



Estimation of site response function using Nakamura technique: a case study from Kumaun Himalaya

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Abstract

The aim of this study is accomplished by utilizing the *H/V* spectral ratio method (Nakamura technique) to investigate the site response at fifteen seismic site stations. Regarding this method, some significant local site parameters such as the fundamental frequencies (f_0) of soft sediments, peak amplitudes (A_0) corresponding to *H/V* spectral ratios, spectrum amplitude, and spectrum rotation were computed over fifteen seismic site stations in the study area. A site response study has been done by using microtremor data from fifteen seismic site stations. The fundamental frequency response varies from 0.67 to 11.54 Hz within the study area. Resulting from this analysis, the fundamental frequency response is low in and around the KHAT, PNGL, and SBLA seismic site stations, which indicates the possibility of thick sedimentary soil cover at greater depth. Similarly, the peak amplification at these seismic site stations is found to be in the range of 2–4. Further, the contour map is prepared with the help of fundamental frequency response values obtained from the *H/V* curve to observe the area of seismic hazard potential in the study region. Also, obtained *H/V* results from different seismic site stations were verified by considering the SESAME guidelines and conditions for reliability. Then, spectrum rotation and spectrum amplitude analysis were carried out to know the characteristics of *H/V* with respect to azimuth and frequency in the sedimentary soil.

Keywords Fundamental frequency · Horizontal to vertical ratio · Kumaun Himalaya · Site response

1 Introduction

An earthquake is the most severe natural hazard and is one of the deadliest events associated with the tectonic process. The continuous continent–continent collisions between the Indian and Eurasian plates are the primary tectonic cause of earthquakes in the Kumaun

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Himalayan. The regular occurrence of low to moderate magnitude earthquakes increases the seismicity in any tectonic setting, making it more vulnerable to hazard. In the recent past, several low to high magnitudes earthquakes have been experienced in the Kumaun Himalayan region. As a result, the Kumaun Himalayan has become the most tectonically active region of the Indian sub-continent in term of the impact on human lives, constructed man-made buildings, and the environment. It is well known and emphasised in several earthquakes that soil site conditions can greatly affect the ground motion during an earthquake. On the other hand, the amplitude and frequency of ground motion may be significantly affected by local site motion during earthquakes. The soil type of any study region is influenced by the seismic ground motion of that region. The evaluation of site response on the characteristics of ground response is one of the most common aspects of any study region.

There are various methods for determining the characteristics of soil which have been used in the recent past for site effect assessment, including seismic reflection; multichannel analysis of surface waves, seismic refraction, uphole, downhole, and cross-hole surveys, spectral analysis of surface waves, continuous generation of surface waves, geotechnical investigations; microtremor measurement, and analysis of strong ground motion records (Choobbasti et al. 2013). Previously, site amplification examination has been done by using various methods such as Standard Spectral Ratio (SSR), Generalized Inverse Scheme (GIS), Coda Wave Technique and Horizontal to Vertical Ratio Technique of any region (Borcherdt 1970; Phillips and Aki 1986; Nakamura 1989; Lermo and Chavez-Gracia 1993; Field and Jacob 1995; Bonilla 1997; Bard 2000). Among all these methods, Horizontal to Vertical (H/V) spectral ratio has become an important tool to estimate the fundamental frequency response and peak amplifications during ground motion (Nakamura 1989; Field 1993; Malagnini et al. 1993; Lachet and Bard 1994; Lermo and Chavez-Garcia 1994; Field and Jacob 1995; Mukhopadhyay and Bormann 2004; Surve and Mohan 2010; Sivaram and Rai 2012; Kumar et al. 2019). The long duration ambient seismic noise and recorded earthquake data can be utilized to estimate the H/V spectral ratio technique over soft deposits (Ohmachi et al. 1991; Field and Jacob 1993; Lachet and Bard 1994; Lermo and Chavez-Garcia 1994; Lachet et al. 1996; Fah et al. 1997; Parolai et al. 2004). This technique has advantages over other geophysical methods in that it is a simple, straight-forward, and fast non-invasive measurement of the seismic sites.

Previously, site response analysis has been done by several authors such as for different tectonic settings. Recently, the Nakamura technique has been utilized for site amplification analysis by using the S-wave of 110 local earthquakes (Praveen et al. 2019). The main purpose behind this analysis was to compute the site amplification in the frequency range of 0.2–10 Hz and several events are considered at a single station for better estimation of resonance frequency (Praveen et al. 2019). Also, the H/V spectral ratio has been estimated for the entire Uttarakhand region (Sharma et al. 2014). Resulting from this analysis, it was observed that site amplification factor and predominant frequency vary between 2.3–9.4 and 1.3–8.3 Hz, respectively, but at most of the sites the predominant frequency varies between 1.3 and 3.8 Hz. These results indicate the characteristics of the region resemble soft rock/compact soils, which are prone to severe seismic hazards (Kumar et al. 2019). Apart from this study region, the Nakamura technique was utilized to calculate the sedimentary thickness in the Bombay region (Surve and Mohan 2010). Globally, the HVSR technique was used to compute the resonance frequency (f_0) and amplification (A_0) of ground motion to minimize the seismic hazard level in the Nile Delta (Khedr et al. 2019).

The primary objective of this study is to quantify the relationship between the local geology and the ground motion, i.e., resonant frequencies and the peak amplification

estimation of the fifteen seismic site stations for the entire Kumaun Himalayan region. The modified Nakamura technique is utilized to estimate the Horizontal to Vertical Spectral Ratio (HVSr) of fifteen seismic site stations. These analyses are completely performed by using microtremor data, but the earthquake data can be used to investigate the site response of this study region. In the present article, we have also estimated the spectrum rotation, and spectrum amplitude through a modified Nakamura technique by using the source tool Geopsy software (www.geopsy.org). These studies have led to reliable estimation of the fundamental frequency response and peak amplification of microtremor data from fifteen seismic site stations during the period of 2012–2018. The fundamental frequency response values were verified by using guidelines of the SESAME European project (2004), which validates that the obtained results are reliable or non-reliable. The obtained values of fundamental frequency response from different seismic site stations have been utilized to prepare the contour map, which indicates thick and thin soil deposition areas in terms of high and low frequency in and around the different seismic site stations. Further, the spectrum rotation and spectrum amplitude analysis has been conducted for the estimation of H/V with respect to azimuth vs frequency.

2 Geological setting

The Kumaun Himalaya region is one of the most active orogens in the world. This region is bounded by latitude 28.5°N–31°N; longitude 79°E–81°E and it is located in the Himalaya's seismic hotspot. The Kumaun Himalaya is also known as the lesser Himalaya. It is also divided into two parts, namely as (i) the inner lesser Himalaya (ii) the outer lesser Himalaya. In the lesser Himalaya, a large variety of rocks are settled and its geological framework is very complex. The major tectonic features of the region include the Southern Tibetan Detachment (STD), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT) (Singh et al. 2012). The Lower Himalaya consists mainly of Precambrian clastic sediments which are structurally bounded by MBT and MCT, whereas the greater Himalaya is comprised of early Cambrian metasedimentary rocks and bounded by MCT and STD. Several Crystalline Klippens are structurally overlain by the Lesser Himalaya Sequence, e.g., Almora Klippen (AK), Baijnath-Gwaldam Klippen, Askot Klippen, and Chiplakot Klippen that crop out south of MCT and are emplaced over LHS by the far-travelled MCT. The Almora Klippen is bounded to the north-by-North Almora thrust (NAT) and towards the south-by-South Almora thrust (SAT). The MCT places the high-grade metamorphic rocks of Higher Himalayan Crystalline (HHC) atop the Lesser Himalaya Sequence (LHS) during the Miocene. The STD marks the upper limit of HHC and separates it from the Tethyan Himalayan sequence. Two strands of MCT in the region have been recognized, namely the Munsiri thrust (MT or MCT-I) and the Vaikrita thrust (VT or MCT-II). The VT bounds the MCT zone from top to bottom by MT. The MCT zone is comparatively low-grade schist and gneiss, along with some mixing of lesser Himalayan rocks and separated from the kyanite-sillimanite bearing rocks of HHC. South of MT, the Lesser Himalaya rocks are exposed, stacked over the Sub-Himalaya along with MBT. The sub-Himalaya crops out south of MBT, which is structurally overlying the Quaternary/or alluvial deposit of the Indo-Gangetic plain by MFT.

In addition, this region belongs to the central seismic gap and has the potential to produce great earthquakes. The main reason for the occurrence of great earthquakes is the under thrusting of the Indian continental plate with the Eurasian continental plate (Valdiya

1980), and thus this region is prone to future earthquakes. Most of the earthquakes were recorded as shallow and restricted to a seismogenic zone within the upper ~25 km of the crust. The study region is experiencing regular occurrences of low to moderate earthquakes in the Kumaun Himalaya. A few recent moderate earthquakes and bigger earthquakes have been experienced in and around the Kumaun Himalayan regions. The region is a critical intraplate segment that is perpetually subjected to several natural threats and thus, neotectonically, an active region (Fig. 1).

3 Data and method

The Nakamura technique is one of the most popular techniques utilized for the investigation of seismic site response over soft soil deposits in any tectonic setting (Nakamura 1989; Pandey et al. 2018; Matassoni et al. 2015). This technique was developed by Nogoshi and Igarashi, (1971), but later modified by Nakamura, (1989). The Nakamura

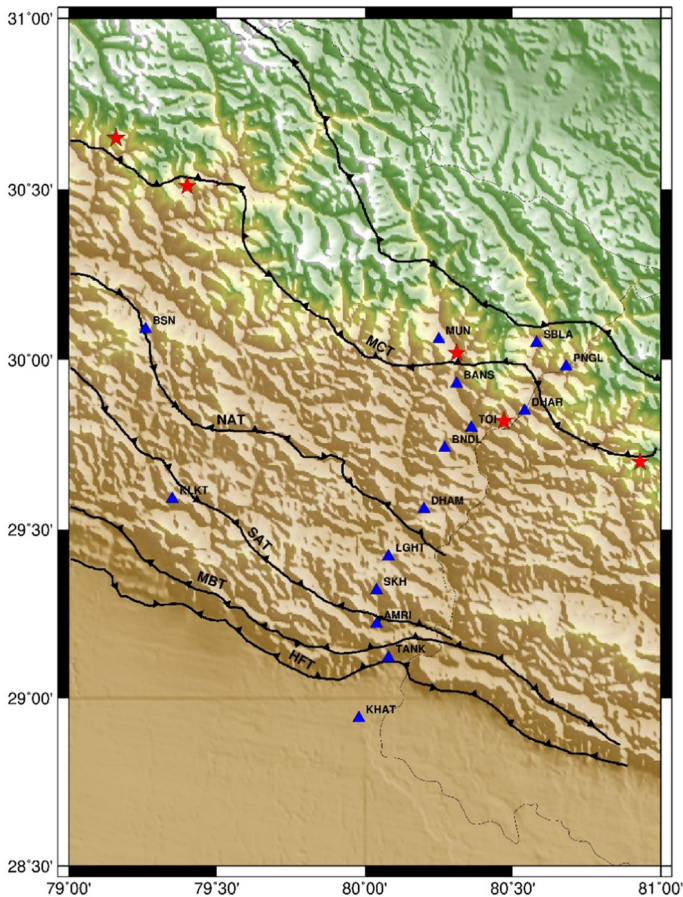


Fig. 1 Tectonic map for the Kumaun Himalaya region. Red stars show the historic earthquakes in the study region. Seismic site stations indicated by blue colours

technique is described as the ratio of Fourier amplitude spectra of horizontal to vertical component of recorded microtremors. Generally, this technique is based on impedance contrast, i.e., the presence of sedimentary soil on hard bedrock. The horizontal component of microtremor data is amplified by the soft soil layer. The Nakamura technique has been adopted to compute the fundamental frequency response with respect to the peak amplification with the help of source tool Geopsy software for different microtremor data recorded at fifteen seismic site stations in this study region. Thus, we have considered only microtremor data, which is recorded at all seismic site stations. However, the earthquake data of three components can be used to compute the seismic site response. In this study, microtremor data was acquired from different seismic site stations installed by Kumaun University, Nainital and the Wadia Institute of Himalayan Geology, Dehradun. Seismic site stations installed by Kumaun University, Nainital are equipped with Trillium 40, 120P/PA, and 120Q/QA seismometers with a high dynamic range of > 138 decibels. The common flat frequency bandwidth is ~0.003–50 Hz. The seismic data is acquired in continuous mode at a rate of 100 samples per second for three-component recording at each seismic site station. Along with these seismometers, all seismic stations are equipped with a Taurus Data Acquisition System (DAS), which is a 24-bit digitizer for a three-channel recording that provides a high dynamic range of > 141 decibels. A Global Positioning System (GPS) of 12 Channels is also installed along with each seismic station for time synchronization having a time accuracy of < 100 microseconds. A seismic network of ten broadband stations (installed by WIHG) in the Kumaun region, equipped with a Trillium 240 seismometer and Taurus digitizer is additionally run as a permanent.

Fast Fourier Transform (FFT) has been applied to the entire three components (NS, EW, and Z components) of a particular seismic site station for each time window (Pandey et al. 2018). Further, a cosine taper of 5% is utilized to avoid spectral leakage. The Konno-Ohmachi algorithm has been applied for smoothing the Fourier amplitude spectra for which the smoothing constant value is 40.00 s (Konno and Ohmachi 1998). The frequency sampling range has been selected in the range of 0.50–25.00 Hz for all recorded microtremor data. The short-term average (STA) and long-term average (LTA) algorithms have been used to split the recorded microtremor data into each time window. For this analysis, STA and LTA are set to 2 s and 30 s, respectively. Thus, the obtained results from the *H/V* analysis have been checked for the reliability and clarity of the peak by using the SESAME guidelines condition. Further, the spectrum amplitude and *H/V* with respect to azimuth have been performed for all recorded microtremor data in the study region. The range of rotation is kept from 0 to 180 degrees for the horizontal components of motion and also the azimuth direction is selected clockwise in the north direction.

4 Result and discussion

The Horizontal to vertical spectral ratio has been applied to estimate the fundamental frequency response and peak amplification of fifteen seismic site stations for the Kumaun Himalayan region. Also, the spectrum rotation, and spectrum amplitude have been computed for all recorded microtremors as mentioned below in Figs. 2, 3, 4, 5, and 6.

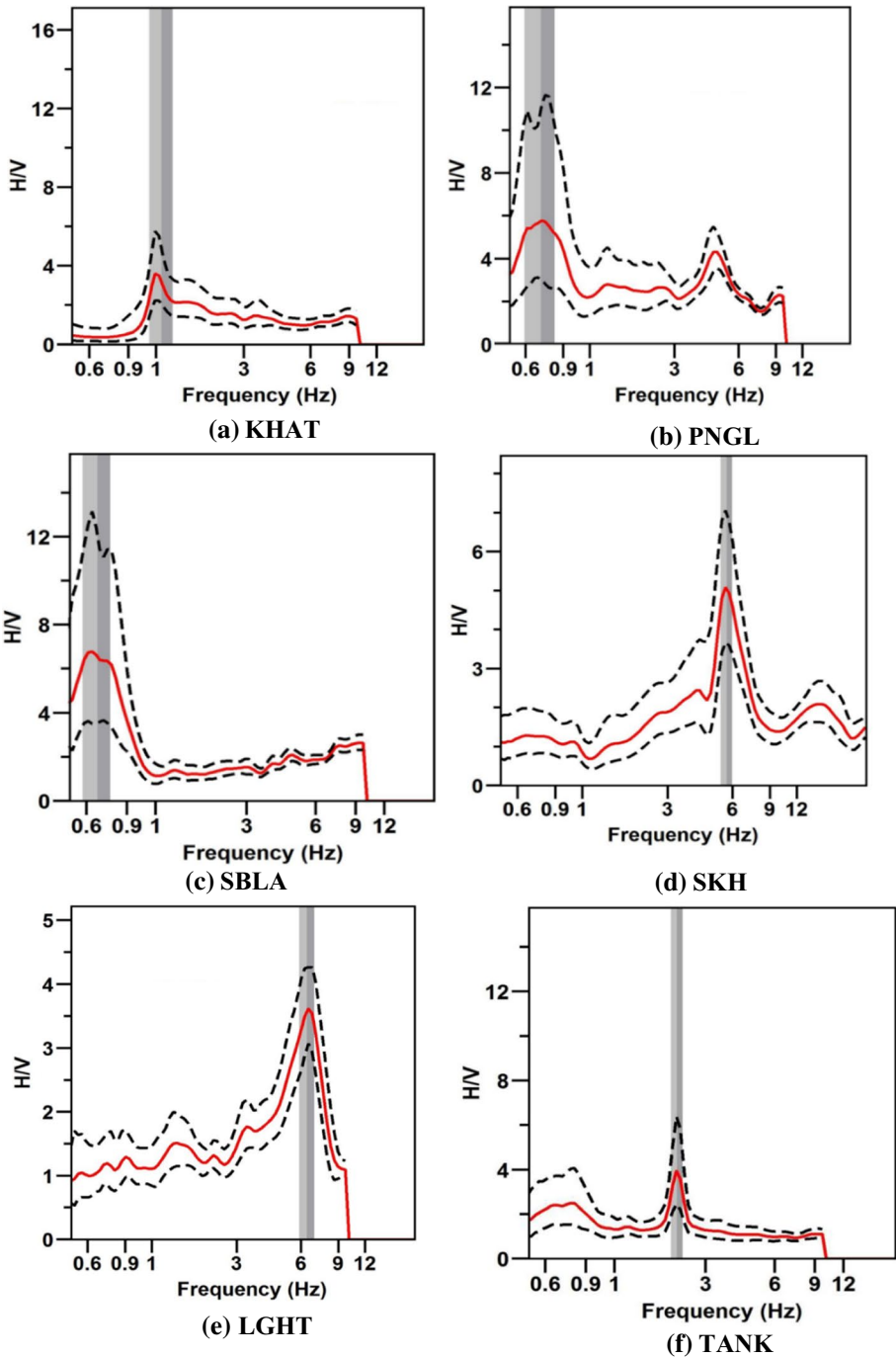


Fig. 2 Plot of fundamental frequency response of fifteen seismic site stations at different frequency ranges and amplifications. Solid red line represents the average H/V value

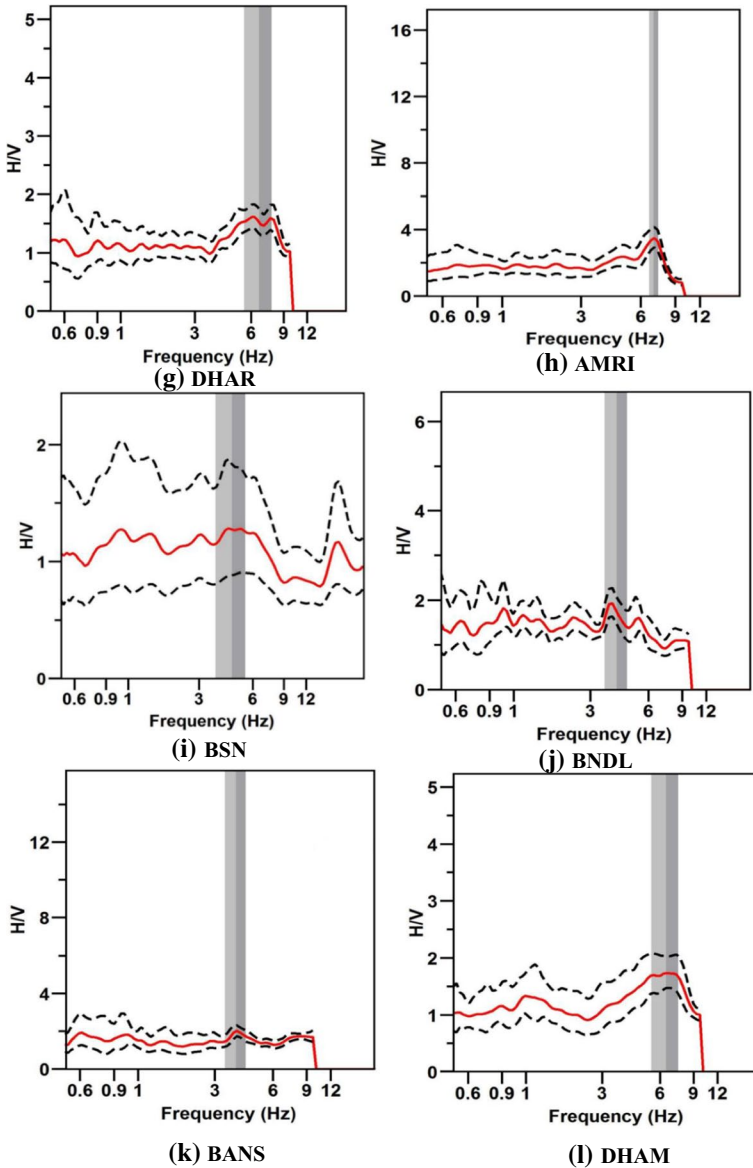


Fig. 2 (continued)

4.1 Fundamental frequency response

The fundamental frequency response with site amplification has been estimated at fifteen seismic site stations in this study region, as depicted in Fig. 2a–o. Low fundamental frequency response and high amplification in the range of 0.6–2.0 Hz with a mean value of 1.3 Hz has been observed at different seismic site stations such as (KHAT, PNGL, SBLA) as depicted in Fig. 2a–c, which indicates that there is a possibility of thick sedimentary

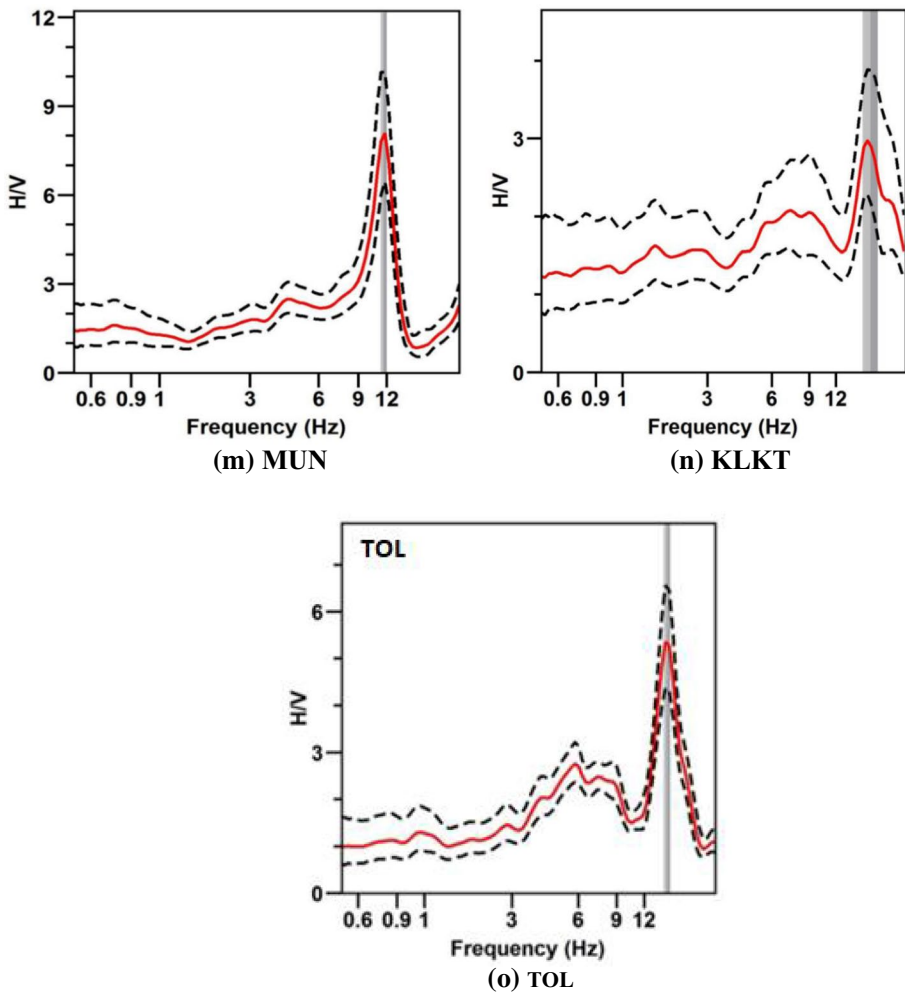


Fig. 2 (continued)

soil cover at greater depth. The moderate fundamental frequency response with moderate amplification is found to be at SKH, LGHT, TANK, and DHAR seismic site stations in the range of 2.0–8.0 Hz with a mean value of 5.0 Hz as shown in Fig. 2d–g. Resulting from this, it indicates that there is a possibility of thick sedimentary soil cover present at moderate depth. However, the moderate fundamental frequency response with low or flat amplification is found to be at some seismic site stations such as AMRI, BSN, BNDL, BANS, and DHAM in the range of 2.0–8.0 Hz with a mean value of 5.0 Hz as depicted in Fig. 2h–l. Low or flat amplification is found to be in and around these seismic site stations because there is the possibility of the presence of thin soil deposition at moderate depth and also, indicating no sharp impedance contrast with shallow bedrock. Previously, it was pointed out that hard rocks such as Granite, Augen gneiss, and Quartzites are present at moderate depth at these seismic site stations (Kumar et al. 2019). Surve and Mohan (2010) did site response analysis for the Mumbai city and they found that flat response (nearly no peak

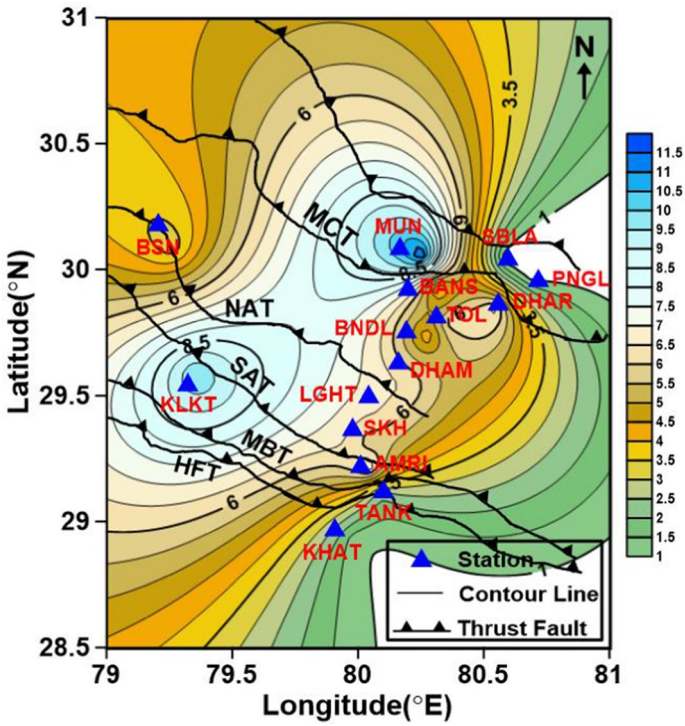


Fig. 3 Contour map of fundamental frequency response for the Kumaun Himalaya region

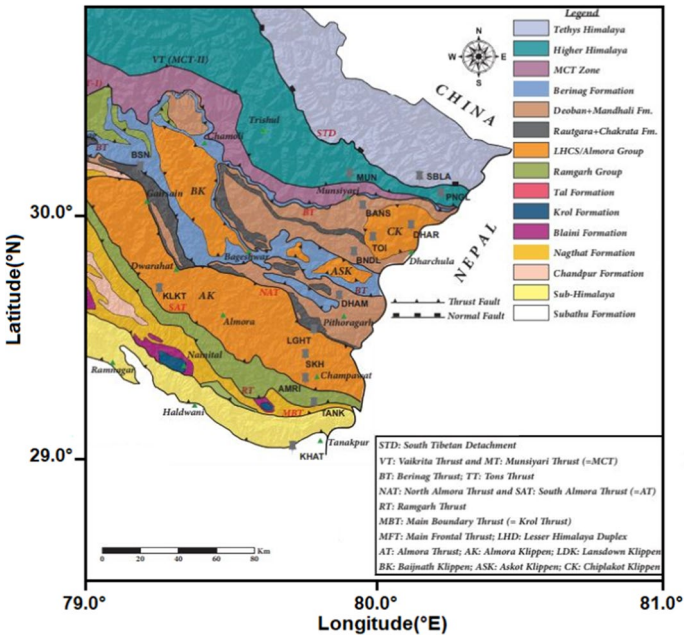


Fig. 4 Lithology structure of the Kumaun Himalaya region

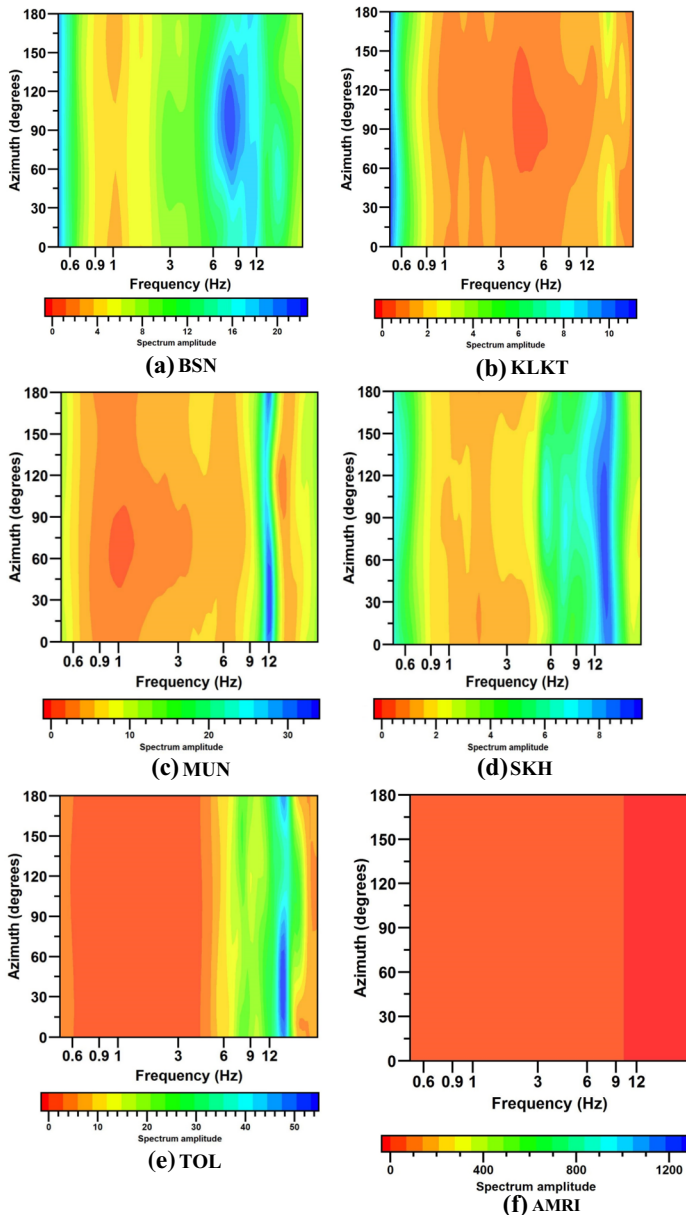


Fig. 5 Plot of the spectrum amplitude with respect to azimuth for fifteen seismic site stations at different frequency

amplification) at some seismic site is due to the presence of hard rock or non-weathered at the site. High fundamental frequency response with low amplification has been observed at different seismic site stations such as KLKT and MUN as depicted in Fig. 2m–o, which indicates the possibility of thin sedimentary soil cover is present at shallow depth in and around these seismic site stations. At these seismic site stations, there is an have exposure

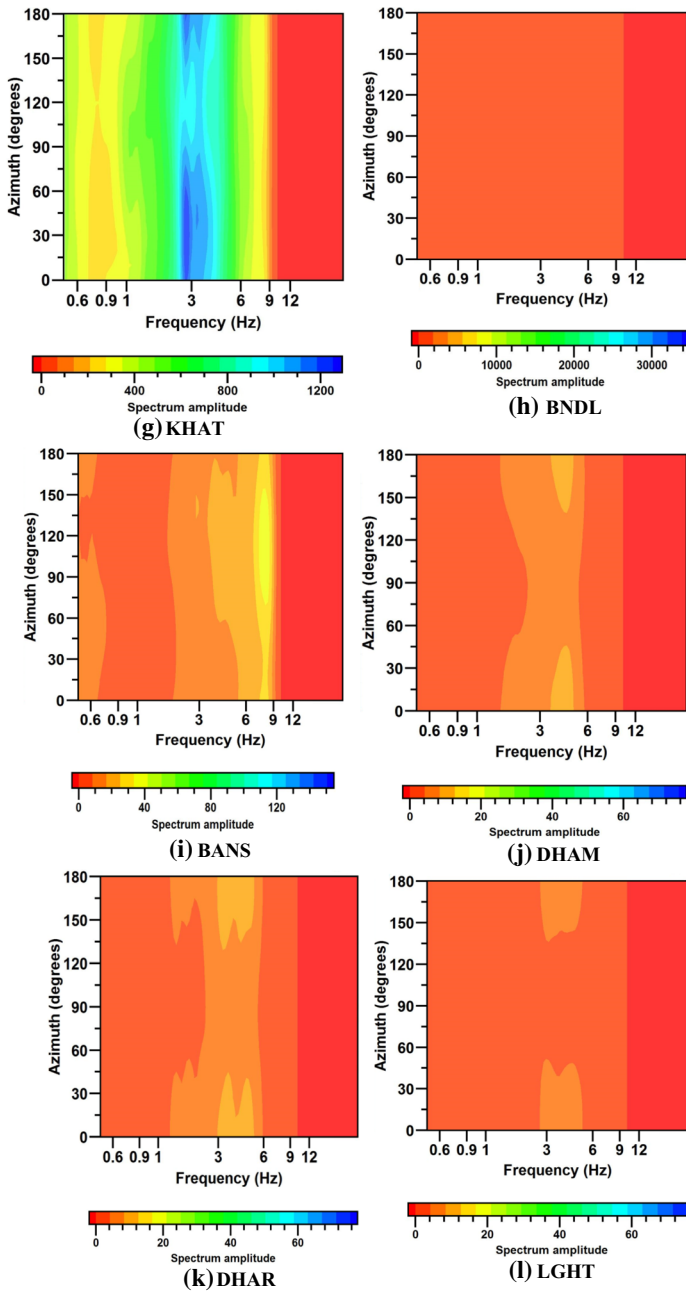


Fig. 5 (continued)

of compacted hard rocks at the shallow depth. However, it has been suggested by several authors, such as Fnais et al. (2010), Pandey et al. (2018), that low and high fundamental frequencies are obtained corresponding to greater and shallower depth, respectively.

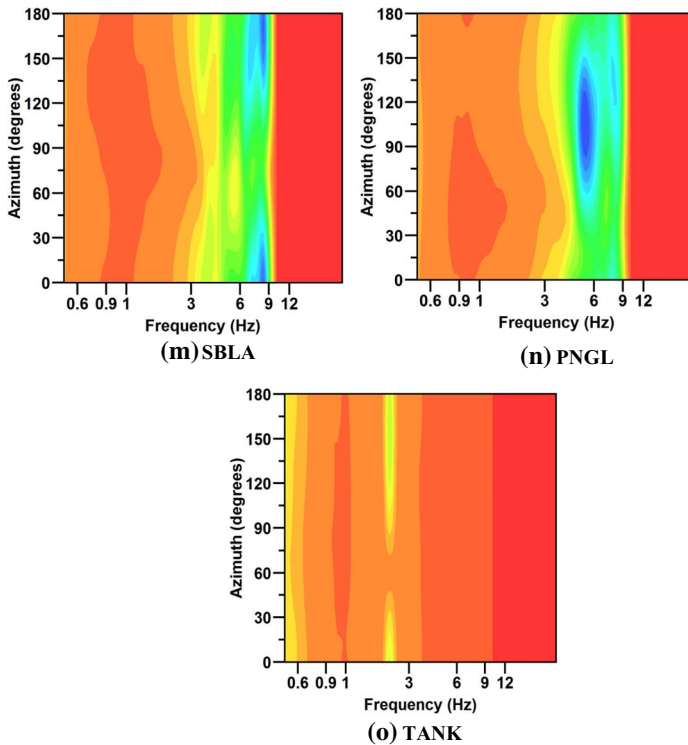


Fig. 5 (continued)

The liquefaction index can be achieved by using frequency response and amplification values in this analysis. As shown in Table 1, the liquefaction vulnerability index (k_g) is estimated by taking the square of amplitude (A_0) divided by the fundamental frequency (f_0) (Natarajan and Rajendran 2015; Pandey et al. 2018). Resulting from this, it has been observed that a high k_g value is present at seismic site SBLA (64.05) while a low k_g value is present at seismic site DHAR (0.35) respectively. Therefore, a High k_g value indicates future expected earthquake damage at the SBLA seismic site and high vulnerability.

The contour map is prepared with the help of fundamental frequency response values, which are obtained from microtremors data of fifteen seismic site stations as shown in Fig. 3. These seismic site stations are located in different geological formations (Mun-syari, Almora, and Subathu formation) which consist of hard rocks such as (Granite, Augen gneiss, Quartzites) and their compactness is higher as compared to the other rocks (Figs. 4, 5).

This contour map is helpful in understanding the sedimentary disparity by the combination of fundamental frequency response results to the sedimentary thickness (Surve and Mohan 2010; Pandey et al. 2018). From Fig. 3, it has been observed that the high fundamental frequency is present in and around the MUN and KLKT seismic site stations, whereas a low frequency is present at different seismic site stations such as PNGL, SBLA and KHAT. However, the rest of the study region displays moderate fundamental frequency response values in and around some seismic site stations such as (AMRI, BSN, LGHT, DHAM, DHAR, etc.). From this analysis, it has been observed

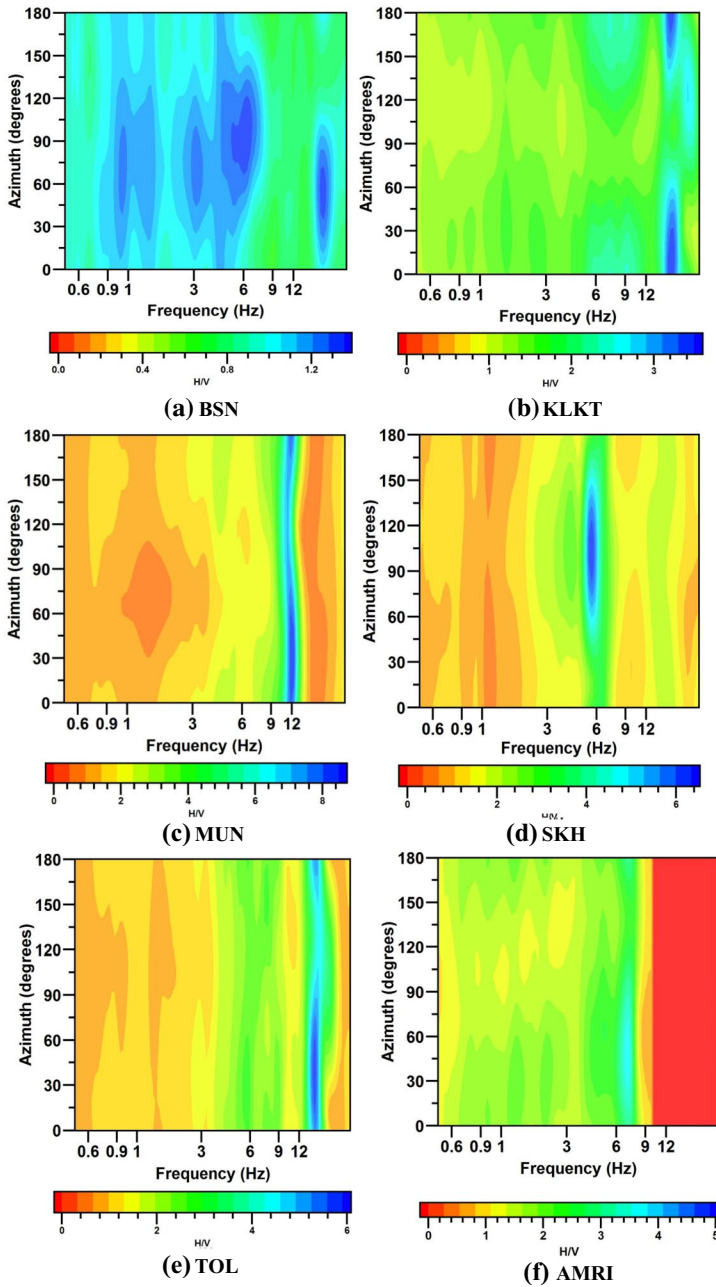


Fig. 6 Plot of the H/V rotation with respect to azimuth for different fifteen seismic site stations at different frequency

that low fundamental frequency responses with high amplification values at greater depth in the vicinity of any seismic site stations represent the seismic hazard potential area in this study region and vice-versa. The MUN seismic site station belongs to

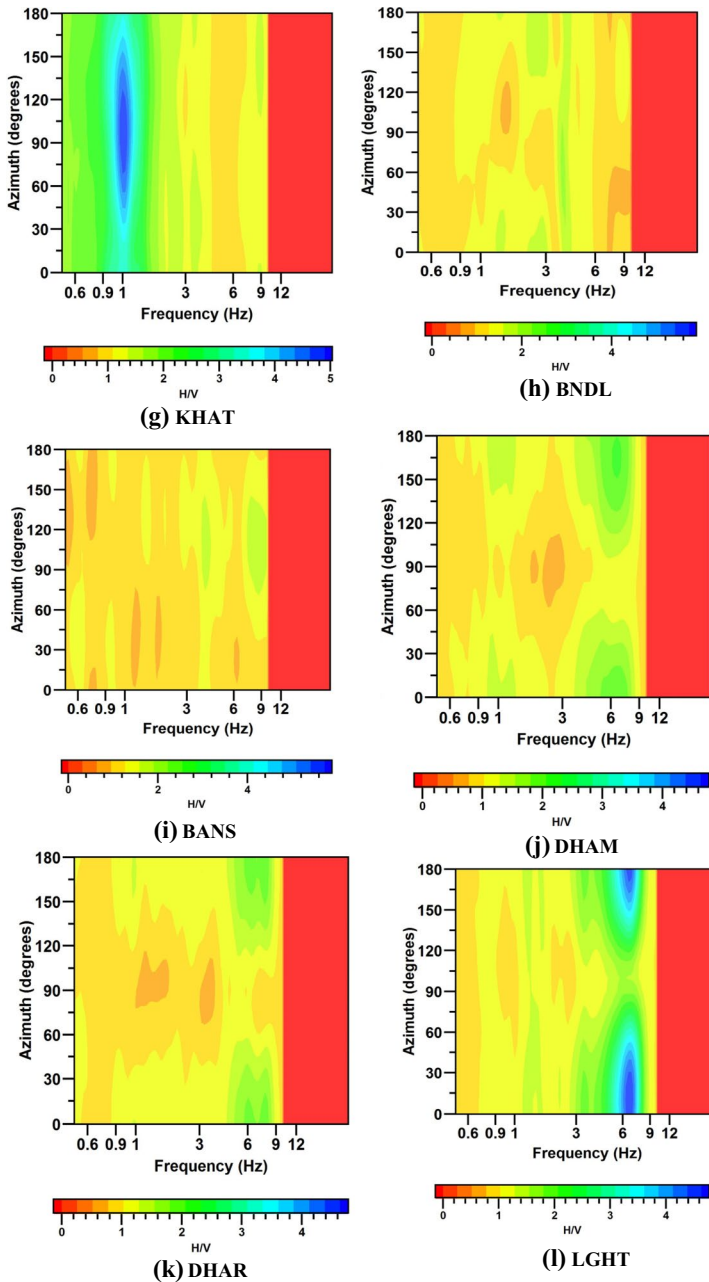


Fig. 6 (continued)

the Munsyari formation, which consists of the granite-granodiorite and augen gneiss (Valdiya 1980). Recently, it was noticed that a high frequency response was observed in and around the MUN seismic site station, which indicates that there is the presence of hard and compacted rock (Kumar et al. 2019). Similarly, high frequency response is

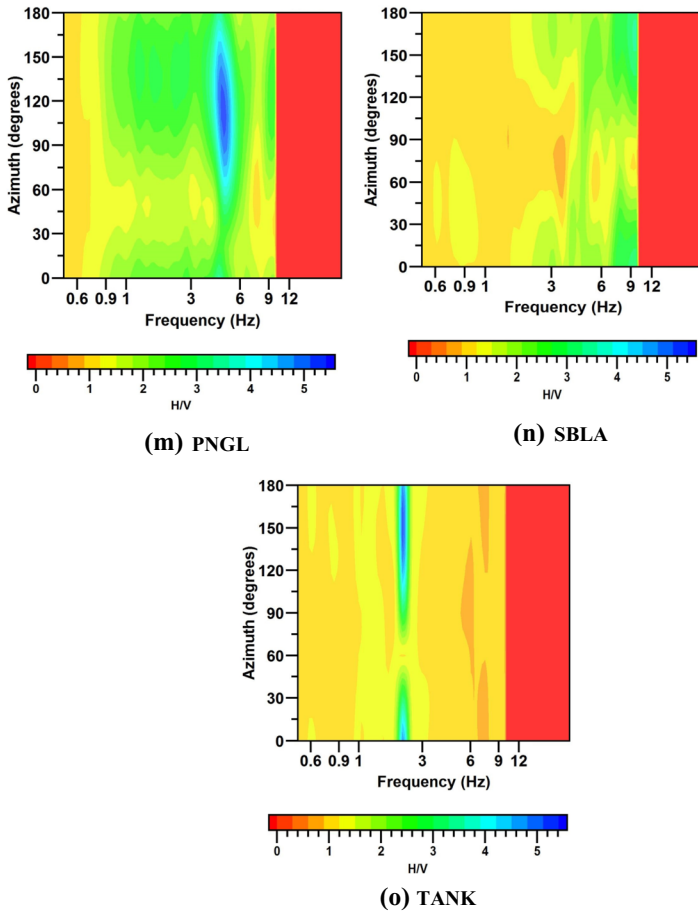


Fig. 6 (continued)

also present at KLKT seismic site station, which belongs to the Almora group. Almora group also contains hard rocks such as Augen gneiss. Therefore, MUN and KLKT stations may not be in the region of high seismic hazard potential. At these seismic site stations there is less chance of damage during an earthquake compared to other seismic stations. The contour map shows that the rest of the seismic site stations have moderate fundamental frequency response in different geological formations.

The observed fundamental frequency response values were verified by applying the conditions of the SESAME, (2004) guidelines project. For data reliability, some of the important conditions such as $f_0 > 10/I_w$, $nc(f_0) > 200$ (where $n_c = n_w \times I_w$) were checked, keeping in view the SESAME (2004) guidelines. Thus, the criteria and reliability parameters show that the obtained fundamental frequency response results from different seismic site stations are reliable as mentioned in Table 2.

Table 1 List of the different fundamental frequency response, amplification and liquefaction index values for the fifteen seismic site stations

S. No.	Station Name	Lat (°N)	Long(°E)	Frequency	Amplification	Duration (In Min)	Liquefaction Index
1	TOL	29.80	80.36	6.30 (0.92)	2.68	25	1.13
2	MUN	30.06	80.25	11.54 (0.58)	8.94	32	6.93
3	BSN	30.09	79.26	3.19 (0.56)	1.35	30	0.57
4	SKH	29.32	80.04	5.64 (0.33)	4.62	25	3.78
5	KLKT	29.59	79.35	10.03 (1.21)	1.93	40	0.37
6	AMRI	29.22	80.04	6.99 (0.36)	3.46	30	1.71
7	KHAT	28.94	79.98	1.27 (0.15)	3.18	30	7.95
8	BNDL	29.74	80.27	4.11 (0.55)	1.75	50	0.74
9	BANS	29.93	80.31	3.86 (0.47)	1.98	15	1.01
10	DHAR	29.85	80.54	6.62 (1.11)	1.53	18	0.35
11	DHAM	29.56	80.20	6.44 (1.02)	1.73	18	0.46
12	LGHT	29.42	80.08	6.39 (0.52)	3.56	18	2.00
13	TANK	29.12	80.08	2.25 (0.13)	3.94	40	6.89
14	SBLA	30.05	80.58	0.67 (0.93)	6.55	20	64.05
15	PNGL	29.98	80.68	0.71 (0.11)	5.74	25	46.60

4.2 Spectrum Amplitude

The presence of strong sources is revealed by direction analysis of the *H/V* curve. In this analysis, the *H/V* curve of fifteen seismic site stations has been performed for directional analysis. Thus, the horizontal component of motions is rotated in the range of 0°–180°. This analysis may be very suitable to check the site dimension, whether the site is 1D or not. An azimuth direction is always counted in a clockwise direction to the north. Therefore, spectrum amplitude has been observed at the different seismic site stations such as BSN, MUN, SKH, TOL, KHAT, SBLA, and PNGL, which indicates the presence of strong sources in 1D (Fig. 5).

4.3 Spectrum rotation

The variation of fundamental frequency with azimuth can be obtained with the help of *H/V* rotate analysis. Figure 6a–o depicts the *H/V* rotate analysis for fifteen seismic site stations. The *H/V* rotate amplitude has been observed in the range of 0.6–12 over 0°–180° at BSN, KLKT, MUN, SKH, TOL, AMRI, KHAT, LGHT, PNGL, and TANK seismic site stations. It is indicated that maximum energy release over this part of the study region. Furthermore, other seismic site stations such as BANS, BNDL, DHAM, DHAR, and SBLA did not provide any significant observations during the *H/V* rotate analysis as shown in Fig. 6b–h.

5 Conclusion

This article presents an approach using Nakamura technique measurements to govern the site response at fifteen seismic site stations. Microtremor data was analysed by employing the *H/V* method. The Nakamura technique is a valuable tool to determine peak frequency

Table 2 Represents the criteria and reliability parameters values of SESAME, (2004) guidelines for the fundamental frequency response results at fifteen seismic site stations. f_0 is the fundamental frequency response, A_0 is the amplitude, N_w is defined as number of windows selected for the average HIV curve, L_w is window length and n_c is number of significant cycles

S. No.	Station Name	Lat(°N)	Long(°E)	f_0 (Hz)	$A_0 > 2$	$f_0 > 10/L_w$	N_w	$n_c = n_w \times L_w$	$n_c (f_0) > 200$	Comment
1	TOL	29.80	80.36	6.30	2.67	0.40	22	550	3465	Reliable
2	MUN	30.06	80.25	11.54	8.94	0.31	18	576	6647	Reliable
3	BSN	30.09	79.26	3.19	1.35	0.33	25	750	2392	Reliable
4	SKH	29.32	80.04	5.63	4.61	0.40	19	475	2674	Reliable
5	KLKT	29.59	79.35	10.03	1.92	0.25	17	680	6820	Reliable
6	AMRI	29.22	80.04	6.99	3.46	0.33	21	630	4403	Reliable
7	KHAT	28.94	79.98	1.27	3.17	0.33	25	750	952	Reliable
8	BNDL	29.74	80.27	4.10	1.74	0.02	24	1200	4920	Reliable
9	BANS	29.93	80.31	3.85	1.97	0.66	18	270	1039	Reliable
10	DHAR	29.85	80.54	6.62	1.53	0.56	17	306	2026	Reliable
11	DHAM	29.56	80.20	6.44	1.73	0.56	20	360	23.18	Reliable
12	LGHT	29.42	80.08	6.39	3.55	0.56	21	378	2415	Reliable
13	TANK	29.12	80.08	2.24	3.93	0.25	18	720	1612	Reliable
14	SBLA	30.05	80.58	0.66	6.54	0.25	23	460	615	Reliable
15	PNGL	29.98	80.68	0.70	5.73	0.25	20	500	564	Reliable

and amplification factor over shallow soft soils. The study area reflects a high variability in terms of fundamental frequency (f_0) and amplification (A_0). Low values of fundamental frequency (f_0) and corresponding higher values of amplification are reflected at some seismic site stations, thus indicating a greater seismic risk triggered by soil amplification in the study area. The fundamental frequency response is found to be in the range of 0.6–11.54 at fifteen seismic site stations. Also, SESAME guidelines have been followed to check the accuracy of the measurements, reliability, and clarity of the peak in the H/V curve. Spectrum rotate and amplitude investigation shows at some seismic site stations the energy is released corresponding to certain azimuth and frequency windows. It indicates that measurement of these local site responses is highly significant to assess the seismic risk in the study area.

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References

- Bard PY (2000) Lecture notes on ‘Seismology, Seismic Hazard Assessment and Risk Mitigation’. International Training Course, Potsdam, p 160
- Bonilla LF, Steidl JH, Lindley GT, Tumarkin AG, Archuleta RJ (1997) Site amplification in the San Fernando Valley, California: variability of site-effect estimation using the S-wave, coda, and H/V methods. (3):710
- Borcherdt RD (1970) Effects of local geology on ground motion near San Francisco Bay. *Bull Seismol Soc Am* 60(1):29–61
- Choobbasti AJ, Rezaei S, Farrokhzad F (2013) Evaluation of site response characteristics using microtremors. *Gradevinar* 65:731–741
- Fah D, Ruttener E, Noack T, Kruspan P (1997) Microzonation of the City of Basel. *J Seismolog* 1:87–102
- Field E, Jacob K (1993) The theoretical response of sedimentary layers to ambient seismic noise. *Geophys Res Lett* 20:2925–2928
- Field EH, Jacob KH (1995) A comparison and test of various site response estimation techniques, including three that are non-reference-site dependent. *Bull Seismol Soc Am* 86:991–1005
- Fnais MS, Abdelrahman K, Al-Amri AM (2010) Microtremor measurements in Yanbu city of Western Saudi Arabia: a tool for seismicmicro zonation. *J King Saud Univ (Sci)* 22:97–110
- Khedr F, Marzouk I, Elrayess M (2019) Site effect estimation using Horizontal to Vertical (H/V) spectral ratio technique in Nile Delta, Egypt. *NRIAG J Astron Geophys* 8(1):84–96
- Konno K, Ohmachi T (1998) Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. *Bull Seism Soc Am* 88:228–241
- Kumar P, Devi S, Monika, Srivastava A, Sandeep, Joshi A, Kumari R (2019) Site response study based on H/V method using S-wave: a case study in the Kumaon Himalaya, India. *Himalayan Geol* 40(2):213–219
- Lachet C, Bard PY (1994) Numerical and theoretical investigations on the possibilities and limitations of Nakamura’s technique. *J Phys Earth* 42:377–397
- Lachet C, Hatzfeld D, Bard PY, Theodulidis N, Papaioannou C, Savvauidis A (1996) Site effects and microzonation in the city of Thessaloniki (Greece) comparison of different approaches. *Bull Seismol Soc Am* 86:1692–1703
- Lermo J, Chavez-Garcia FJ (1993) Site effects evaluation using spectral ratios with only one station. *Bull Seismol Soc Am* 83:1574–1594

- Lermo J, Chavez-Garcia FJ (1994) Are microtremors useful in site response evaluation? *Bull Seismol Soc Am* 84:1350–1364
- Malagnini L, Rovelli A, Hough SE, Seeber L (1993) Site amplification estimation in the garigliano valley, central Italy, based on dense array measurements of ambient noise. *Bull Seismol Soc Am* (6):1744–1755
- Matassoni L, Fiaschi A, Silengo MC, Lotti A, Saccorotti G (2015) Preliminary seismic microzonation in a mountain municipality of Tuscany (Italy). *Open Geosci* 7:559–571
- Mukhopadhyay S, Bormann P (2004) Low cost seismic microzonation using microtremor data: an example from Delhi, India. *J Asian Earth Sci* 27:1–280
- Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface Q. *Rep Railw Tech Res Inst* 30:25–33
- Natarajan T, Rajendran K (2015) Estimation of site response based on spectral ratio between horizontal and vertical components of ambient vibrations in the source zone of 2001 Bhuj earthquake. *J Asian Earth Sci* 98:85–97
- Nogoshi M, Igarashi T (1971) On the amplitude characteristics of microtremor (part 2). *J Seismol Soc Japan* 24:26–40
- Ohmachi T, Nakamura Y, Toshinawa T (1991) Ground motion characteristics of the san Francisco Bay area detected by microtremor measurements. In: *Proceedings of the second international conference on recent advances in geotechnical earthquake engineering and soil dynamics*. Missouri, LP08, pp 1643–1648
- Pandey AK, Roy PNS, Baidya PR, Gupta AK (2018) Estimation of Current seismic hazard using Nakamura technique for the northeast India. *J Natl Hazards* 93(2):1013–1027
- Parolai S, Richwalski SM, Milkereit C, Bormann P (2004) Assessment of the stability of *H/V* spectral ratios from ambient noise and comparison with earthquake data in the Cologne area (Germany). *Tectonophysics* 390:57–73
- Phillips WS, Aki K (1986) Site amplification of coda waves from local earthquakes in central California. *Bull Seismol Soc Am* 76:627–648
- Sivaram K, Rai SS (2012) An assessment of site response from the study of the *H/V* ratios in the Garhwal Himalaya, India. *Curr Sci* 103(5):547–554
- Surve G, Mohan G (2010) Site response studies in Mumbai using (*H/V*) Nakamura technique. *Nat Hazards* 54:783–795
- Valdiya KS (1980) *Wadia institute geology of the kumaun lesser himalaya of himalayan geology*, Dehradun, p 291

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