequency of 4 to 6-storey buildings. This implies that these buildings on Quaternary sediments can expect maximum damage during large earthquakes. This happened at Ahmedabad during 2001 Bhuj earthquake, where most of 4–5-storey buildings got damaged, in spite of the fact that Ahmedabad is at a distance of 240 km from the source.

Figure 5 shows the average H/V ratios for the sites (Adesar, Naliya, Bhachau, Dudhai, Dwarka and Lakadia) located on Tertiary deposits. The maximum amplification at these sites varies from 1.9 to 3.8 with predominant frequency in the range 2–10 Hz. The estimated average amplification at predominant frequency for this group is 3.3 ± 0.7. The predominant frequency of most of the sites except Dudhai and Bhachau varies between 2 and 4 Hz, whereas for Dudhai and Bhachau, it is 8.9 and 10 Hz, respectively. The predominant frequency of 9–10 Hz approximately corresponds to the natural frequency of single-storey buildings. Bhachau and Dudhai towns had witnessed the maximum damage and casualties during 2001 Bhuj earthquake. Prior to 2001 Bhuj earthquake, most of the Bhachau town were comprised of 1–2-storey buildings and constructed without following any building codes. Almost 95% of these buildings were damaged during the earthquake. In a similar study, Mandal et al. (2005) estimated the site amplification values for Quaternary/Tertiary sites in the Kachchh region using the aftershocks of 2001 Bhuj earthquake. They have used the strong motion and broadband data in the analysis and estimated average amplification values of 0.75–6.03 at frequencies 1–3 Hz. We obtained the amplification values as 1.2–4.7 for the same frequency band for the sites of Quaternary/ Tertiary in the Kachchh region, which are in agreement with Mandal et al. (2005). For the
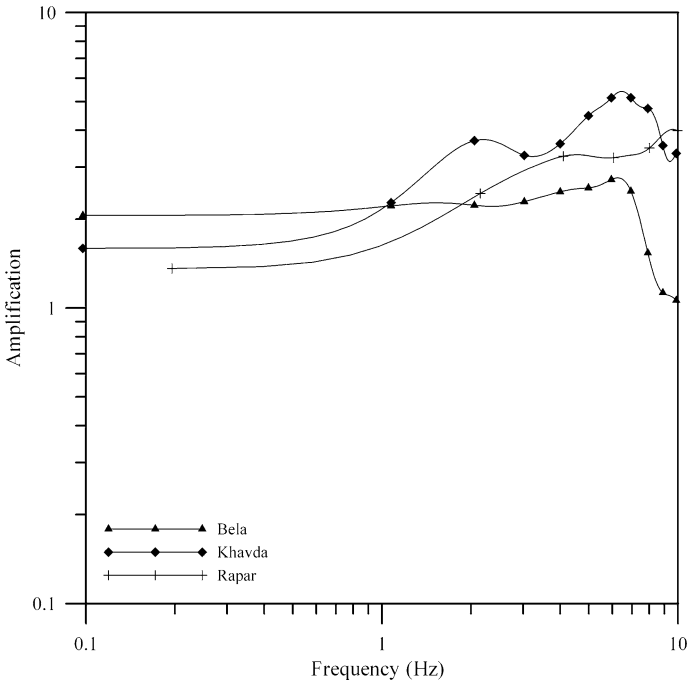
Fig. 8 Average site amplifications of the sites located on Jurassic rocks

frequency band of 3–10 Hz, Mandal et al. (2005) obtained the amplification values of 0.49–3.27 for the sites on Quaternary/Tertiary deposits, while the values evaluated in our study are 0.66–5.19. The study by Mandal et al. (2005) was concentrated only in the Bhuj aftershock zone. Our study covers almost the entire Kachchh.

The average H/V plots for the sites Nakhatarana, Suvai and Surendernagar located on Cretaceous rocks are shown in Fig. 6. In this case, the maximum amplification of 2.5–4.0 has been observed corresponding to the predominant frequency of 2.4–8.2 Hz. Suvai is located on the edge of the Great Rann of Kachchh and shows the amplification of 3.4 in this group. The higher amplification at this site may be due to the basin effect as amplification increases at the basin edges. The average amplification for the sites of Cretaceous rocks is 3.3 ± 0.8, which is less than those located on Quaternary (3.7) and equal to that on Tertiary (3.3) deposits. This may be related to the age of these rocks, as Cretaceous rocks are older than Quaternary and Tertiary deposits.

Figure 7 shows the average H/V plots for the 11 sites (Amreli, Anjar, Dayapar, Junagarh, Kevadia, Lalpur, Morbi, Rajkot, Ukai, Una and Valsad) located on Deccan trap. Out of these, 6 sites (Lalpur, Junagarh, Morbi, Rajkot, Una and Amreli) fall in Saurashtra region, 2 sites (Anjar and Dayapar) in Kachchh region, while the remaining 3 sites (Kevadia, Ukai and Valsad) in south mainland Gujarat. The maximum amplification for these sites lies in the range 2.6 – 6.3 with the average of 4.2 ± 1.1 at predominant frequencies. The predominant frequencies for most of the sites except Rajkot and Una are high and fall in the range 6–10 Hz. For Rajkot and Una, the predominant frequencies are in the range 1.3–3.2 Hz, respectively. We note from Fig. 7 that the overall amplification at all the frequencies for most of the sites is between 1 and 2 except at predominant frequencies.
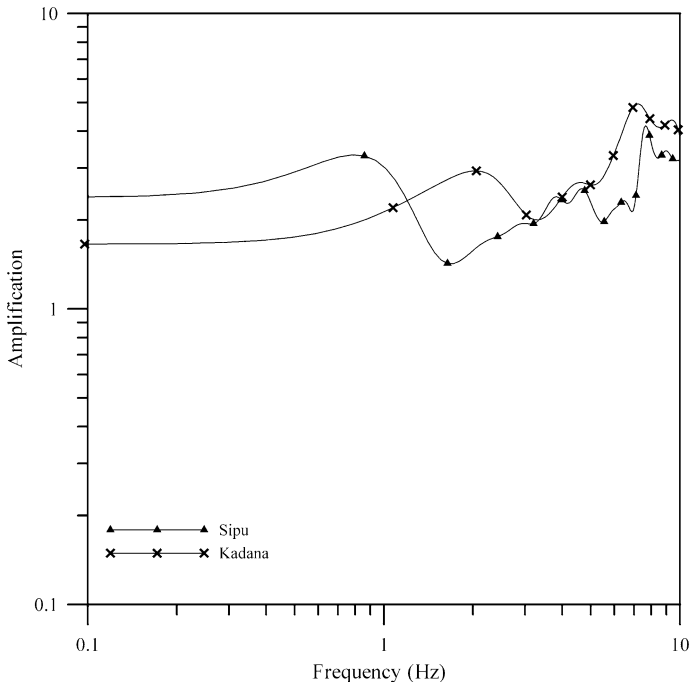
Fig. 9 Average site amplifications of the sites located on Proterozoic rocks

Morbi is having the maximum amplification of 6.3. The site is located in the transition zone between Deccan trap and Quaternary formations. Also, during 2001 Bhuj earthquake, many buildings (1–3 storey) were severely damaged at Morbi town, and MMI of VIII was assigned. This may be due to the high amplification at 5–6 Hz.

The average H/V plots corresponding to the three sites (Bela, Khavda and Rapar) situated on Jurassic rocks are shown in Fig. 8. All these sites fall in Kachchh region. We note that the maximum amplification varies from 2.8 to 5.4 with predominant frequencies in the range of 6.3–9.6 Hz. Rapar situated in Wagad area shows the amplification of 4.0 at 9.6 Hz, corresponding to natural period of single-storey buildings. This high amplification might have caused the damage to 80% of the buildings during 2001 Bhuj earthquake. The maximum amplification in this group is observed at Khavda. Khavda is located on hill top. The topographic effect might be the factor for the increase in amplification. The average site amplification at predominant frequency for this group of sites is 4.1 ± 1.3. We note that this average value of amplification is higher than those of corresponding to the sites Quaternary, Tertiary and Cretaceous, even though the Jurassic rocks are older. This needs further investigation with the data from more number of sites on Jurassic rocks.

Figure 9 shows the average H/V plots for the 2 sites (Sipu and Kadana) located on the Proterozoic rocks and belongs to Lunavada group of rocks. These rocks are exposed in the north-eastern part of Gujarat, bordering Rajasthan and Madhya Pradesh. These sites show the maximum amplification of 4.2 and 5 with predominant frequencies of 7.7 and 7.2 Hz. The estimated average amplification at predominant frequency for the sites of Proterozoic rocks is 4.6 ± 0.5.
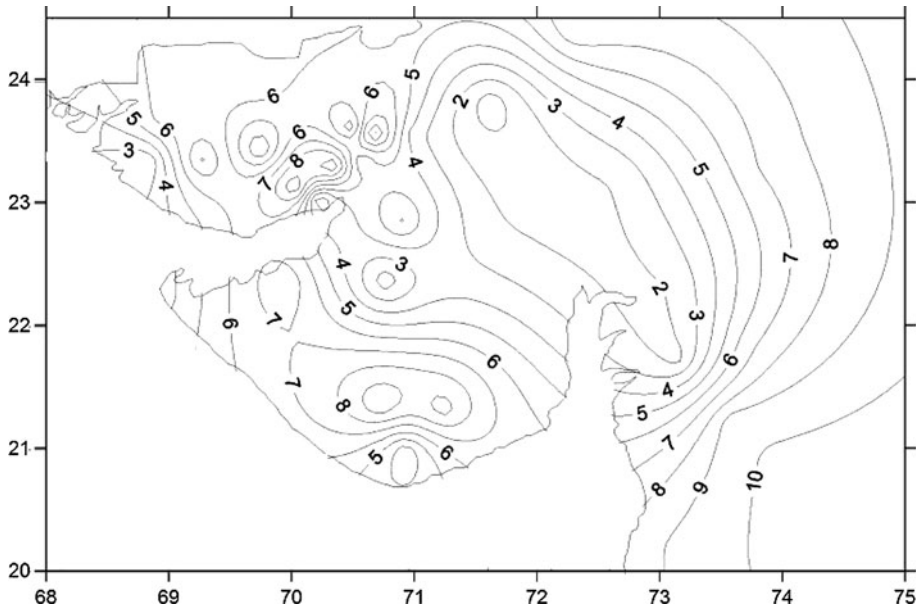
Fig. 10 Spatial distribution of predominant frequencies (contour interval is 1 Hz)

The spatial distribution of predominant frequencies obtained at different sites (Table 2) is shown in Fig. 10. We note from this figure that the predominant frequencies in the Cambay basin area located in the central Gujarat, comprising of thick Quaternary alluvium, vary from 1 to 3 Hz. The predominant frequencies lie in the range 5–8 Hz for most of the Saurashtra region comprising of Deccan basalt. A small area in the north-eastern part of Saurashtra region comprising of alluvium soil shows the predominant frequencies <3 Hz. In Kachchh region, the redominant frequencies vary from 3 to 6 Hz in the western Kachchh, 6–9 Hz in central and eastern regions of Kachchh. The predominant frequency gradually increases from 3 to 10 Hz in mainland Gujarat region. In southern Gujarat, mostly covered by Deccan trap, the predominant frequencies are in the range of 6–10 Hz, and in NE Gujarat, covered by Proterozoic rocks, it is between 5 and 8 Hz. The amplifications at different frequencies corresponding to single-storey buildings (10 Hz), double-storey buildings (5 Hz), 3–4-storey buildings (2 Hz), tall (1 Hz) and high-rise buildings (0.17 Hz) have been estimated from the site response curves (Fig 3) and given in Table 2. The contour maps of amplifications corresponding to these frequencies are shown in Figs. 11, 12, 13, 14 and 15.

We note from Fig. 11 that the amplification for single-storey buildings is <3 for most of the Gujarat region. In southern Saurashtra, northern and eastern Gujarat, the amplification varies from 2 to 4, and it varies from 2 to 3 in eastern Kachchh region. For most of Saurashtra, south Gujarat, central and western Kachchh, the amplification for single-storey buildings is estimated to be <2. The cities Amreli and Junagarh in Saurashtra, Anjar and Rapar in Kachchh and Kadana in mainland have amplification of around 4 for single-storey buildings. For the double-storey buildings, the site amplification is estimated to be 1–3 for almost whole of Gujarat region (Fig. 12). The amplification varies from 3 to 4 for few patches in northern and southern Kachchh and NE Saurashtra regions. The towns Morbi in Saurashtra and Bhachau, Rapar, Mandvi, Naliya and Lakhpat in Kachchh fall in these
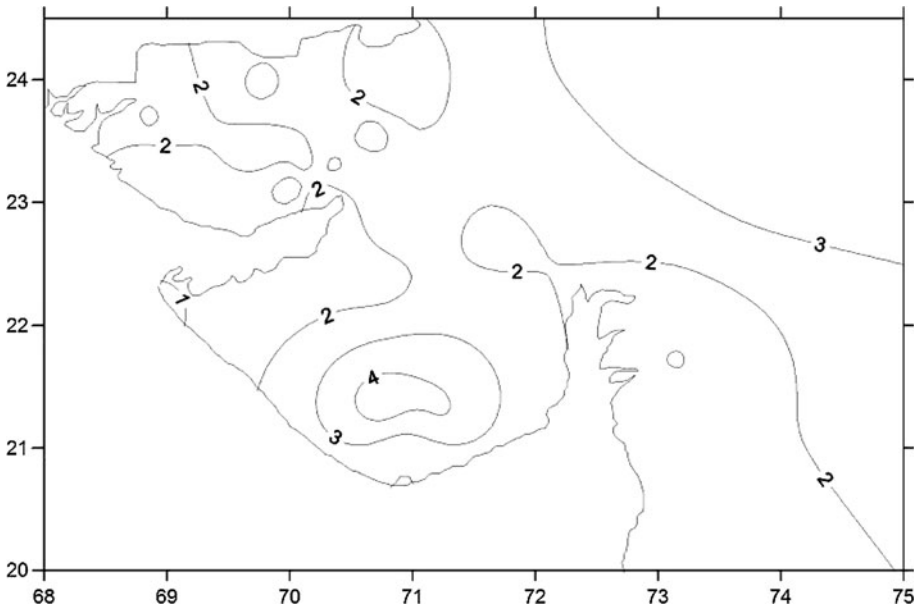
Fig. 11 Spatial distribution of site amplifications estimated at 10 Hz (single-storey buildings)
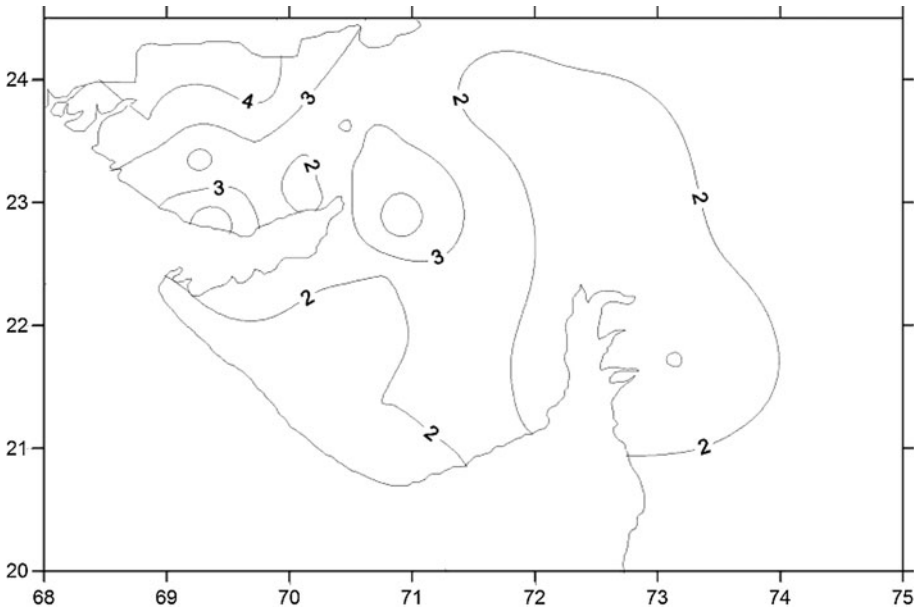

Fig. 12 Spatial distribution of site amplifications estimated at 5 Hz (double-storey buildings)

patches. This shows the significant hazard to 2-storey buildings of these patches. The amplifications for the 3–4-storey buildings have been estimated to be <2 for north and south Gujarat, and north-west and south-east Saurashtra (Fig. 13). It varies from 2 to 3 in
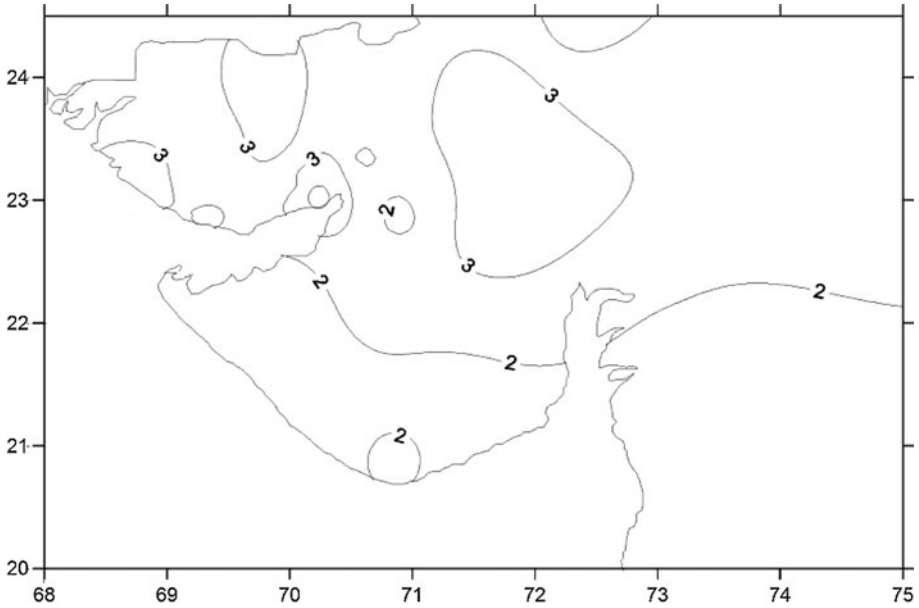
Fig. 13 Spatial distribution of site amplifications estimated at 2 Hz (3–4-storey buildings)
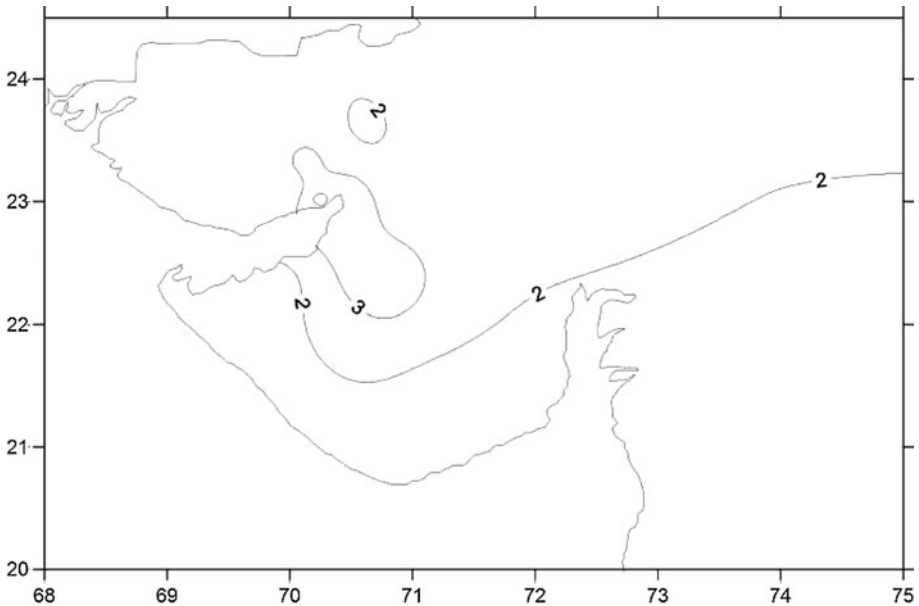

Fig. 14 Spatial distribution of site amplifications estimated at 1 Hz (tall buildings)

Cambay basin, central Gujarat, north-east Saurashtra and western Kachchh. The site amplifications are expected to be between 3 and 5 in the central Kachchh. This indicates that there is a significant hazard to 3–4-storey buildings in parts of Kachchh and Saurashtra
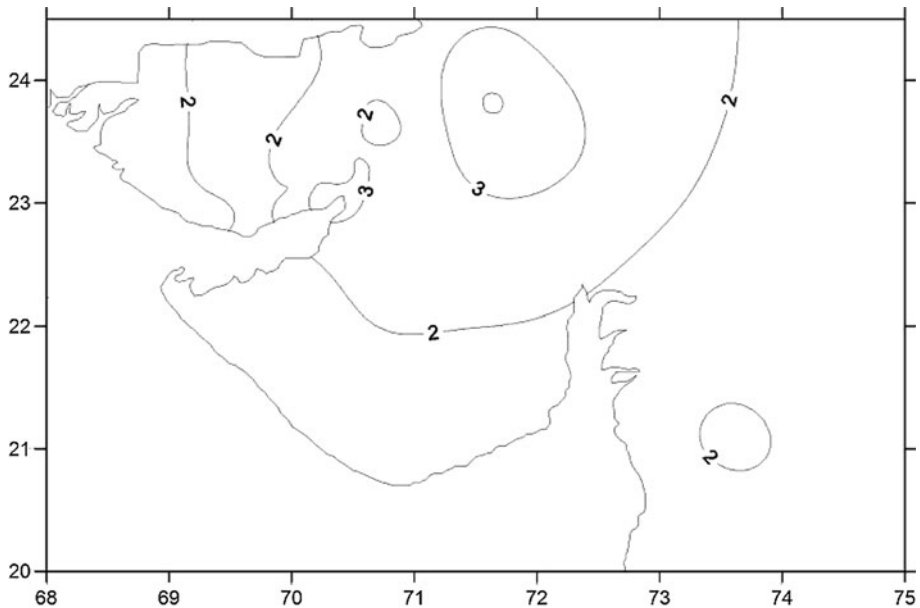
Fig. 15 Spatial distribution of site amplifications estimated at 0.17 Hz (high-rise buildings)

comprising of Kandla, Gandhidham, Khavda, Naliya, Surendernagar and Radhanpur where the amplification is around 4. The site amplifications corresponding to tall buildings are found to be <2 in south Gujarat, north-west, south-east and north-east Saurashtra and central Kachchh region (Fig. 14). It varies from 2 to 3 for the rest of Gujarat except few patches comprising of towns Rajkot, Kandla and Dudhai, where site amplification is around 4. The tall buildings in these towns are exposed to significant hazard. The site amplifications are found to be <2 for high-rise buildings and large structures in most of Gujarat as shown in Fig. 15. However, a small patch in north-western part of mainland comprising of Radhanpur and Lakadia towns shows the site amplifications between 3 and 4.

5 Conclusions

The site amplification functions have been estimated at 32 sites located on varied geology and age (from Proterozoic to Jurassic, Cretaceous, Tertiary and Quaternary) in Gujarat region. The horizontal-to-vertical spectral ratio (HVSR) technique has been used for this purpose, taking local earthquake data recorded at these sites. This is the first study reporting the site amplification functions for whole of Gujarat region. The average values of the site amplification at predominant frequencies are 3.7 ± 1.3 at 2.4 Hz for Quaternary sites, 3.3 ± 0.7 at 5.3 Hz for Tertiary, 3.3 ± 0.8 at 4.6 Hz for Cretaceous, 4.2 ± 1.1 at 7.2 Hz for Deccan, 4.1 ± 1.3 at 7.5 Hz for Jurassic and 4.6 ± 0.5 at 7.5 Hz for Proterozoic sites. The estimated site amplifications have been correlated with the damage occurred at few sites during 2001 Bhuj earthquake. More damage at Bhachau and Rapar towns in Kachchh region during 2001 Bhuj earthquake are due to large amplifications at

predominant frequencies of most of the buildings constructed in these regions. The predominant frequency of Gandhinagar having geological conditions similar to Ahmedabad matches with 4–5-storey buildings. Most of the buildings damaged in Ahmedabad during 2001 Bhuj earthquake are 4–5 storey. The spatial distribution of predominant frequencies and the site amplifications at different frequencies corresponding to the natural frequencies of different storey buildings presented here are useful for the evaluation of seismic hazard in the region. The site amplification functions obtained here can be used in the estimation of strong ground motions at different sites in the Gujarat region.

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