


Estimation of current seismic hazard using Nakamura technique for the Northeast India

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Received: 29 June 2016 / Accepted: 23 April 2018 / Published online: 8 May 2018
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Abstract Some regions of Indian subcontinent are highly earthquake prone area, and some are not. However, among them north-east region of India is most geologically complex one, which are found to be highly earthquake hazard prone region. This region has experienced several disastrous earthquakes like Assam earthquake of 1950 for 8.1 and Shillong earthquake of 1897 for 8.7 magnitude in the past. Several methods are used for seismic hazard measurement. Among these methods the site response analysis is found to be most valuable part of the seismic hazard assessment. In this work we have used Nakamura technique (H/V site response spectral ratio) for estimating the site amplification of seismic ground motion. Fundamental frequencies estimated are in the range 0.6–10 Hz for the 15 broadband stations of India Meteorological Department distributed over the study region. ZIRO station and its surrounding area are found to have high liquefaction indices (kg) value of 250. The horizontal-to-vertical ratio curve variation of higher amplitude with lower frequency helped to find thick soil zones in Aizawl and Agartala. Similar analysis also gave flat response at some sites near Jorhat and Dibrugarh having thin soil. The H/V rotate analysis helped us to see the variation of fundamental frequency with azimuth. Based on the observations, frequency and amplitude counter map of the north-east region represented. Further considering the site amplification due to very high fundamental frequency for Shillong, Guwahati, Imphal and Itanagar city can be considered under high seismic hazard scanner in the north-east India region.

Keywords Fundamental frequency response · Liquefaction · Site response · Spectral ratio · Spectrum rotation

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1 Introduction

North-east India has witnessed couple of disastrous large earthquakes (8.7 M_w , 1897; 8.1 M_w , 1950) in past and also smaller size earthquakes (6.9 M_w , 2011; Imphal earthquake (6.7 M_w , 2016) in recent times. These earthquakes have created havoc hazards on manmade engineered and non-engineered structures. As the characteristics of seismic waves generated by earthquakes travelling through different geological conditions lead to varieties of damage. Each of these damages is unique in nature that is controlled by local site condition. The effect of local site condition such as loose soil cover, thick alluvium cover, impedance contrast between top layer and basement rock, etc. (Fnais et al. 2010). The most quantitative aspect, i.e. amplification due to inherent property of soil like resonant frequency, is attempted by various researchers globally, for understanding the ground vibration characteristic during earthquakes (Singh et al. 1988; Parolai et al. 2001; Giacomo et al. 2005; Surve and Mohan 2010; Sivaram and Rai 2012; Natarajan and Rajendran 2015; Prasad et al. 2014). Popular Nakamura Technique (Yutaka 2000) gives reliable estimate of horizontal-to-vertical (H/V) site spectral ratio for particle motion of ground that responds to various background noise or microseismic events. This ratio helped many researchers to estimate site spectral ratio H/V and corresponding amplification factor, resonant frequency and depth of uncompact top soil cover (Singh et al. 1988; Parolai et al. 2001; Surve and Mohan 2010; Sivaram and Rai 2012; Natarajan and Rajendran 2015; Prasad et al. 2014).

However, “site response” or “site effects” such as amplification of earthquake waves at a particular frequency range, multiple path reflection effect of surface elevation, nonlinear top surface soil response leading to surface ruptures such as liquefaction can be studied (Ohta et al. 1978; Aki 1993; Natarajan and Rajendran 2015 etc.). Hazards exaggerated by site effects can therefore be linked to the plausible neighbouring sources rather than its size. Shillong earthquake reported to generate 1 g (9.8 m/sec^2) acceleration that was able to throw boulders from the surface (Oldham 1899; Bilham and England 2001). Even recent Imphal Earthquake 6.7 M_w , 2016 created substantial disaster in the valley. Thus, such strong motions can really play a significant role on sedimentary basins as well as hard rock structure which are also considered threat due to hazard prone topographic and 2D, 3D geological features.

North-east India region comprises of valley, thrust faults, plateau, subduction structure and possibly all kinds of complex seismotectonic settings (Kayal and De 1991; Rajendran et al. 2004; Jade et al. 2007; Thingbaijam et al. 2008; Roy et al. 2015). Here, we have estimated regional spatial ground motion characteristic from fifteen sites AGT—Agartala, AZL—Aizawl, DIBR—Dibrugarh, GTK—Gangtok, GUWA—Guwahati, ITNA—Itanagar, JORH—Jorhat, KOHI—Kohima, LKP—Lekhapani, SAIH—Siaha, SHL—Shillong, TAWA—Tawang, TEZP—Tezpur, TURA—Tura, ZIRO—Ziro located at different geologic setup for thirteen earthquakes whose noise has been considered as shown in Fig. 1. The site effect and ground amplification due to the different frequency value estimated at all sites in order to have a quantitative comparison of hazard for further classification.

2 Methodology

In this study we have adopted Nakamura method, which is a useful tool, usually applied for reliable estimate of fundamental resonance frequency with respect to high amplitude peak. Several techniques adopted for the site response, namely reference site method (RSM),

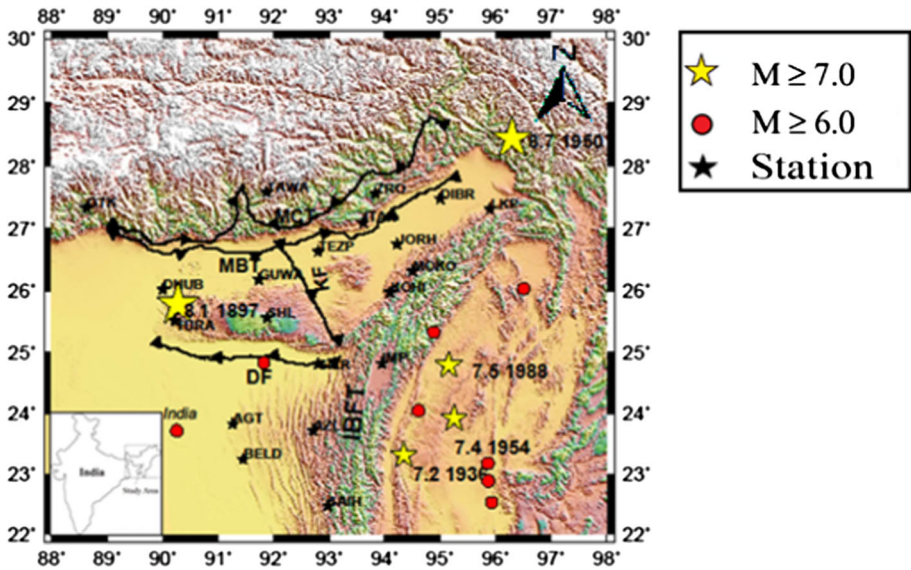


Fig. 1 Map of north-east region showing the main boundary thrust along TEZP and DIBR station, the main central thrust along GTK station in the black line. Yellow star represents major historical earthquake from 1897 to 1990 and black star show the station location in the map. These are the following Station of the north-east region, India, AGT—Agartala, AZL—Aizawl, DIBR—Dibrugarh, GTK—Gangtok, GUWA—Guwahati, ITNA—Itanagar, JORH—Jorhat, KOHI—Kohima, LKP—Lekhapani, SAIH—Siaha, SHL—Shillong, TAWA—Tawang, TEZP—Tezpur, TURA—Tura and ZIRO—Ziro

generalized inversion technique (GIT) which can be applied for estimation of site response (Surve and Mohan 2010). In the present study, initially whole set of earthquake raw data were processed by Nakamura technique which was developed by Nogoshi and Igarashi (1971) and later it was modified by Nakamura (1989). The Nakamura technique importance has been proved by various applications such as study of microzonation purpose. The horizontal-to-vertical ratio for background noise is a well-known useful tool for site response studies globally. Entire analysis for the H/V ratio to determine site response spectral curves was carried out with the source tool Geopsy software for (www.geopsy.org) all thirteen events data. We have used background noise only by removing all the thirteen events which are recorded for all the stations. Initially, we have selected the entire three components (NE, EW and Z component) of a particular station and applied the fast Fourier transform (FFT) for each time window. Here, we have used cosine tapper, whose width was 0.05 for all components to avoid spectral leakage. As it has been stated by Konno and Ohmachi (1998), that we need to do smoothing for all component of the H/V curve; therefore, this is achieved by using the logarithm function at the selected smoothing constant 40.00 s. All the microseismic noise data performed at frequency sampling in the range of 0.50–15.00 Hz. Also, we have used low pass filtering to retain frequencies in the range of 5.00 Hz. The shortest window length was selected within the 40.00 s time series on the basis of level of noise stability and the frequency of interest for all components in each site. In order to maintain clarity of the peaks, the number of window was kept at 40 or less. Further understanding of the microseismic noise is generally done with the use of STA/LTA algorithm. STA is short-term average and depends on the frequency of interest or event; the window length considered here is at least four times the period of interest. LTA is a long-term average, which is based on the background noise level and the

dominating frequency. Generally, the LTA window length considered here is at least four times the STA window length. Here, STA, LTA were automatically selected and was performed at 1.00 and 30.00 s, respectively, for each window. Further analysis was done with the help of rotation, whose range was kept from 0° to 180° for the horizontal component of motions. Conventionally, the azimuth direction is always kept clockwise to the north direction. Horizontal-to-vertical rotate is being implemented to represent the H/V in the horizontal plane, i.e. azimuth is considered as variable, for any type of 3D signal of ambient vibrations. Here, a sequence of horizontal to vertical is intended from 0° to 180° for every 10° increment, and it is depicted graphically on a frequency versus azimuth plot. Results are being displayed between 0° – 180° and 180° – 360° which is basically found to be symmetric for the 0° – 180° .

3 Results and discussion

After carrying out the analysis using above technique, the horizontal-to-vertical (H/V) site response spectral ratio and H/V rotate presented with different fundamental frequency over 15 sites of the north-east Indian region which are shown in Figs. 2a–d, 3a–e, 4a–f and 5a–c. Following three main fundamental frequency intervals were obtained, i.e. 0.6–2.0 Hz with mean value 1.3, 2.0–8.0 Hz with mean value 5 and 8.0–12 Hz with mean value 10 Hz. These values can be characterized from horizontal-to-vertical site response spectral ratio. The geology of north-east India region consists of very complex subsurface stratigraphy sequence; the major area is composed of tertiary rocks. The sediments thickness is more in the north-eastern part and some area of south-western part, whereas the lower Assam and south-western part have less sediments thickness within the study area. The possibility of high impedance contrasts cannot be overruled for the observed clear peaks in the H/V site response spectral ratio curve for some of the sites like Guwahati, Itanagar and Imphal. Similar nature was observed in the cases of Bhuj, Gujarat region (Natarajan and Rajendran 2015). In the present time, the sediment thickness for Guwahati station and its surrounding is found to be very less. Figure 2a–d shows the high amplification with lower-frequency range from 0.6 to 2.0 Hz with mean value 1.3 Hz for the site ZIRO, and this is possible due to thick soil along with the presence of low- to medium-grade metamorphic rocks at greater depth (Bhusan et al. 1991). Figure 3a–e represents high amplification within lower-frequency range of 0.6–2.0 Hz with mean value 1.3 Hz for the site AGT, DIBR, JORH, KOHI, LKP, and this may be possibly due to thick soil. Several authors (Bakliwal and Das 1971; Dikshitulu et al. 1995; Kumar 1997; Kayal 2001, 2008; Ramamoorthy and Ramasamy 2015) reported the presence of sedimentary rocks such as sandstone at greater depth for these sites. Figure 4a–f shows the presence of sedimentary rocks at moderate depth due to which the high amplification with moderate frequency at GTK, SAIH, SHL, TURA, TEZP (Roy and Asthana 1989; Biswas et al. 2015; Kayal 2001) sites, whereas the TAWA (Bhusan et al. 1991; Kumar 1997) site indicates the presence of metamorphic rocks at moderate depth and that is found to be in the range of 2.0–8.0 Hz with mean value 5 Hz. The horizontal-to-vertical ratio of background micro-seismic noise curve represents high amplification with low frequency indicating the presence of possible thick soil. Again, we got the low amplification with higher frequency in the range 8.0–12 Hz with mean value 10 Hz at GUWA, IMP (Kayal 2001, 2008; Nandy et al. 1983) possibly due to alluvial deposition, whereas at ITNA (Kumar 1997) site sedimentary rocks such as sandstone, claystone, shale are found at shallower depth, which

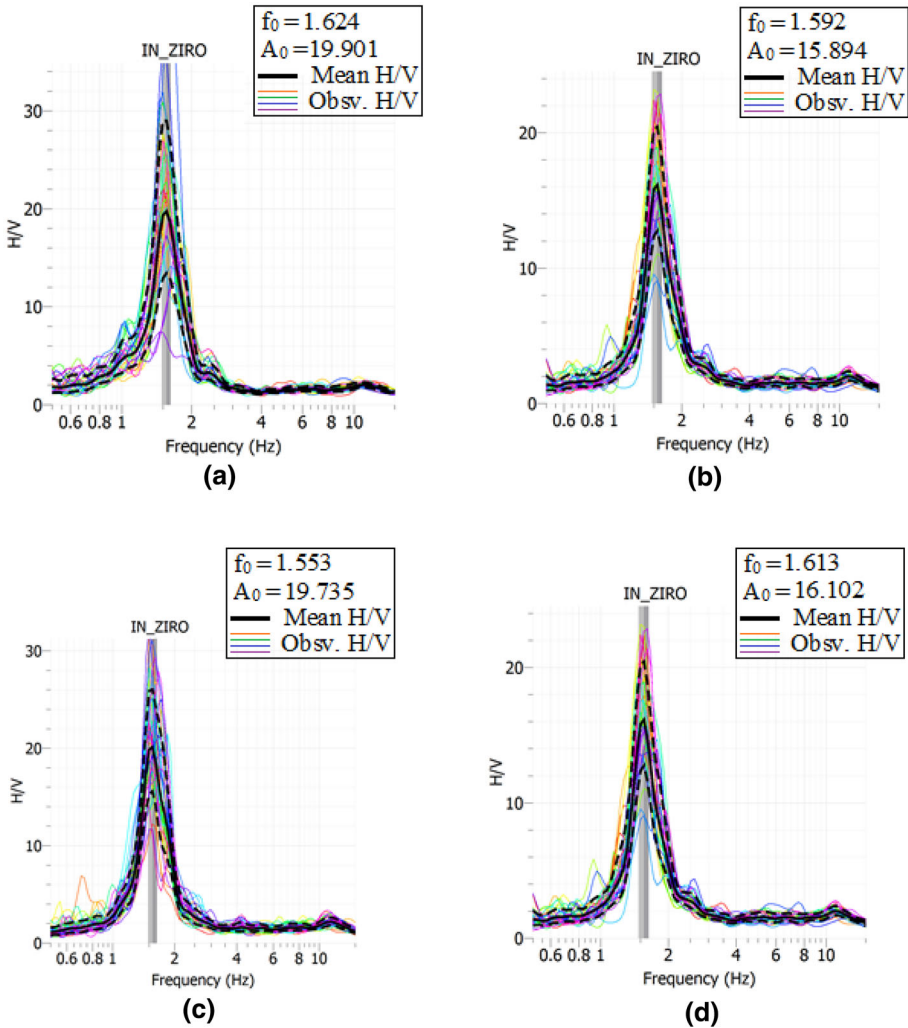
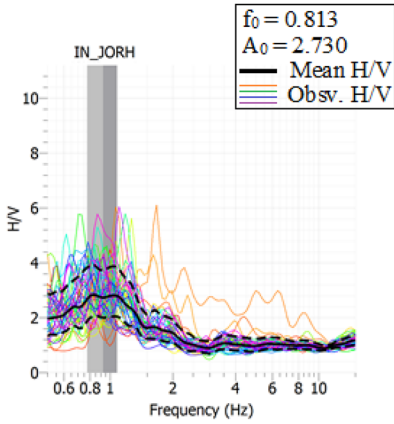
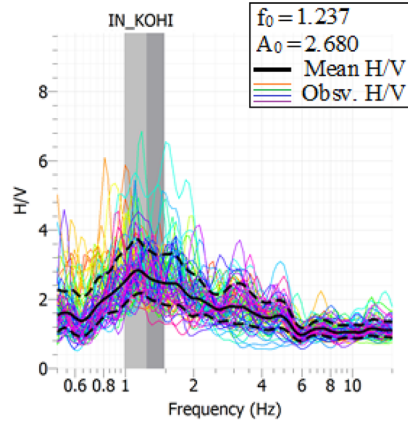


Fig. 2 a–d Comparison of fundamental frequency response at the ZIRO station for different fundamental frequency and magnitude, which shows that same trend at low frequency in the range of 0.6–2.0 Hz. The different colour lines represent the observed value of H/V, and solid black line represents the value of mean H/V with different frequency and amplitude for each and every plot

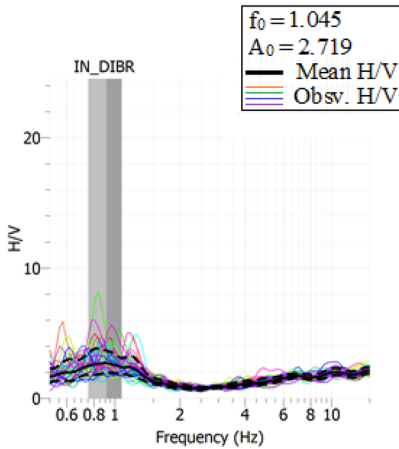
shows the presence of thin soil as shown in Fig. 5a–c. Similar kind of observation reported by Fnais et al. (2010), where area with greater depth gave low fundamental frequency but also higher fundamental frequency value was obtained in the area where basement depth was found to be shallower. Ghosh et al. (2010) undertook many geophysical surveys (gravity, magnetic, seismic) in the upper Assam valley and surrounding region where they have observed the complex basement thickness, which varies from north to south direction within the range of 4.5–6 km. At some sites (AGT, DIBR, JORH, GTK and SAIH) flat response was obtained with lower-frequency range indicating no sharp impedance contrast with very shallow bedrock. Even Surve and Mohan (2010) did not get peak amplification rather they have observed nearly flat response in the presence of typical hard rock/non-



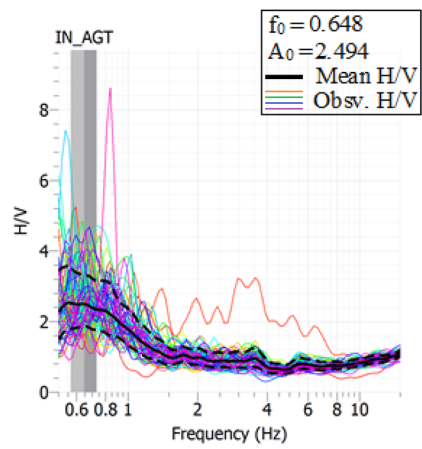
(a)



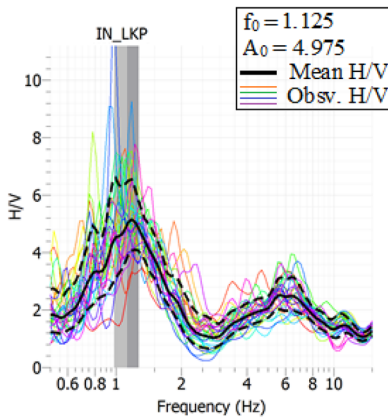
(b)



(c)



(d)



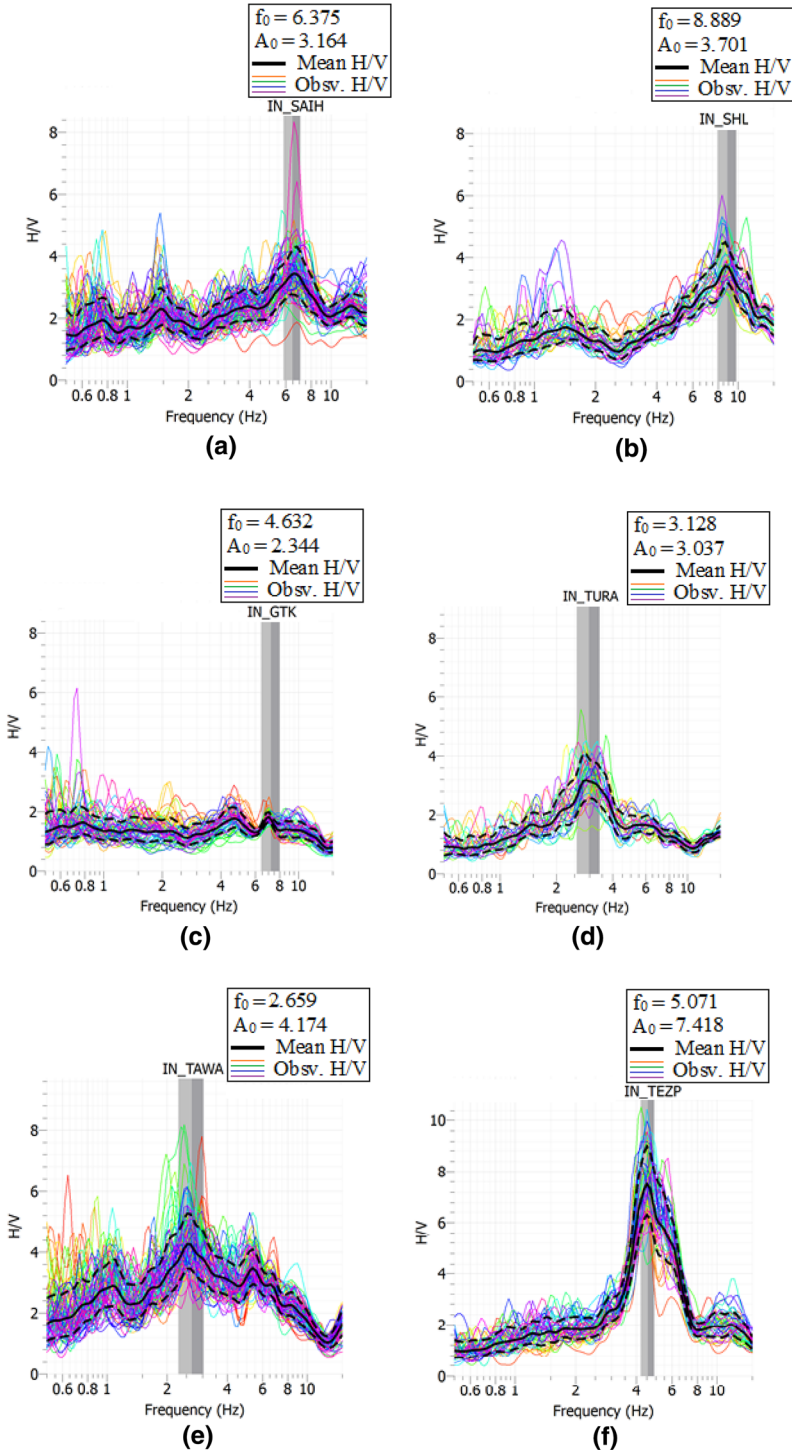
(e)

◀ **Fig. 3 a–e** Fundamental frequency response of various stations of different frequency and magnitude, which shows there is thick soil present at the high amplitude with low frequency in the range of 0.6–2.0 Hz. The different colour lines represent the observed value of H/V, and solid black line represents the value of mean H/V with different frequency and amplitude for and every plot

weathered sites for their H/V ratio spectral site responses curve. In the H/V rotate analysis of AZL station as shown in Fig. 6a, the fundamental frequency peak is found in the range of 1–2 Hz with mean value 1.5 Hz and H/V rotate amplitude is found to be above 4.00 over 20°–80°. Thus, we may say that the maximum energy release has taken over this part of the region. Further H/V rotate analysis for the stations (AGT, DIBR, GTK, GUWA, JORH, KOHI and LKP) did not give any significant observations, and that is represented in the figures (Fig. 6b–h).

The contour map of average frequency and average amplitude for the fifteen sites is shown in Figs. 7 and 8. According to the contour map, we are able to infer about the variation in the thickness of the sediments, supported by combined presence of fundamental frequency, i.e. higher and lower values for the entire study region. The higher fundamental frequency found to be predominant in the northern and north-eastern portion of study area near Guwahati and Itanagar. Further lower frequency is found in the south-western area near Agartala of the study region. Thus, we may say that above analysis may not give direct relation between fundamental frequency and sediment thickness, but it can be used for the understanding the sediment thickness variations, as it is stated by other authors in case of Bombay (Surve and Mohan 2010).

The H/V maximum fundamental frequency (f_{\max}) and maximum amplitude (A_{\max}) mean that we have considered the maximum frequency and maximum amplitude of each station (15 broadband stations) corresponding to each adopted noise data (13 events) for the purpose to find out the most hazardous region in and around all the broadband stations and compare those with the plotted contour map of fundamental resonance frequency. Perhaps this will check whether it gives the same response or not. Suppose if we consider the maximum frequency and maximum amplitude at each station corresponding to each adopted noise data, this will indicate the region which is most hazardous situated in and around the seismic station (Figs. 9, 10). Here, we have obtained same trend for f_{\max} and fundamental resonance frequency as shown by the contour plot, where some cases of high or low frequency were also seen along with amplitude value at some stations. Contour map of H/V maximum fundamental frequency f_{\max} (Fig. 9) shows that the northern part of the area has values more than 8.5 Hz, while south-western part has value less than 2.5 Hz of this study area. Again H/V maximum amplitude A_{\max} analysis represents lower amplitude of 3.5 in the portion of south-western and south-eastern as shown in Fig. 10. Again, maximum amplitude of 18 is seen in the northern portion in Fig. 10. Our observation corroborates with the gravity and magnetic survey of Ghosh et al. (2010) where he reported 12 km thickness of sediments in the Mizoram state. However, we may state that we have seen that fundamental frequency which gives more reliable results compared to other frequencies for the estimated H/V amplitude (Natarajan and Rajendran 2015). Liquefaction vulnerability index (kg) is calculated by taking the square of amplitude (A_0) divided by fundamental frequency (f_0) (Natarajan and Rajendran 2015). Estimation of low fundamental frequency and high amplitude from the H/V curve for the ZIRO station lead to high value of kg as given in Table 1. Above obtained high value of kg indicates future expected earthquake damage for ZIRO station is highly vulnerable. The high kg value and high amplification value is obtained at the ZIRO station. This high value is supported by the presence of thick succession of low- to medium-grade metamorphic rocks such as granite gneiss from surface exposure to maximum depth in and around the ZIRO station (Bhusan et al. 1991).



◀ **Fig. 4 a–f** Fundamental frequency response of various stations of different frequency and magnitude, which shows there is moderate soil present at the high amplitude with moderate frequency range of 2.0 to 8.0 Hz. The different colour lines represent the observed value of H/V, and solid black line represents the value of mean H/V with different frequency and amplitude for each and every plot

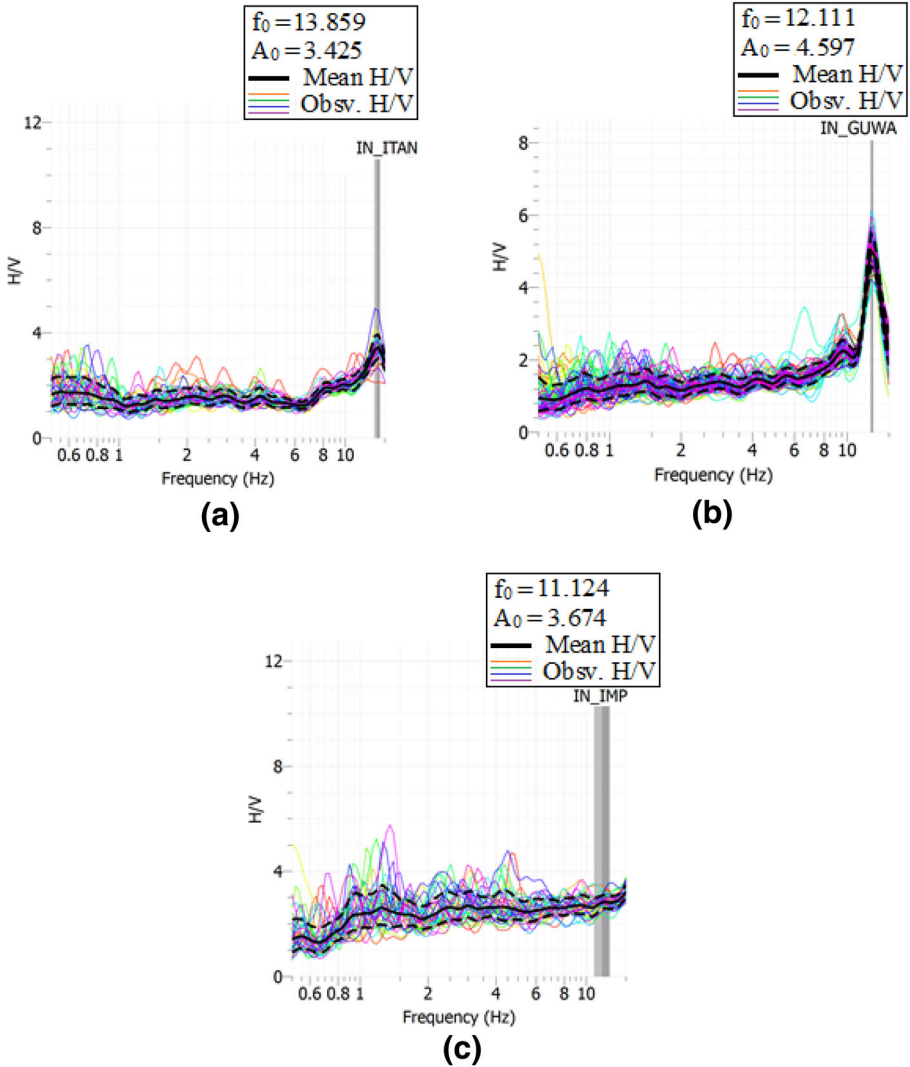


Fig. 5 a–c Fundamental frequency response of various stations of different frequency and magnitude, which shows there is thin soil present with high frequency range of 8.0–12.0 Hz. The different colour lines represent the observed value of H/V, and solid black line represents the value of mean H/V with different frequency and amplitude for each and every plot

4 Conclusions

After carrying out the above H/V site spectral ratio analysis for the study area using ambient noise by removing thirteen earthquake events recorded in fifteen stations. We have set a background for further microzonation study. The result shows that the fundamental

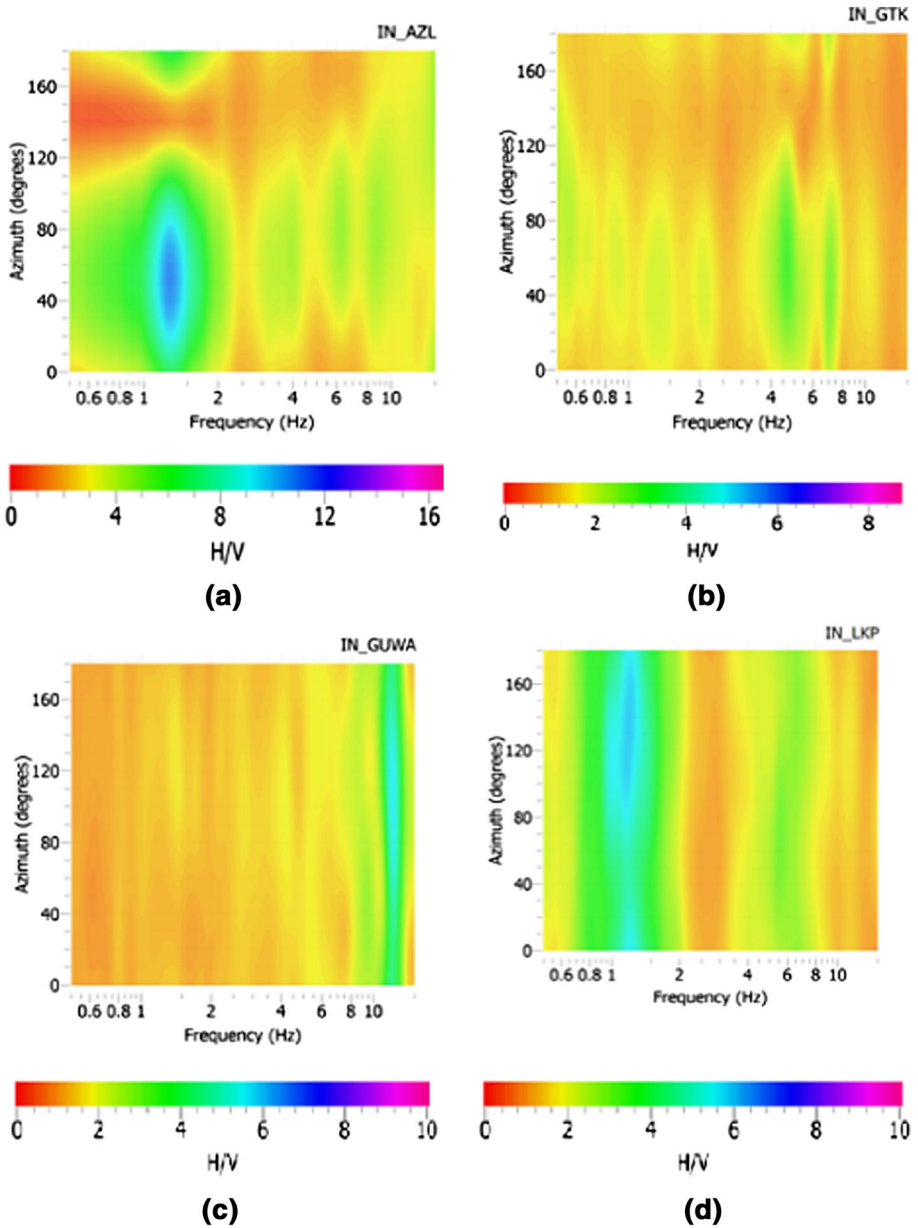


Fig. 6 a–h Illustration for the horizontal-to-vertical rotation plotted with respect to azimuth for different event at different frequency

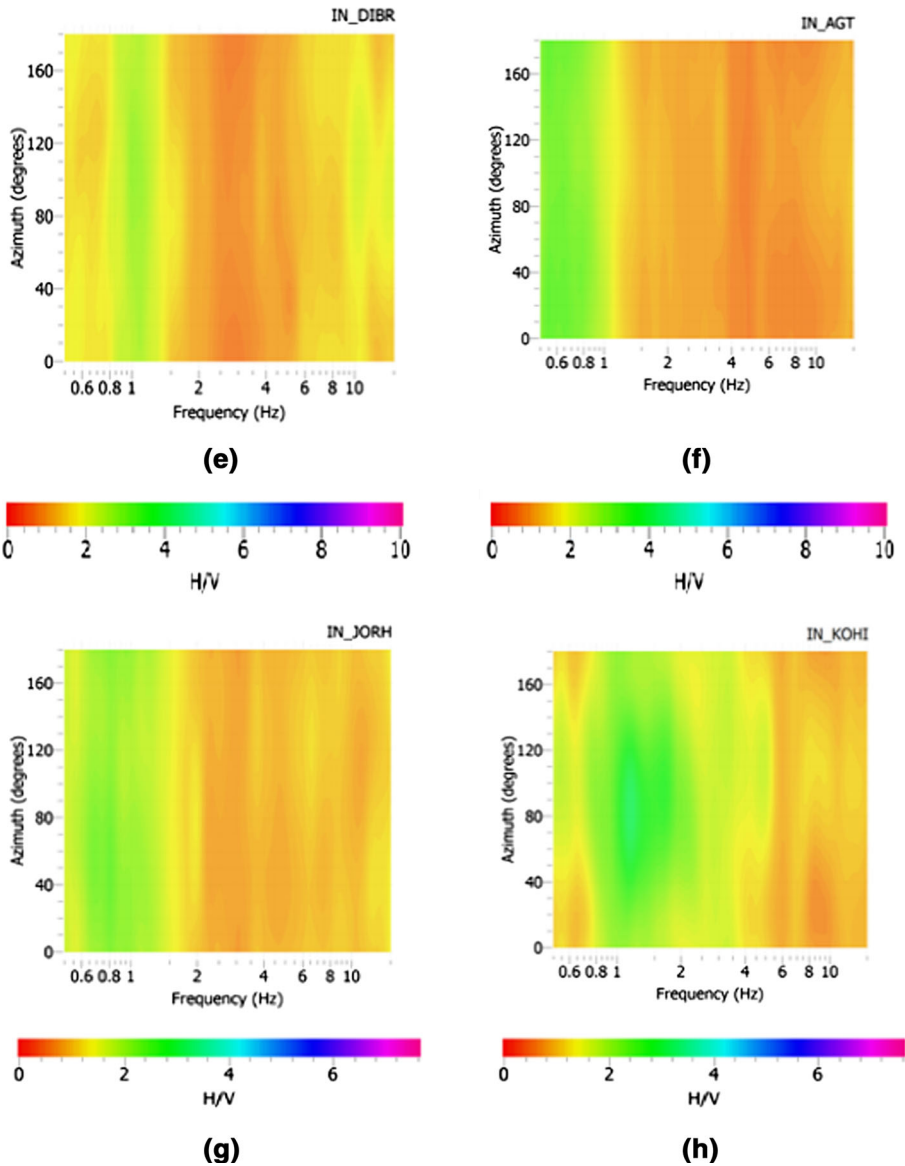


Fig. 6 continued

frequency varies as well as amplitude changes for different sites, which are located in complex geological domain having variation in sediment thickness or topography. The fundamental frequency found to be in the range 0.6–10 Hz for the entire study region observed by the sites. In the case of northern part of the study area where the low fundamental frequency range is found to be 0.6–2.0 Hz which is due to thick soil of region brought by major Brahmaputra river and other tributary. The major cities are found to be in the close proximity of such observations are Guwahati, Itanagar and Tezpur. In the southern part of the study region shows lower fundamental frequency in the range of

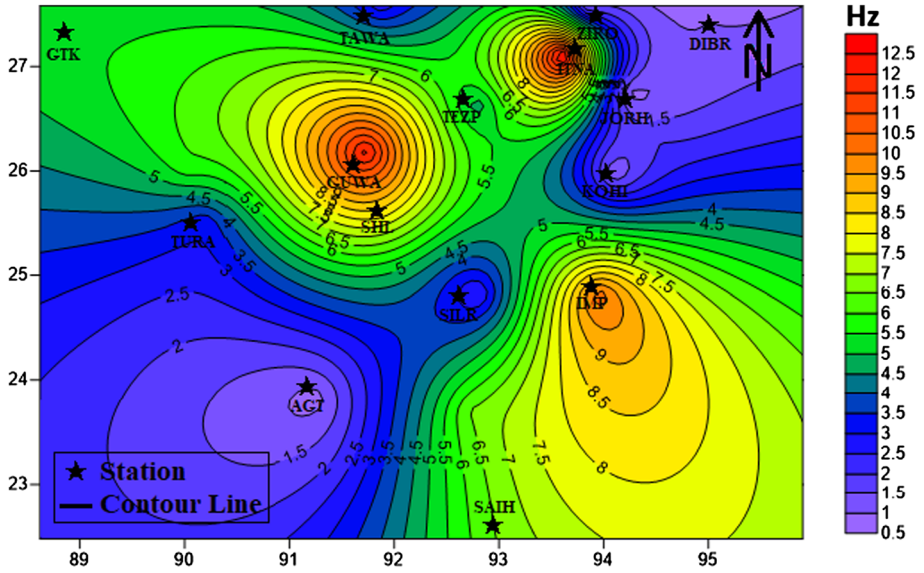


Fig. 7 Contour map for H/V fundamental resonance frequency of north-east region

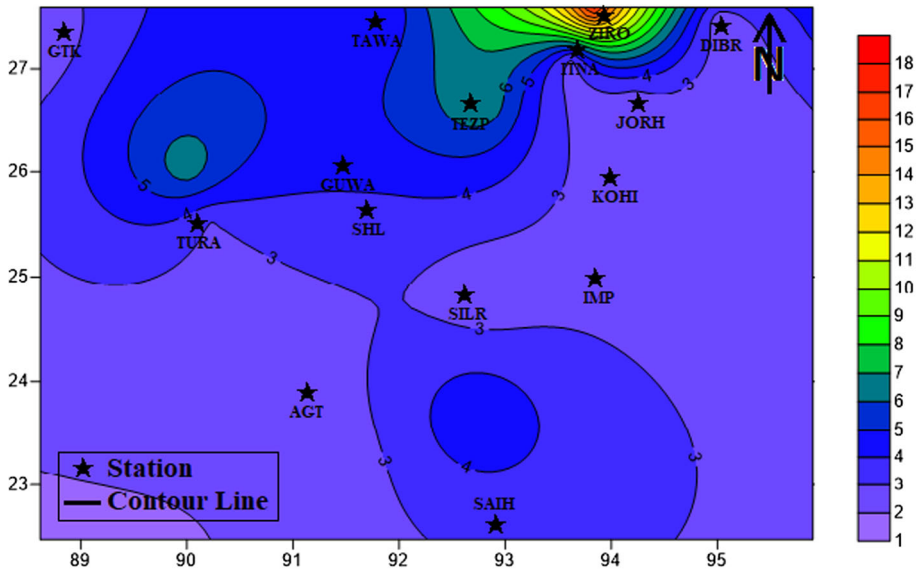


Fig. 8 Contour map for H/V amplitude response of north-east region

2.0–8.0 Hz due to soft or moderate sediments deposit. The major city around these sites are Agartala and Aizawl where impedance contrast present between bed rock and the overlying sediments has shown very high seismic ground motion.

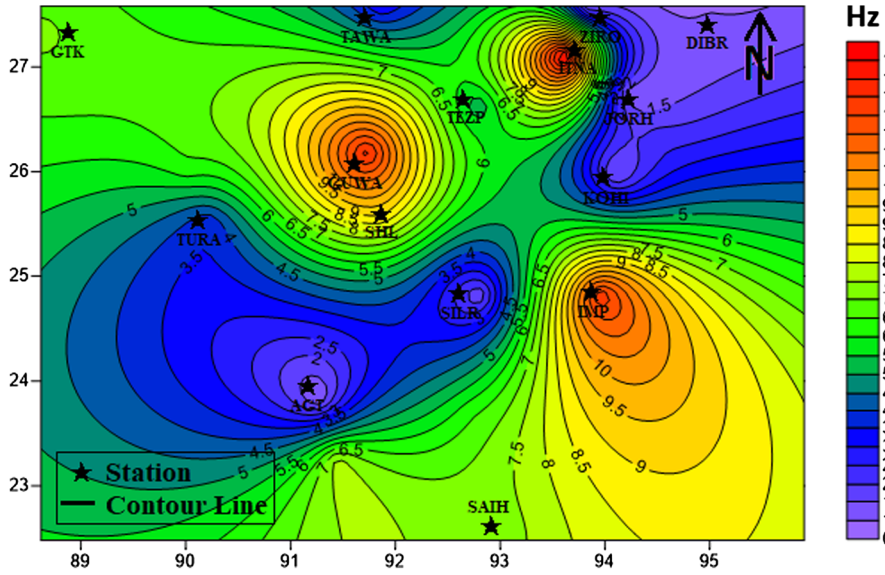


Fig. 9 Contour map of maximum frequency f_{max} of the event for north-east region

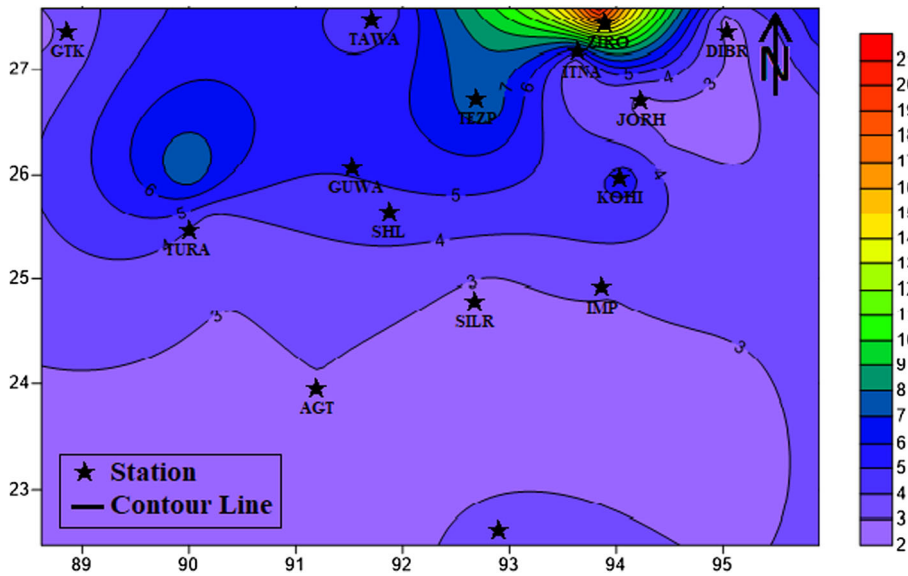


Fig. 10 Contour map of maximum amplitude A_{max} of the event for north-east region

According to the above obtained results which found to be reliable for the recorded microseism noise data. This study helped to evaluate the site response for thicker and thin deposits. The above results may be crucial for planning of geotechnical survey and possibility may lead to the same result on shallow and deep soil layers.

Table 1 Site response parameters estimated for the sites at north-east region

Seismic station	Latitude	Longitude	Data duration (min)	f_0 (Hz)	A_0	kg	Local geology
ZIRO	27.56	93.83	31	1.55	19.73	250.76	Metamorphic rocks
IMP	24.82	93.95	32	11.12	3.67	1.21	Alluvium deposited
LKP	27.31	95.90	33	1.12	4.97	21.99	Sedimentary rocks
DIBR	27.48	95.00	34	1.04	2.71	7.07	Sedimentary rocks
KOHI	25.97	94.10	60	1.23	2.68	5.80	Sedimentary rocks (sandstone)
JORH	26.75	94.22	60	0.81	2.73	9.16	Sedimentary rocks
AGT	23.83	91.26	60	0.64	2.49	9.60	Sedimentary rocks
SAIH	22.48	92.97	33	6.37	3.16	1.57	Sedimentary rocks
TURA	25.52	90.22	33	3.12	3.03	2.94	Sedimentary rocks (sandstone)
GTK	27.33	88.62	33	4.63	2.34	1.18	Sedimentary rocks
TEZP	26.63	92.80	34	5.07	7.41	10.85	Sedimentary rocks
TAWA	27.58	91.87	60	2.65	4.17	6.55	Metamorphic rocks (granitic gneiss)
SHL	25.56	91.88	60	8.88	3.70	1.54	Sedimentary rocks
GUWA	26.18	91.73	33	12.11	4.59	1.74	Alluvium deposited
ITAN	27.10	93.62	34	13.85	3.42	0.84	Sedimentary rocks (sandrock, claystone)

Acknowledgements The authors are thankful to IMD, Centre for Seismology, Ministry of Earth Sciences, Government of India, New Delhi, for providing the earthquake data of north-east India region. PNSR gratefully acknowledge Ministry of Earth Science, Government of India (Project Number: MOES/P.O. (Seismo)/1(148)/2012) for partly sponsoring this work. The authors acknowledge Paul Wessel and University of Hawaii for General Mapping Tools (Wessel and Smith 1998).

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