Chapter 14
Comparative Analysis of SSR and HVSR Method for Site Response Analysis

Sasanka Borah, Jayanta Pathak, and Diganta Goswami

Abstract The Northeast part of India falls under seismic Zone V (IS:1893–2002), the highest seismic activity zone. However, there is a lack of sufficient dense seismic arrays in the region to record the seismic activity. Irrespective of the availability of the seismic records this study attempts to decsribing the two site response analysis methods: Standard Spectral Ratio (SSR) and Horizontal to Vertical Spectral Ratio (HVSR). Three locations in the west Guwahati Region of the state of Assam in Northeast India, namely, Boko-Palashbari, Goalpara and Guwahati Central Region, have been considered for this study in order to analyze available strong motion data and quantify the site response. The quantification is attempted in terms of site amplification. This chapter also provides a comparison between the two methods under study. 5(five) and 15(fifteen) strong-motion recordings of earthquake events have been considered in this study for the SSR and HVSR methods respectively. The strong motion as recorded in Nongstoin has been considered as a reference site station record for the SSR study. This finding of this study compliments the findings of Field and Jacob (Field and Jacob in Bull Seismol Soc Am 85:1127–1143, 1995) that, if the SSR estimates are taken as the most reliable, the HVSR method under-predicts the site response. The results provided by HVSR are less than that of the SSR results by a factor of 2–4.

Keywords Strong motion · SSR · HVSR · Site amplification

S. Borah (✉) · J. Pathak · D. Goswami
Department of Civil Engineering, Assam Engineering College, Guwahati 781013, Assam, India
e-mail: sasankaborah.ce@aec.ac.in

J. Pathak
e-mail: jayantapathak.ce@aec.ac.in

D. Goswami
e-mail: digantagoswami2@gmail.com

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14.1 Introduction

The earthquakes have always surprised the engineers with their random, nature and variable damage potential for similar magnitudes and epicentral distances. It has been observed over the years that the damage potential varies from place to place within a similar radius from the source of the earthquakes. The various studies on the distribution of damages due to earthquakes have shown that the effects of the geology of the area on ground shaking represent an important factor in engineering seismology as well as in engineering design. Figure 14.1 schematically shows the general wave propagation when an earthquake occurs. It is seen in general that waves generated at the source propagate through the earth and, in general, show a trend of decreasing amplitude with increasing distance if there is no local site effect.

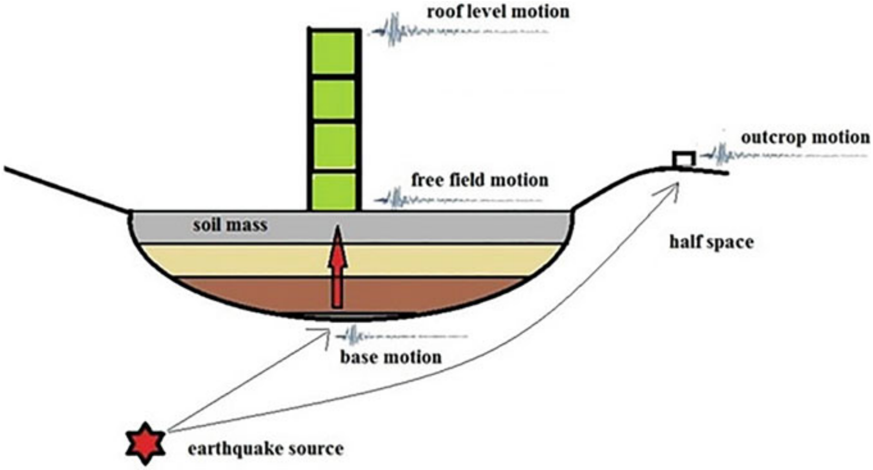

Fig. 14.1 Simplified representation of seismic wave propagation and site response

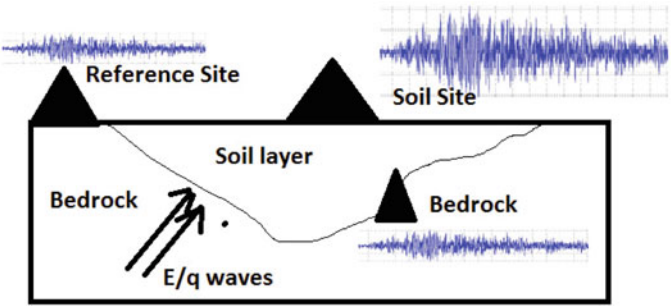

Fig. 14.2 Schematic description of the SSR method

The modification of the ground motion due to "***site response***" which is recorded at stations located in different soil conditions will be different and can be related to various factors governed by the local site conditions. In general, the main factor for such modification is the impedance contrast [43] between the soft sedimentary cover (with low density and wave propagation velocity) and the bedrock (with high density and wave propagation velocity). The impedance contrasts determine how strongly the waves at particular frequencies (the fundamental resonance frequency and the higher harmonics) are modified within the soft layer. Generally, the higher the impedance contrast, the greater the trapped energy, therefore, **the** higher the modification of the seismic waves within the layer. This modification results in various intensities of the earthquake ground shaking at various locations depending on the soil conditions and in turn may result in various categories of damage.

Estimation of site response can be done by various site response analysis methods. The suitability of most of the methods is based on the availability of strong-motion data. The present work adopted the two most widely accepted site response analysis methods namely—Standard Spectral Ratio (SSR) and Horizontal to Vertical Spectral Ratio (HVSR) of strong-motion data. The SSR and HVSR method require the availability of recorded strong ground motions. The SSR and the HVSR method involve waveform analysis. These methods were chosen to assess the site-specific response of a soil deposit in the Western Guwahati region because the recorded waveform data-set in the form of three-component time-history was available (for SSR and HVSR analysis).

It is to be noted that while the SSR method is a reference site method involving waveform analysis, the HVSR method is a non-reference site method (single station method) involving waveform analysis. The SSR and HVSR method involve the determination of site response in the form of ratios in the frequency domain. The site response data obtained is defined as the "*site transfer function*" or "*amplification ratio*" plot for the site concerned. The data of these plots can be used to obtain the time history of the site, modified due to site response.

This chapter attempts to compare the results obtained by the two methods and give a discussion on the results obtained. The area of the study includes three locations in the west Guwahati Region of the state of Assam in India, namely, Boko-Palashbari, Goalpara and Guwahati Central Region.

14.2 Standard Spectral Ratio (SSR Analysis)

One of the most popular, widely used and accepted techniques, which involves standard reference sites to characterize site amplification, is Standard Spectral Ratio (SSR) technique. It has been used by various authors to determine the site response [8, 18, 30, 47, 49]. The SSR is a technique where the site response is defined as the ratio of the Fourier amplitude spectrum of ground motions recorded at a soil-site to that of ground motions recorded at a rock-site record located nearby, from the same earthquake and component of motion [6].

In this method it is assumed that earthquake records obtained from the reference site (an earthquake recording station located on a hard rock outcrop) are free from site effects and contain the same source properties, and when the two sites are closely located, the path or propagation effects are also same for the pair of records. Hence, the ratio of the Fourier amplitude spectra of the sedimentary site to the reference site expresses the local site effects or in other terms amplification at the sedimentary or soil site.

Alternatively, it can be said that the technique depends on two basic assumptions [27]:

(a) The source and paths effects at both sites are similar.
(b) The reference site has a negligible site response, that is, its spectrum is flat.

The first assumption requires that the distance between both sites is limited in order to have a similar wave field (with similar incidence angles and azimuths) arriving at the two sites. This effect can also be reached with increasing source-receiver distance compared to the distance between the two recording sites [17].

The second assumption implies that the record on the rock site, which usually is a free field station on the ground surface, is equivalent to the input motion at some depth, not taking into account the free-surface effects [31].

Obtaining pure outcropping rock sites consisting of geological bedrock which is close to basins of sedimentary deposits or soft alluvial sites, as well as unweathered outcropping sites at the ground surface, are very hard to find [27, 47]. Difficulties in the application of SSR are discussed by Safak [49] and Steidl et al. [53]. Safak [49] pointed out problems in the application of the spectral ratio method to real records because the spectral ratios could be significantly influenced by their processing procedure. Apart from the theoretical background, one of the major problems when applying the standard spectral ratio method is identifying a pure bedrock site that meets the mentioned pre-requisites even when bedrock sites are available. However, the assumed condition that an outcropping rock reference site is free of any site effects is often not valid because a seemingly good rock site may have an amplification of its own. Therefore, a careful examination of the reference site is necessary to accurately estimate amplification/site response in sedimentary sites [53]. Steidl et al. [53]concluded that surface rock sites are inevitably affected by amplification at a frequency as low as 4–5 Hz because of the thin weathered layer that is almost always present on rock sites. They advocated the use of seismic stations at the bottom of deep boreholes. Steidl et al. [53] showed that deep bore hole records, when corrected for the effects of downward propagating waves, are more reliable records to be used as reference site motion. This conclusion is well-substantiated but impractical in most places, especially in developing countries because of the large cost involved.

14.2.1 Standard Spectral Ratio (SSR) Method

The Standard Spectral Ratio (SSR) method is defined as the ratio of ground motions records of that of a soil site to that of a rock site, where the rock site is used as a reference site (Fig. 14.2). It is assumed that earthquakes recorded on the reference site (i.e. recorded on a station placed on outcropping hard bedrock) contain the same source and propagation effects as that of the records from the other sites that is

$$Standard\ Spectral\ Ratio\ (SSR) = \frac{U_{ij}(x,y)}{U_{ik}(x,y)} = \frac{S_i(x)Z(x)_j A_{ij}(x,y)}{S_i(x)Z(x)_k A_{ik}(x,y)} \quad (14.1)$$

where

U_{ij}(x,y) = Fourier Amplitude of the ground motion observed at a soil site j for an event i,

U_{ik}(x,y) = Fourier Amplitude of the ground motion observed at reference site k for an event i,

S_i(x) = source function,

Z_i(x) = response of the site,

A_{ij}(x,y) = Attenuation function of soil site,

A_{ik}(x,y) = Attenuation function of reference site,

x = the frequency,

y = distance from epicenter and.

k = reference station.

It is to be noted that similar to what is schematically indicated in Fig. 14.1, the ground motion recorded at one station is considered as the convolution of three terms, specifically the source $S_i(f)$, the path $A_{ij}(f,r)$ and site response $Z_j(f)$. If the stations are nearby, and the reference station is not affected by site effects, then $A_{ij}(f,r) \approx A_{ik}(f,r)$. Thus, the spectral ratio directly provides the site response at the non-reference stations. The major drawback of this method is that rock stations may also have their own response. Furthermore, a good reference site might be located too far away from the target site, therefore, not allowing the assumption of similarity in the wave paths towards the two stations.

14.2.2 Selection of Reference Site

Of the two datasets considered for the study and of all the recording stations, Nongstoin station recordings were considered as reference site motion. Table 14.1

Table 14.1 Time histories recorded at Nongstoin

Earthquake event	Epicenter	Region	Magnitude (Mw)	Focal depth (km)	Epicentral distance (km)
11 Aug. 2009	24.4 N 94.8E	Myanmar	5.6	22	378
03 Sep. 2009	24.3 N 94.6E	Myanmar	5.9	100	363
21 Sep. 2009	27.3 N 91.5E	Bhutan	6.2	8	197
29 Oct. 2009	27.3 N 91.4E	Bhutan	5.2	5	197
29 Oct. 2009	26.6 N 90.0E	Kokrajhar	4.2	10	174

gives the details of the recordings at Nongstoin station (Table 14.2).

The basic conditions for the application of SSR are [45]:

(a) the existence of simultaneous recordings at a soil site and at the reference site,
(b) the reference site has to be free of any site effects, and
(c) the distance between the soil site and the reference one ought to be small (i.e. smaller than the epicentral distance), to consider that the effect of the propagating path of the seismic energy is the same for the two sites.

It can be clearly seen from Table 14.3 that the first condition of application of SSR technique, i.e., the existence of simultaneous recordings at a soil site and the reference site for the same earthquake event, is satisfied by the recording of Boko-Palashbari, Guwahati-Central, and Goalpara. Moreover, Nongstoin is characterized as Site Class A with site geology consisting of granite [34]. Therefore, recordings of this station can safely be assumed to be that of a reference site that satisfies the second condition. Further, as indicated in Table 14.4, the inter-station distance between Nongstoin and Boko-Palashbari, Guwahati-Central, Goalpara stations is less as compared to the epicentral distance as is required by the third condition, for each earthquake considered for SSR analyses. Thus it can be conservatively assumed that the effect of the propagating path of the seismic energy is the same for the two sites considered respectively.

14.2.3 Dataset and Data Processing of Earthquake Records

From the 5(five) earthquake events, a total of 16 earthquake recordings having three components of motion, i.e. E-W(East–West), N-S(North–South) and VT(Vertical) wereselected for the analyses. Of these 11(eleven) were related to soil sites (Boko, Goalpara, and Guwahati) and 5(five) were related to reference site (Nongstoin).

The complete duration of all the records was Fourier transformed to obtain the Fourier Amplitude Spectra (FAS) of the respective components by using the software code DEEPSOIL [21].

14.2.4 Analyses and Discussion

The analyses were carried out for 3(three) soil sites with reference to a single rock/reference site. A total of 5(five) earthquake events qualified for the SSR evaluation technique as given in Table 14.2 within the area of study. SSR analysis of all three components of the records i.e. EW, NS, and VT was carried out. SSR method employs a comparison of round records in the frequency domain. Additionally, in this study, the properties of ground motions of the soil sites were compared with that of the reference site in the time domain as well. The comparison in the time domain was carried out in the form of ratios of soil versus reference site of the PGA, PGV and PGD respectively and presented in Table 14.13.

Table 14.2 Properties of recorded motions (Nongstoin station)

Earthquake event	Maximum acceleration (g)			Maximum velocity (m/s)			Maximum displacement (m)			Duration (second)
	EW	NS	VT	EW	NS	VT	EW	NS	VT	
11Aug. 2009	0.014	0.016	0.015	0.004	0.004	0.002	0.003	0.003	0.006	73.040
03 Sep. 2009	0.009	0.010	0.007	0.003	0.003	0.002	0.002	0.008	0.008	73.475
21 Sep. 2009	0.028	0.019	0.016	0.012	0.009	0.013	0.017	0.009	0.014	106.335
29 Oct. 2009	0.010	0.008	0.05	0.003	0.003	0.002	0.007	0.009	0.009	67.080
29 Oct. 2009	0.006	0.010	0.003	0.002	0.003	0.001	0.009	0.001	0.004	65.985

Table 14.3 Selected reference site and soil site motions and epicentral distances

Earthquake event	Epicenter	Focal depth (km)	Boko-Palashbari (soil site)	Guwahati-central (soil site)	Goalpara (soil site)	Nongstoin (Ref. site)
			25.976 N 91.230E	26.190 N 91.746E	26.152 N 90.627E	25.522 N 91.264E
11 Aug. 2009	24.4 N 94.8E	22	400	366	463	378
03 Sep. 2009	24.3 N 94.6E	100	388	356	450	363
21 Sep. 2009	27.3 N 91.5E	8	148	125	153	197
29 Oct. 2009	27.3 N 91.4E	5	+	+	147	197
29 Oct. 2009	26.6 N 90.0E	10	+	+	80	174

Table 14.4 Inter-station distances (in km)

Stations	Nongstoin	Boko-Palashbari	Goalpara	Guwahati-Central
Nongstoin	0	50	90	80
Boko	50	0	60	50
Goalpara	90	60	0	120
Guwahati	80	50	120	0

Table 14.5 Properties of recorded motions (Guwahati-central station)

Earthquake events	Maximum acceleration (g)			Maximum velocity (m/s)			Maximum displacement (m)			Duration (second)
	EW	NS	VT	EW	NS	VT	EW	NS	VT	
11 Aug. 2009	0.013	0.011	0.013	0.006	0.004	0.004	0.003	0.004	0.001	73.040
03 Sep. 2009	0.012	0.007	0.007	0.007	0.003	0.003	0.004	0.006	0.004	71.065
21 Sep. 2009	0.028	0.024	0.013	0.011	0.009	0.006	0.016	0.038	0.021	107.280

14.2.4.1 Guwahati-Central Site

The Guwahati-Central station has been classified as Site Class ‘C’ [34]. The station was triggered and had recorded 3(three) events out of the total of the 5(five) events that had been considered for the study. Table 14.5 shows the duration and peak values of acceleration, velocity and displacement of the recorded ground motions of Guwahati-Central site. Figures 14.3, 14.4 and 14.5 represent the SSR plots of EW, NS and VT components respectively, for records of the 3(three) earthquake events of Guwahati-Central site with respect to Nongstoin station. From Figs. 14.3, 14.4 and 14.5 it can be seen that the SSR plot of the components was flatter in respect of the 21-Sep-2009 earthquake event as compared to the 11-Aug-2009 and 03-Sep-2009 earthquake events. The 11-Aug-2009 and 03-Sep-2009 earthquake events showed comparable plots for all the components. However, the 03-Sep-2009 earthquake event showed an SSR plot slightly having a higher amplitude in the frequency range of 2.0–3.0 Hz.

14.2.4.2 Boko-Palashbari Site

Boko station has been classified as Site Class ‘C’ [34]. The station was triggered and had recorded 3(three) events out of the total of the 5(five) events that had been considered for the study. Table 14.6 shows the duration and peak values of acceleration, velocity and displacement of the recorded ground motions of Boko-Palashbari site. Figures 14.6, 14.7 and 14.8 represent the SSR plots of EW, NS and VT components

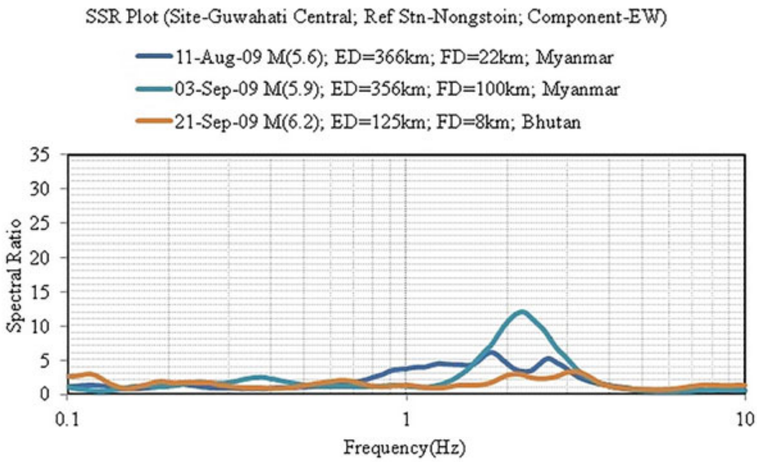

Fig. 14.3 SSR Plot of Guwahati-Central station, EW-component

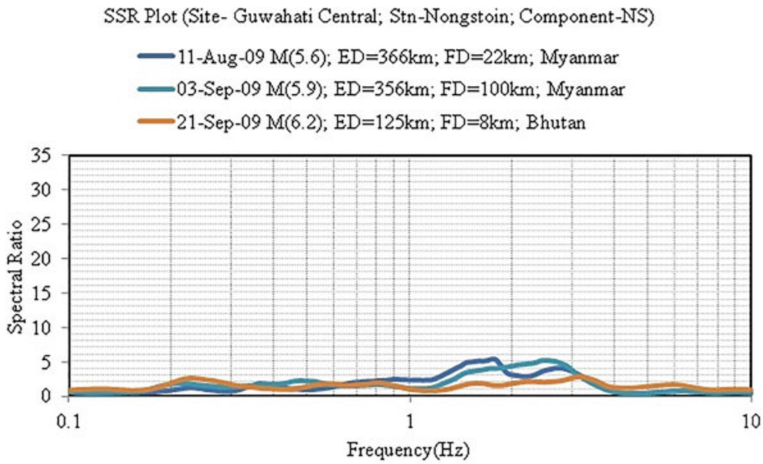

Fig. 14.4 SSR Plot of Guwahati-Central station, NS-component

respectively, for records of the 3(three) earthquake events of the Boko-Palashbari site with respect to Nongstoin station. The SSR plot as shown in Figs. 14.6, 14.7 and 14.8 shows that the maximum amplitude for the horizontal components i.e. the EW and NS components falls in the frequency range of 0.5–1.0 Hz. The vertical component, however, shows higher SSR amplitude in the frequency range of 1.0–3.0 Hz.

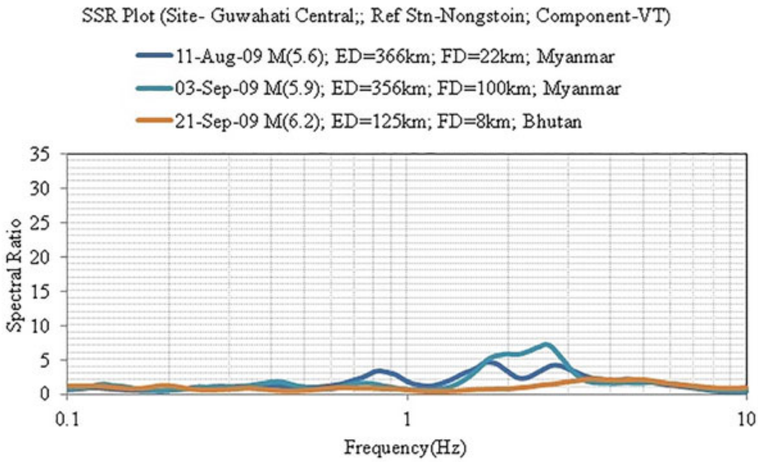

Fig. 14.5 SSR Plot of Guwahati-Central station, VT-component

Table 14.6 Properties of recorded motions considered (Boko-Palashbari station)

Earthquake event	Maximum acceleration (g)			Maximum velocity (m/s)			Maximum displacement (m)			Duration (second)
	EW	NS	VT	EW	NS	VT	EW	NS	VT	
11 Aug 2009	0.016	0.017	0.008	0.006	0.004	0.002	0.004	0.008	0.011	77.550
03 Sep 2009	0.014	0.009	0.005	0.003	0.003	0.002	0.003	0.004	0.007	72.675
21 Sep 2009	0.021	0.021	0.013	0.012	0.010	0.008	0.019	0.025	0.005	113.875

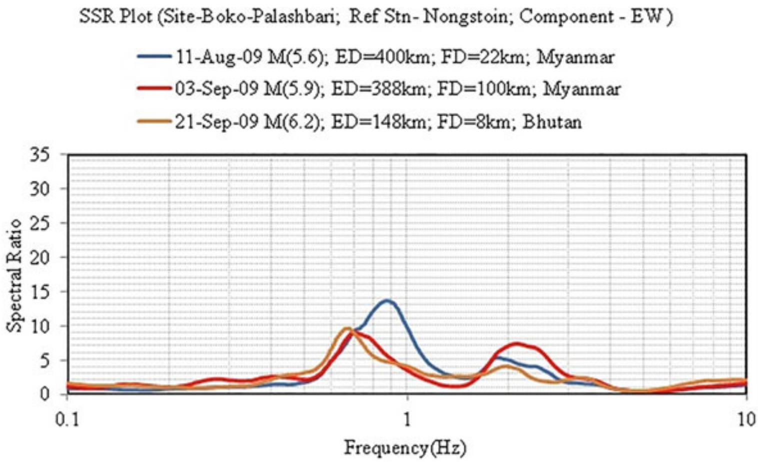

Fig. 14.6 SSR plot of Boko-Palashbari station, EW-component

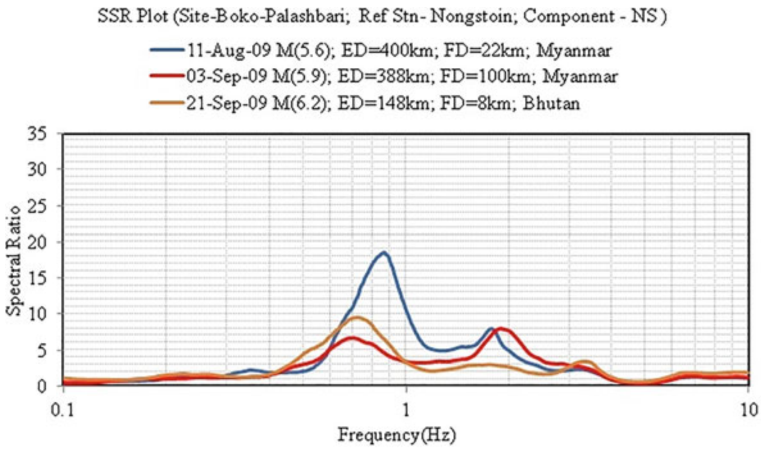

Fig. 14.7 SSR plot of Boko-Palashbari station, NS-component

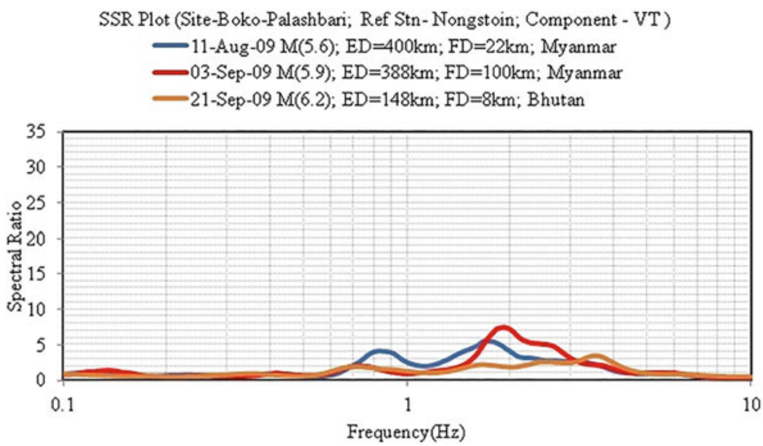

Fig. 14.8 SSR plot of Boko-Palashbari station, VT-component

14.2.4.3 Goalpara Site

Goalpara station has been classified as Site Class ‘C’ [34]. The station was triggered and recorded 5(five) events out of the total of the 5 events that had been considered for the study. Table 14.7 shows the duration and peak values of acceleration, velocity and displacement of the recorded ground motions of Goalpara site. Figures 14.9, 14.10 and 14.11 represent the SSR plots of EW, NS and VT components respectively, for records of the 5(five) earthquake events of Goalpara site with respect to Nongstoin station. From Figs. 14.9, 14.10 and 14.11 it can be seen that the maximum amplitude

Table 14.7 Properties of recorded motions considered (Goalpara station)

Earthquake event	Maximum acceleration (g)			Maximum velocity (m/s)			Maximum displacement (m)			Duration (second)
	EW	NS	VT	EW	NS	VT	EW	NS	VT	
11 Aug 2009	0.016	0.013	0.008	0.005	0.005	0.004	0.005	0.003	0.004	73.965
03 Sep 2009	0.006	0.006	0.004	0.002	0.002	0.002	0.005	0.003	0.007	66.620
21 Sep 2009	0.042	0.041	0.024	0.033	0.030	0.013	0.012	0.022	0.099	113.83
29 Oct 2009	0.015	0.011	0.007	0.006	0.006	0.004	0.003	0.019	0.036	75.405
29 Oct 2009	0.015	0.022	0.011	0.004	0.007	0.003	0.002	0.007	0.036	68.415

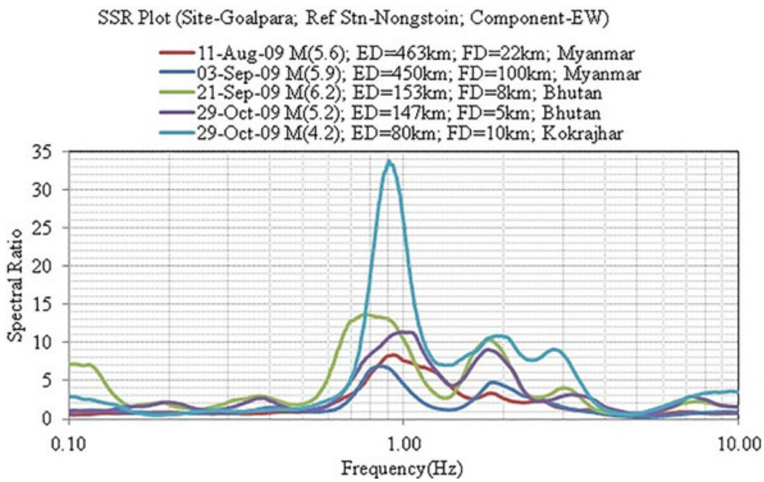

Fig. 14.9 SSR plot of Goalpara station, EW-component

of the SSR plot is in the frequency range of 0.60–2.0 Hz for the horizontal components, whereas for the vertical component the maximum values lie in a frequency range of 1.0–3.0 Hz.

14.2.5 Site Amplification

In this study, the definition of site amplification from SSR study is adopted as the maximum SSR amplitude. The corresponding frequency at which the maximum amplification is obtained is termed the fundamental frequency of the site. The site

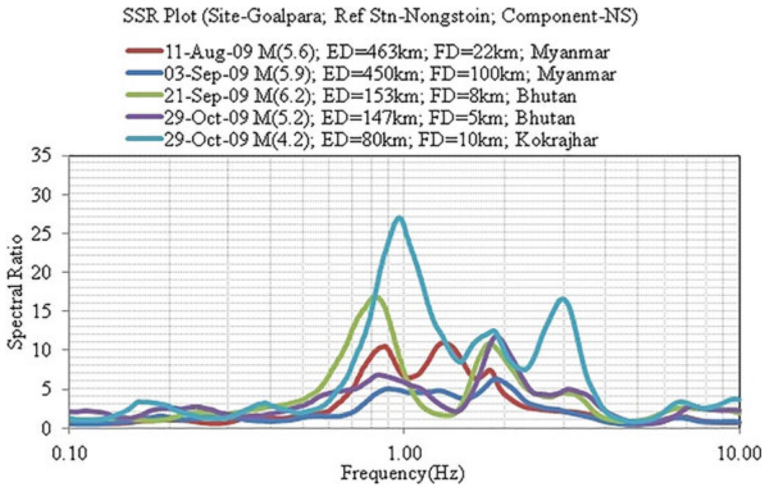

Fig. 14.10 SSR plot of Goalpara station, NS-component

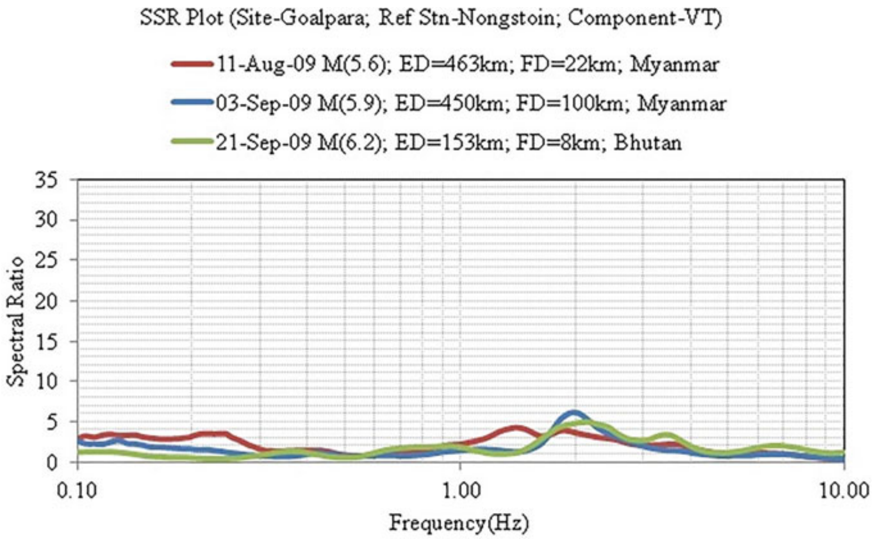

Fig. 14.11 SSR plot of Goalpara station, VT-component

amplification observed at Boko, Guwahati and Goalpara from the SSR analysis is provided in Table 14.8.

Table 14.8 Maximum SSR amplitude and corresponding frequency

Earthquake event	Magnitude (Mw)	Focal depth (km)	(SSR) site amplification/frequency								
			Boko-Palashbari (soil site)			Guwahati-Central (soil site)			Goalpara (soil site)		
			EW	NS	VT	EW	NS	VT	EW	NS	VT
11 Aug. 2009	5.6	22	13.60/0.87	18.48/0.85	5.54/1.69	5.99/1.81	5.34/1.77	4.61/1.75	8.32/0.91	10.77/1.28	4.27/1.38
03 Sep. 2009	5.9	100	9.04/0.69	7.99/1.89	7.42/1.87	12.11/2.20	5.19/2.48	7.19/2.58	6.78/0.82	6.29/1.88	6.19/1.93
21 Sep. 2009	6.2	8	9.66/0.66	9.54/0.72	3.55/3.49	3.30/3.05	2.79/3.13	2.19/3.44	12.90/0.76	16.85/0.82	5.00/2.08
29 Oct. 2009	5.2	5	–	–	–	–	–	–	11.29/1.04	11.78/1.88	4.30/1.75
29 Oct. 2009	4.2	10	–	–	–	–	–	–	33.74/0.70	27.14/0.96	9.69/1.99

14.2.6 Observations

The results of the SSR analysis have been provided in Table 14.8. At the Boko-Palashbari site, the amplification varied from 7.99 to 18.59 while for Guwahati-Central and Goalpara sites the same varied from 2.19–12.16 and 4.27–33.74. It is observed that, for all the sites, the maximum amplification was for the horizontal component as compared to the vertical.

Site amplification for the Boko-Palashbari site showed maximum amplitude for the horizontal components of the 11th August 2009 earthquake which had the lowest magnitude of 5.6 (Mw) among the three and had the maximum epicentral distance of 400 km. The fundamental frequency for the Boko site for the horizontal components ranged from 0.66 to 1.89 Hz, which reflects the characteristics of a soil site with a soft consistency.

Site amplification for Guwahati-Central showed maximum amplitude for the horizontal components of the 3rd September 2009 earthquake which had a magnitude of 5.9 (Mw) and the highest focal depth of 100 km and an epicentral distance of 356 km. The fundamental frequency of Goalpara was found to be in the range of 1.75–3.44 Hz.

Site amplification for Goalpara showed maximum amplitude for the horizontal components of the lowest magnitude earthquake of 4.2 (Mw) at an epicentral distance of 80 km and focal depth of 10 km. The fundamental frequency of Goalpara was found to be in the range of 0.70–1.88 Hz.

Mittal et al. [33] observed that the vertical component also undergoes significant amplification in order 20. Similar observations of amplification of vertical component in the present study were also observed at Boko-Palashbari showing amplification of the vertical component of the order 7.42 which is almost similar to that observed for the NS-component of the same earthquake of 3rd September 2009. Guwahati-Central showed amplification of vertical component which exceeded that of the NS-component of the 3rd September 2009 earthquake by a value of 2, which is significant. In general, Guwahati-Central showed amplification of the vertical component of the maximum order 7.19. The Goalpara site also showed a significant amplification of the vertical component to the order 9.69. However, the amplification of the vertical component of the 3rd September 2009 earthquake showed similar values for the horizontal as well as the vertical components. Of all the earthquakes considered for the study, it is observed that the 3rd September 2009 earthquake which had a magnitude of 5.9 (Mw) and focal depth of 100 km produced higher amplification of the vertical component with values exceeding that of the horizontal component for Guwahati site.

Further, peak site amplification is given in Tables 14.9, 14.10 and 14.11 for the frequency ranges 0.1–1.0, 1.0–3.0 and 3.0–10.0 Hz for EW, NS and VT components respectively. These frequency ranges are considered based on the fact that the natural frequencies of multistoried buildings (3–10 floors) range between 1 and 3 Hz, whereas the natural frequencies for 1–3 storey buildings vary from 3 to 10 Hz. The frequency range 0.1–1.0 Hz is the natural frequency of more than 10 storey buildings

Table 14.9 Site amplification in frequency range for earthquake events (EW-component)

Earthquake event	Peak amplification in frequency range (EW component)								
	Boko-Palashbari (soil site)			Guwahati-Central (soil site)			Goalpara (soil site)		
	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz
11 Aug. 2009	13.60	10.15	1.71	3.67	6.07	3.54	8.45	7.67	1.44
03 Sep. 2009	8.94	7.35	2.64	2.54	12.16	5.14	6.90	4.81	1.55
21 Sep. 2009	9.67	4.23	2.48	2.98	3.22	3.32	13.77	10.47	4.10
29 Oct. 2009	**	**	**	**	**	**	11.32	11.30	3.17
29 Oct. 2009	**	**	**	**	**	**	33.74	25.38	8.44

Table 14.10 Site amplification in frequency range for earthquake events (NS-component)

Earthquake	Peak Amplification in frequency range (NS component)								
	Boko-Palashbari (soil site)			Guwahati-Central (soil site)			Goalpara (soil site)		
	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz
11 Aug 2009	18.59	11.33	2.40	2.48	5.34	3.57	10.46	10.91	2.18
03 Sep 2009	6.71	7.99	2.92	2.29	5.19	3.68	5.04	6.30	2.12
21 Sep 2009	9.56	3.50	3.44	2.61	2.67	2.80	17.00	10.95	4.51
29 Oct 2009	**	**	**	**	**	**	6.86	11.79	5.02
29 Oct 2009	**	**	**	**	**	**	27.14	25.79	16.60

Table 14.11 Site amplification in frequency range for earthquake events (VT-component)

Earthquake	Peak amplification in frequency range (VT component)								
	Boko-Palashbari (soil site)			Guwahati-Central (soil site)			Goalpara (soil site)		
	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz
11 Aug 2009	4.15	5.44	2.73	3.35	4.61	3.59	3.54	4.28	2.17
03 Sep 2009	1.99	7.47	3.04	1.82	7.21	3.91	2.71	6.24	1.98
21 Sep 2009	1.95	2.66	3.56	1.23	1.77	2.21	2.06	5.04	3.48
29 Oct 2009	**	**	**	**	**	**	8.02	4.32	3.98
29 Oct 2009	**	**	**	**	**	**	7.78	9.72	6.77

Table 14.12 Peak site amplification in frequency range

Site	Peak site amplification in frequency range			Peak spectral ratio (amplification)
	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	
Boko –Palashbari	18.59	11.33	3.56	18.59
Guwahati-Central	3.67	12.16	5.14	12.16
Goalpara	33.74	25.79	16.60	33.74

Table 14.13 SSR results

Site	Amplification parameters			
	Peak SSR (amplification)	PGA (PGA_{soil}/PGA_{rock})	PGV (PGA_{soil}/PGA_{rock})	PGD (PGA_{soil}/PGA_{rock})
Boko –Palashbari	18.59	1.56	1.50	2.78
Guwahati-Central	12.16	1.33	2.33	4.22
Goalpara	33.74	3.67	3.33	9.00

[52]. It can be seen in Table 14.12 that site amplification for Guwahati site is highest at the frequency range 1–3 Hz while for Boko-Palashbari and Goalpara regions the frequency range 0.1–1.0 Hz shows the highest site amplification thus governing the design considerations of their respective buildings categories respectively.

Additionally, Table 14.13 provides the various amplification parameters in terms of SSR, PGA, PGV, and PGD amplification respectively.

14.2.7 Summary

In this chapter an introduction to the SSR method is provided. The SSR method is further applied to the study region by employing recorded strong motions of Guwahati-Central, Boko-Palashbari and Goalpara sites. Site response in terms of various amplification parameters is provided in Table 14.13.

From the observations and results obtained a general conclusion may be assumed that earthquakes originating at a greater focal depth tend to amplify the vertical component. This contradicts the study by Lang [26] where it was stated that SSR does not depend on the focal depth, however, agreement with the statement that SSR does not depend on the magnitude or epicentral distance [20] is achieved in this study.

14.3 Horizontal to Vertical Spectral Ratio (HVSR) Analysis

14.3.1 Introduction

Horizontal to Vertical Spectral Ratio (HVSR) method which is a non-reference site technique was originally proposed by Nakamura [38] to interpret microtremors measurements and provides an alternative for the SSR method. Since this method requires no measurement at a reference site, this method overcomes the basic difficulty faced by the SSR technique which is the availability of a reference station. This method rests on the hypothesis that the vertical component of ground motion contains more information about the source of ground motion than does the horizontal components [29]. This technique, originally applied to microtremors [16, 26, 41], has also been applied to weak ground motion studies [12, 15, 29] and, in some cases, to strong ground motion studies [11, 29, 57].

Non-reference site technique or single station Horizontal to Vertical Spectral Ratio [29] follows the same idea of Nakamura technique, i.e., in the case of a soft layer that overlaps a generic stiff bedrock the incident vertical wave field does not undergo significant modification along with the whole source to site path with respect to the horizontal one. In this wave supposing a 1D configuration of the considered site, the simple ratio between the Fourier Amplitude Spectrum (FAS) of the horizontal component and FAS of the vertical component (both selected in the S-phase) allows us to detect the real response of the site (due to the body wave only).

The H/V method has been used for microzonation studies to predict site response to earthquake seismicity [25, 38, 48] and also as a method to estimate unconsolidated sediment thickness, map the bedrock surface, and infer fault locations (e.g., [9, 22, 42]).

A large number of experiments [14, 19, 29, 54] have shown that the HVSR procedure can be successfully applied for the identification of the fundamental frequency of sedimentary deposits. These observations were supported by several theoretical 1-D investigations [16, 26, 30, 60, 57]. Although the HVSR method has been able to identify the fundamental frequency of soil sites having relatively simple geology, the amplification factor of HVSR is highly debated [1, 2, 5, 32, 37, 50], and a comprehensive conclusion as to how the amplification can be explained using this method is yet to be defined. However, owing to its simplicity this method has been used for various microzonation studies [11] to have a preliminary assessment of the seismic vulnerability of a site due to seismic amplification.

14.3.2 HVSR Technique

The technique was originally proposed by Nakamura [38] to interpret microtremor measurements. The method states that microtremor energy consists mainly of Rayleigh waves and that site amplification is due to the presence of the surface of a soft layer overlying a half-space. Under these conditions, there are four components of ground motion involved: horizontal and vertical components in the half-space, and horizontal and vertical components at the surface. According to Nakamura, it is possible to estimate the amplitude effect of the source, A_S, by the ratio,

$$A_S = \frac{V_S}{V_B} \tag{14.2}$$

where V_S = FAS of the vertical component of motion at the surface,

V_B = FAS of the vertical component of motion at the half-space.

Therefore, the definition of an estimate of site effect of interest in earthquake engineering, S_E, can be given as the ratio.

$$S_E = \frac{H_S}{H_B} \tag{14.3}$$

where H_S = FAS of the horizontal component of motion at the surface, and,

H_B = FAS of the horizontal component of motion at the base of the soil layer.

Now, to compensate S_E by the effect of the source, a modified site effect function, S_M, is calculated, where.

$$S_M = \frac{S_E}{A_S} \tag{14.4}$$

Which is equivalent to.

$$S_M = \frac{\left(\frac{H_S}{V_S}\right)}{\left(\frac{H_B}{V_B}\right)} \tag{14.5}$$

Now, if it is accepted that the ratio H_B/V_B is equal to unity, the site effect function, corrected by the source term, may be written as.

$$S_M = \frac{H_S}{V_s} \tag{14.6}$$

The assumption that H_B/V_B is equal to unity (within a factor of 2, the usual uncertainty when using spectral ratios, e.g. Tucker and King [58], Tucker et al. [59] was verified by Nakamura experimentally, using microtremor measurements at various depths in the borehole.

Mucciarelli and Gallipolli [36] reported that the HVSR technique as is generally known is not a single entity but several variations of the HVSR method are present. In this study, the HVSR methodology of Microzonation of Guwahati City [11] has been adopted for the analysis in an attempt to supplement the site response study carried out earlier in the greater Guwahati region.

14.3.3 HVSR Methodology Adopted

In the present study, the $HVSR_{ij}(f_k)$ is computed at each j site for the ith event at the central frequency f_k from the root mean square average of the amplitude spectra [11] as.

$$HVSR_{ij}(f_k) = \frac{\frac{1}{\sqrt{2}}\sqrt{abs\left|H_{ij}(f_k)\right|_{NS}^{2} + abs\left|H_{ij}(f_k)\right|_{EW}^{2}}}{abs\left|V_{ij}(f_k)\right|}. \qquad (14.7)$$

where

$\left|H_{ij}(f_k)\right|_{NS}$ = FAS of horizontal NS component.

$\left|H_{ij}(f_k)\right|_{EW}$ = FAS of horizontal EW component.

$V_{ij}(f_k)$ = FAS of vertical component.

Finally, the event average $HVSR_{ij}^{ave}$ (f_k) [18] is computed at each site for the kth frequency to consider the contribution of all the seismic events recorded at that station.

Additionally, amplification of PGA, PGV and PGD is also determined by obtaining the ratio of the horizontal to the vertical component.

14.3.4 Selection of Records

Earthquake records (accelerogram) considered for HVSR analysis were selected only for those stations which were of importance with respect to the present study. The selected sites were Guwahati, Boko-Palashbari, and Goalpara. Out of the 30(thirty) earthquake events available, it was found that 15(fifteen) events (as given in Table 14.14) were responsible for triggering the selected 3 nos. of stations.

All the recordings had three components of motion, two orthogonal and one vertical. Of the selected 15(fifteen) events, the Boko-Palashbari station was triggered by 6(six) events, Guwahati by 13(thirteen) events and Goalpara by 9(nine) events. Thus, a total of 28(twenty-eight) three-component motions were recorded.

All the 74 (28 × 3) records were Fourier transformed and smoothed. The individual properties of each component of the recordings are indicated in Tables 14.15, 14.16 and 14.17 for the respective stations.

Table 14.14 Selected earthquake motions and epicentral distances

Earthquake event	Epicenter	Magnitude (Mw)	Focal depth (km)	Boko-Palashbari (soil site)	Guwahati Central (soil site)	Goalpara (soil site)
				25.976 N 91.230E	26.190 N 91.746E	26.152 N 90.627E
25 Apr. 2009	26.4 N 91.7E	4	10	66	24	**
11 Aug. 2009	24.4 N 94.8E	5.6	22	400	366	463
19 Aug. 2009	26.6 N 92.5E	4.9	20	152	88	**
30 Aug. 2009	25.4 N 94.8E	5.3	85	364	318	**
03 Sep. 2009	24.3 N 94.6E	5.9	100	388	356	450
21 Sep. 2009	27.3 N 91.5E	6.2	8	148	125	153
29 Oct. 2009	27.3 N 91.4E	5.2	5	**	**	147
29 Oct. 2009	26.6 N 90.0E	4.2	10	**	**	80
29 Dec. 2009	24.5 N 94.8E	5.5	80	**	318	426
31 Dec. 2009	27.3 N 91.4E	5.5	7	**	127	147
26 Feb. 2010	28.5 N 86.7E	5.4	28	**	561	468
12 Mar. 2010	23.0 N 94.5E	5.6	96	**	450	526
26 Jul. 2010	26.5 N 91.3E	4.1	31	**	56	**
11 Sep. 2010	25.9 N 90.2E	5	20	**	158	**
21 Nov. 2010	25.1 N 95.3E	5.8	80	**	377	**

14.3.5 Selection of Time Window

While determining HVSR the entire horizontal and vertical accelerogram are divided into a fixed number of time-windows and then the average HVSR of each time-window is considered for interpretation. Sairam et al. [52] used a time window of 10.50 s, starting from 0.50 s before S-wave phase arrival. This time-window was chosen to best contain most of the high-amplitude of the S-wave energy of earthquake

Table 14.15 Properties of recorded motions (Boko-Palashbari station)

Earthquake event	Maximum acceleration (g)			Maximum velocity (m/s)			Maximum displacement (m)			Duration (second)
	EW	NS	VT	EW	NS	VT	EW	NS	VT	
25 Apr. 2009	0.011	0.009	0.010	0.004	0.002	0.001	0.005	0.005	0.003	70.320
11 Aug. 2009	0.016	0.017	0.008	0.006	0.004	0.002	0.004	0.008	0.011	77.550
19 Aug. 2009	0.008	0.019	0.005	0.002	0.004	0.001	0.003	0.008	0.003	66.725
30 Aug. 2009	0.007	0.012	0.005	0.002	0.003	0.002	0.002	0.007	0.004	66.725
03 Sep. 2009	0.014	0.009	0.005	0.003	0.003	0.002	0.003	0.004	0.007	72.675
21 Sep. 2009	0.021	0.021	0.013	0.012	0.010	0.008	0.019	0.025	0.005	113.875

Table 14.16 Properties of recorded motions (Goalpara station)

Earthquake event	Maximum acceleration (g)			Maximum velocity (m/s)			Maximum displacement (m)			Duration (second)
	EW	NS	VT	EW	NS	VT	EW	NS	VT	
11 Aug. 2009	0.016	0.013	0.008	0.005	0.005	0.004	0.005	0.003	0.004	73.965
03 Sep. 2009	0.006	0.006	0.004	0.002	0.002	0.002	0.005	0.003	0.007	66.620
21 Sep. 2009	0.042	0.041	0.024	0.033	0.030	0.013	0.012	0.022	0.099	113.830
29 Oct. 2009	0.015	0.011	0.007	0.006	0.006	0.004	0.003	0.019	0.036	75.405
29 Oct. 2009	0.015	0.022	0.011	0.004	0.007	0.003	0.002	0.007	0.036	68.415
29 Dec. 2009	0.008	0.010	0.006	0.003	0.004	0.002	0.002	0.006	0.020	70.055
31 Dec. 2009	0.010	0.009	0.009	0.006	0.005	0.004	0.013	0.013	0.032	82.350
26 Feb. 2010	0.005	0.005	0.003	0.002	0.002	0.002	0.004	0.017	0.016	89.900
12 Mar. 2010	0.004	0.005	0.003	0.02	0.002	0.003	0.008	0.019	0.056	95.660

Table 14.17 Properties of recorded motions (Guwahati-Central station)

Earthquake event	Maximum acceleration (g)			Maximum velocity (m/s)			Maximum displacement (m)			Duration (second)
	EW	NS	VT	EW	NS	VT	EW	NS	VT	
25 Apr. 2009	0.013	0.014	0.015	0.002	0.002	0.002	0.003	0.007	0.004	66.185
11 Aug. 2009	0.013	0.011	0.013	0.006	0.004	0.04	0.003	0.004	0.001	73.040
19 Aug. 2009	0.020	0.030	0.021	0.006	0.010	0.005	0.014	0.002	0.003	71.660
30 Aug. 2009	0.015	0.009	0.010	0.005	0.003	0.003	0.004	0.004	0.004	68.450
03 Sep. 2009	0.012	0.007	0.007	0.007	0.003	0.003	0.004	0.006	0.004	71.065
21 Sep. 2009	0.028	0.024	0.013	0.011	0.009	0.006	0.016	0.038	0.021	107.280
29 Dec. 2009	0.011	0.005	0.009	0.004	0.002	0.003	0.003	0.014	0.008	80.765
31 Dec. 2009	0.010	0.007	0.006	0.004	0.002	0.002	0.015	0.006	0.005	80.470
26 Feb. 2010	0.003	0.002	0.001	0.001	0.001	0.001	0.004	0.008	0.010	82.785
12 Mar. 2010	0.006	0.005	0.005	0.002	0.003	0.001	0.015	0.009	0.004	91.615
26 Jul. 2010	0.022	0.016	0.017	0.005	0.004	0.004	0.002	0.006	0.010	94.720
11 Sep. 2010	0.004	0.005	0.003	0.002	0.002	0.001	0.008	0.004	0.003	90.895
21 Nov. 2010	0.009	0.009	0.007	0.005	0.005	0.002	0.005	0.027	0.012	112.435

records. In Microzonation of Guwahati city [11] a time window of 5.0-s duration starting from the onset of S-wave arrival and containing the maximum of S-wave arrival was considered for analysis. Bonilla et al. [4] stated that using a longer time results in better spectral resolution. Borcherdt et al. [6] also mentioned that the most stable estimate of the site response is generally provided by spectra computed from the entire seismogram as opposed to some portion.

However, it was also stated by Bonilla et al. [4] that, using longer time windows will result in the inclusion of scattered and reflected energy and also the effect of surface waves in the spectra. Bonilla et al. [4] and Field and Jacob [18] found no statistical variation in site response computed with spectra of different time windows. However, Castro et al. [7] suggested that S-waves could be contaminated at a larger epicentral distance, which demands variable time windows for the estimation of the HVSR using S-waves.

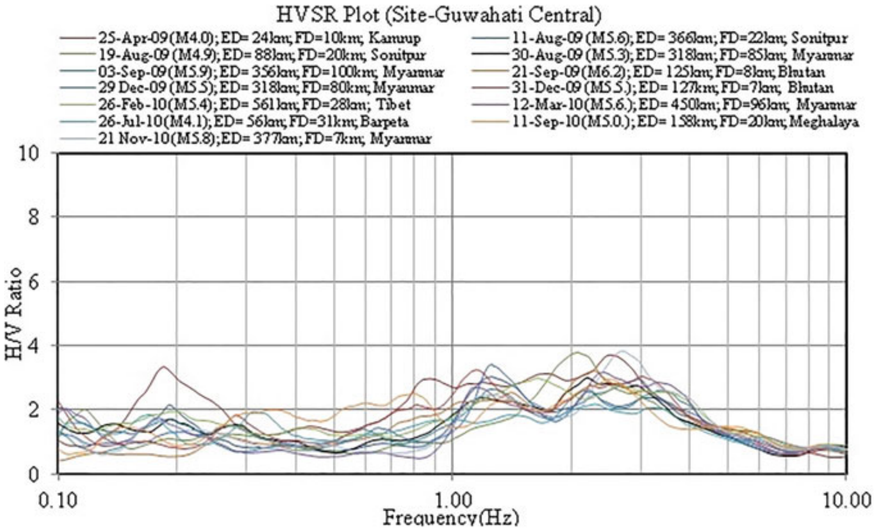

Fig. 14.12 HVSR plot of earthquake recordings of Guwahati-Central station

In this study, the entire accelerogram is used for analysis considering it as a single-window in order to obtain a better spectral resolution and stable estimate of site response.

14.3.6 Analysis Results

All the records considered were analyzed using spreadsheets developed for the purpose. The records were analyzed for the usual frequency range of 0.1–10.0 Hz, which is the frequency range of practical interest in engineering [53]. The HVSR versus Frequency data were plotted on a semi-log plot. Figures 14.12, 14.13 and 14.14 show the HVSR plots for Guwahati-Central, Boko-Palashbari and Goalpara respectively.

14.3.7 Site Amplification from HVSR of Strong Motion

Site Amplification from HVSR has often been a debated topic with various quarters putting forth various reasoning regarding its adequacy in determining site amplification. Since the application of HVSR to earthquake motions, various scholars [26, 28, 39] have used the term amplification to define the site effects of the HVSR method. Lang [26] studied the qualitative evaluation of different empirical methods on instrumented seismic data as per scientific literature and commented that the HVSR method

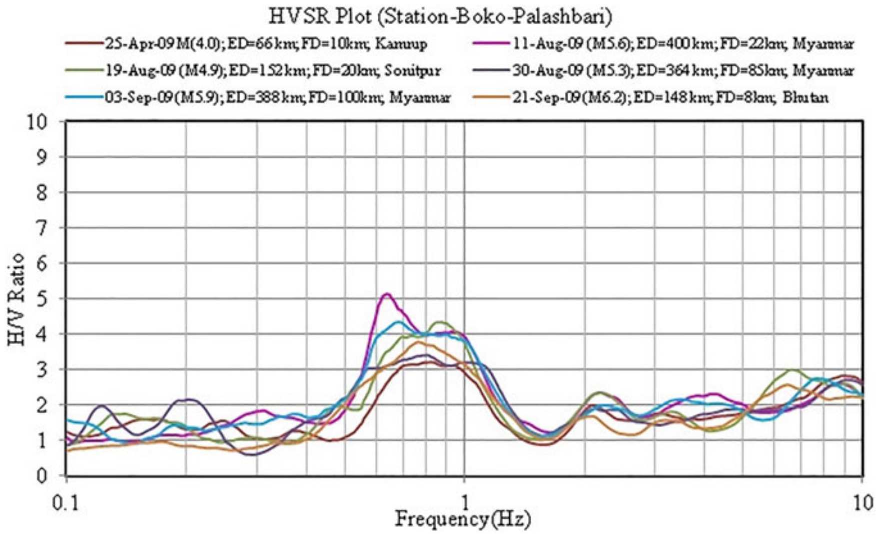

Fig. 14.13 HVSR plot of earthquake recordings of Boko-Palashbari station

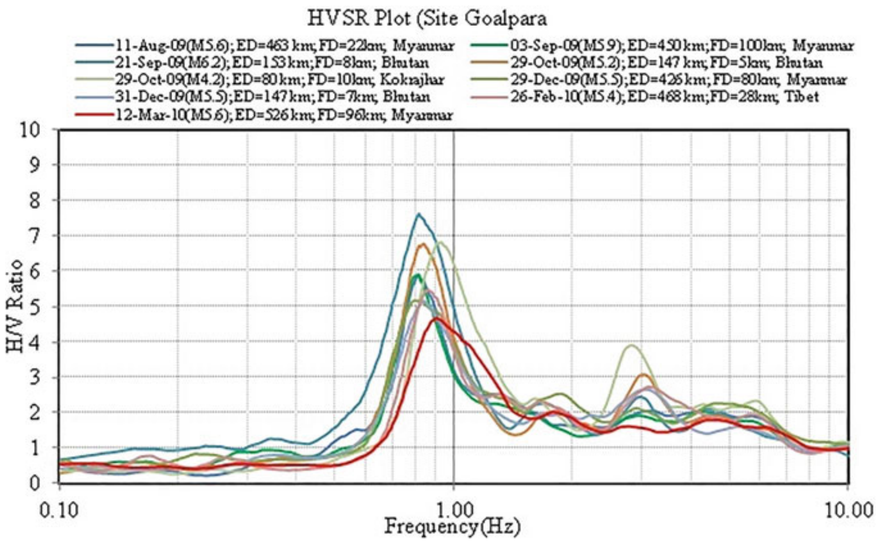

Fig. 14.14 HVSR plot of earthquake recordings of Goalpara station

when applied to earthquake data provided the predominant site frequency (Fundamental Frequency) and level of site amplification with high accuracy. It is however not quantified, as to how and to what degree the accuracy was applicable. Following Lang [26] an attempt has been made in this study to define the site amplification.

Generally, site amplification from HVSR is defined as the maximum amplitude of the HVSR curve obtained. The results obtained from this study, where three sites have been evaluated are tabulated in Table 14.18.

The HVSR curve from 13(thirteen) earthquake events used in the case of Guwahati site produced curves that are consistent in shape and have shown site amplification with a minimum of 2.16 and a maximum of 3.81. Goalpara site showed site amplification within the range of 4.68–7.60 for the 9 earthquake events considered for the site, while the Boko-Palashbari site indicated site amplification in the range of 3.21–5.15 for the 6 earthquake events considered.

14.3.8 Determination of Fundamental Frequency

The Fundamental Frequency (FF) is defined as the frequency at which the HVSR curve has a peak value, or, in other terms, it is the frequency (for a particular earthquake) or frequency range (for a set of earthquakes) at which the amplitude ratio value of the curve is maximum and is a characteristic of a site. Nakamura [37] suggested that this peak value ratio is at the S-waves resonance frequency of the layered structure and the location of the peak does not depend on the source characteristics. This suggestion is further strengthened by Lachet and Bard [25], who reported that the H/V spectral ratios obtained for different source characteristics clearly exhibit a peak whose position was constant regardless of the source type and the source function. Lachet and Bard [25] further based on their study on the peak frequency of HVSR for various geological structures suggested that H/V spectra were a reliable indication of the fundamental resonance frequency of a horizontally layered structure which has been asserted by many authors [27, 47]. The fundamental frequencies as obtained in this study for the three sites are indicated in Table 14.18.

The Fundamental Frequency range of Guwahati site as obtained from the HVSR curves is in the frequency band of 1.14–2.69 Hz, for the Goalpara site it is 0.80 Hz to 0.93 Hz while for Boko-Palashbari it is 0.63–0.82 Hz.

From Fig. 14.12, multiple HVSR peaks in Guwahati as compared to Boko-Palashbari and Goalpara are observed which may be attributed to Rayleigh wave ellipticity for the site with high-impedance contrasts at two very different scales. This has resulted in the fundamental frequency band being wider as compared to Boko-Palashbari and Goalpara respectively. From Figs. 14.13 and 14.14, for Boko-Palashbari and Goalpara respectively, where the bedrock depth was almost at depth $> = 100$ m clear peaks were identifiable.

14.3.9 Determination of Bedrock Depth

The depth of bedrock is related to the fundamental frequency by the relation [53].

Table 14.18 Fundamental frequency (FF) and corresponding amplification (Am)

Earthquake event	Epicenter	Magnitude (Mw)	Focal depth (km)	Boko-Palashbari		Guwahati Central		Goalpara	
				FF (Hz)	Am	FF (Hz)	Am	FF (Hz)	Am
25 Apr. 2009	26.4 N 91.7E	4	10	0.82	3.21	2.50	3.69	**	**
11 Aug. 2009	24.4 N 94.8E	5.6	22	0.63	5.15	1.25	3.02	0.81	5.89
19 Aug. 2009	26.6 N 92.5E	4.9	20	0.85	4.32	2.06	3.80	**	**
30 Aug. 2009	25.4 N 94.8E	5.3	85	0.79	3.42	2.20	3.01	**	**
03 Sep. 2009	24.3 N 94.6E	5.9	100	0.68	4.33	1.25	2.65	0.81	5.90
21 Sep. 2009	27.3 N 91.5E	6.2	8	0.76	3.78	2.26	3.22	0.81	7.60
29 Oct. 2009	27.3 N 91.4E	5.2	5	**	**	**	**	0.84	6.78
29 Oct. 2009	26.6 N 90.0E	4.2	10	**	**	**	**	0.93	6.80
29 Dec. 2009	24.5 N 94.8E	5.5	80	**	**	1.26	3.42	0.80	5.18
31 Dec. 2009	27.3 N 91.4E	5.5	7	**	**	1.14	3.23	0.84	5.16
26 Feb. 2010	28.5 N 86.7E	5.4	28	**	**	1.63	3.00	0.85	5.47
12 Mar. 2010	23.0 N 94.5E	5.6	96	**	**	2.39	3.16	0.90	4.68
26 Jul. 2010	26.5 N 91.3E	4.1	31	**	**	2.30	2.16	**	**
11 Sep. 2010	25.9 N 90.2E	5	20	**	**	2.50	2.95	**	**
21 Nov. 2010	25.1 N 95.3E	5.8	80	**	**	2.69	3.81	**	**

** not analyzed

Table 14.19 Depth of bedrock

Site	Fundamental Frequency (FF) band (Hz)	Shear wave velocity range, versus (m/s)	Depth to bedrock (m)
Boko–Palashbari	0.80–0.93	200–375	53.76–117.18
Guwahati-Central	1.14–2.69	200–375	18.59–2.24
Goalpara	0.63–0.82	200–375	60.98–148.81

$$FF = \frac{V_s}{4H} \tag{14.8}$$

where FF = Fundamental Frequency

V_s = Shear wave velocity

H = Depth to bedrock

Using the relation the bedrock to for all the three sites is determined. The Shear wave velocities are adopted from Mittal et al. [33], where it is classified that Guwahati, Boko-Palashbari, and Goalpara sites fall under the site class C (alluvium) and had a shear wave velocity range of 200–375 m/s. However it must be mentioned that the shear wave velocity as mentioned by Mittal et al. [33] is for the top 30 m of the soil strata, and its applicability for the calculation of the depth to bedrock is questionable. Despite this fact, it could be assumed that in the case where the shear wave velocity profile is not available, a good preliminary estimate of the bedrock depth could be made from the above assumption. The calculations of depth to bedrock are summarized in Table 14.19.

14.3.10 Observations and Discussions

In this chapter, an attempt to determine site transfer function, fundamental frequency and depth of bedrock was carried out. From the results obtained for Guwahati station which is situated in greater Guwahati and the other two stations, which lie in the study region, it can be seen that as we travel towards the western part of Guwahati the fundamental frequency range shifts to the lower range indicating trapping of seismic energy by the soft alluvial layer. Also, it is seen that the amplification ratio increases significantly (from 2.16 to 7.60) as we move towards the western part of the Guwahati region. This perhaps explains the reason why site response analysis should be taken up for the western part of Guwahati. It is observed that the peak amplification in Guwahati-Central is observed to be 3.81. Nath et al. [39] reported a peak amplification value of 6.5 for the same area. The deviation of results can be attributed to various reasons. For example, first of all, the derivation of the present peak amplification factor is based on the evaluation of 13(thirteen) earthquake strong-motion recordings, while that of Nath et al. [39] is based on 2(two) recordings. Furthermore, Nath

Table 14.20 Site amplification in frequency range for earthquake events

Earthquake event	Peak amplification in frequency range (Hz)								
	Boko-Palashbari			Guwahati-Central			Goalpara		
	0.1–1.0	1.0–3.0	3.0–10.0	0.1–1.0	1.0–3.0	3.0–10.0	0.1–1.0	1.0–3.0	3.0–10.0
25 Apr. 2009	3.21	2.90	2.82	3.32	3.70	2.87	**	**	**
11 Aug. 2009	5.15	3.92	2.61	2.13	3.02	2.37	5.89	3.14	2.12
19 Aug. 2009	4.32	3.70	2.98	2.03	3.80	2.44	**	**	**
30 Aug. 2009	3.42	3.21	2.71	1.88	3.01	2.71	**	**	**
03 Sep. 2009	4.33	3.81	2.76	1.72	2.65	2.62	5.90	3.04	2.05
21 Sep. 2009	3.78	3.13	2.57	2.18	3.22	2.60	7.60	4.84	2.42
29 Oct. 2009	**	**	**	**	**	**	6.78	4.04	3.08
29 Oct. 2009	**	**	**	**	**	**	6.80	6.11	3.61
29 Dec. 2009	**	**	**	1.51	3.42	2.93	5.18	3.18	2.26
31 Dec. 2009	**	**	**	2.49	3.23	3.02	5.16	3.73	2.66
26 Feb. 2010	**	**	**	1.95	3.00	2.62	5.47	3.66	2.72
12 Mar. 2010	**	**	**	2.04	3.16	2.85	4.68	4.28	1.69
26 Jul. 2010	**	**	**	1.94	2.16	2.06	**	**	**
11 Sep. 2010	**	**	**	2.52	2.95	2.26	**	**	**
21 Nov. 2010	**	**	**	1.64	3.81	3.39	**	**	**

et al. [39] adopted a cubic spline interpolation smoothing technique, while in this study a log-triangle smoothing procedure as developed by David Boore and adapted by DEEPSOIL [21] is applied. Additionally, Numerical instability as reported by Kausel and Assimiki [23] could be another reason for the varying results. However, considering all these uncertainties, it can be said that the method has predicted fairly reasonable results of peak amplification in the case of Nath et al. [39] and this study (Tables 14.20 and 14.21).

Further site amplification ranges are given in 20, 21 and 22 for the frequency ranges 0.1–1.0 Hz, 1.0–3.0 Hz and 3.0–10.0 Hz. These frequency ranges are considered based on the fact that the natural frequencies of multistoried buildings (3–10 floors)

Table 14.21 Site amplification range in frequency range

Site	Amplification range in frequency range			Peak amplification
	0.1–1.0 Hz	1.0–3.0 Hz	3.0–10.0 Hz	
Boko–Palashbari	3.21–5.15	2.90–3.92	2.57–2.98	5.15
Guwahati-Central	1.51–3.32	2.16–3.81	3.06–3.39	3.81
Goalpara	4.68–7.60	3.04–6.11	1.69–3.69	7.60

range between 1 and 3 Hz, whereas the natural frequencies for 1–3 storey buildings vary from 3 to 10 Hz. The frequency range 0.1–1.0 Hz is the natural frequency of more than 10 storey buildings. It can be easily seen that the frequency range which will govern the design of buildings in Boko-Palashbari and Goalpara is 0.1–1.0 Hz, while for Guwahati it is critical that buildings falling in the frequency range of 1.0–3.0 Hz are likely to be affected more.

Additionally, Table 14.22 provides the various amplification parameters in terms of HVSR, PGA, PGV, and PGD amplification respectively.

A comparison of the results of SSR (Table 14.13) and that of HVSR (Table 14.18) shows that the FAS amplification is of greater magnitude in the case of SSR as compared to HVSR. However, PGA, PGV and PGD amplification can be considered broadly to be within the same range.

14.3.11 Summary

In this chapter, an introduction to the HVSR analysis of strong-motion is provided. The HVSR analysis of three soil sites is carried out, and the results are presented. Also, the determination of FF and bedrock depth is attempted from the results of the HVSR analysis. Further, the results are provided in the form of peak HVSR ratio, PGA, PGV and PGD amplification respectively. Lermo and Chavez-Garcia [29], Mucciarelli and Gallipolli [35] etc. are a few of the studies which have reported that the HVSR method is known to be able to identify the fundamental frequency of a site under observation. It has been found in this study that the fundamental frequency range of the Boko-Palashbari site is 0.80–0.93 Hz,Guwahati-Central is 1.14–2.69 Hz and that of Goalpara is 0.63–0.82 Hz. DST [11] has reported a fundamental frequency of 1.5–2.5 Hz which compares well with the results of the present study. Further, basement depth obtained from the HVSR method implies that Boko-Palashbari, Guwahati Central and Goalpara may have bedrock at a depth ranging from 53.76–117.18 m, 18.59–82.24 m and 60.98–148.81 m respectively. This range of values of bedrock depth compares well with that of the bedrock depth of <100 m for Guwahati-Central and >100 m for Boko Palashbari and Goalpara respectively. Further, the site amplification of the western Guwahati region as per the HVSR method can be ranged between 5.1. and 7.60.

Table 14.22 HVSR results

Site	Amplification parameters			
	Peak HVSR (amplification)	PGA ($PGA_{EW, NS}/PGA_{VT}$)	PGV ($PGV_{EW, NS}/PGV_{VT}$)	PGD ($PGD_{EW, NS}/PGD_{VT}$)
Boko–Palashbari	5.15	2.70	3.00	4.40
Guwahati-Central	3.81	2.50	2.50	2.50
Goalpara	7.60	1.86	3.67	6.56

14.4 Comparision of Results

Several studies have attempted to compare the results of site response obtained by various methods. Field and Jacob [18], Theodulidis et al. [56], Lachet et al. [25], Riepl et al. [47], Nath et al. [39], Mucciarelli et al. [36], Ergin et al. [13], Molnar et al. [34], Pilz et al. [43] are a few studies, where comparison of site response analysis methods has been carried out in the past.

The results obtained by employing the SSR and HVSR methods in this study are provided in terms of FAS amplification only and can be seen in Table 14.23. A simple observation of the results shows that the FAS amplification is highest in the case of SSR as compared to HVSR.

The amplification as observed consisted of a higher value for SSR as compared to HVSR for all the site, which is in agreement with the observations reported by several authors [18, 25, 54, 56] that HVSR provides a lower value of amplification as compared to SSR.

From the results of HVSR and SSR as given in Table 14.23, it can be observed that the ratio of SSR to that of HVSR for Boko-Palashbari is 3.61, for Guwahati Central is 3.19 and for Goalpara is 4.44, which is within the range as observed and reported by Theodulidis et al. [56]. Theodulidis et al. [56] reported that the most prominent difference between the HVSR and the SSR was in their absolute levels, with the latter being 2 (two) to about 6 (six) times higher. The reason for systematically lower amplitude values of HVSR as compared to SSR could be attributed to the relative enrichment of the vertical component as reported by Raptakis et al. [45].

In the study, it was also attempted to determine the fundamental frequency of the soil sites from the waveform analysis. The term "*fundamental frequency*" denotes the frequency at which the Fourier amplitude ratio is maximum for the concerned earthquake event and is used in many studies (e.g., [10, 25, 54]. It also has to be mentioned that various authors have used various terms while defining the frequency with respect to the maximum amplitude. For example Taber [54] has termed it as "*predominant frequency*", Field and Jacob [16] reported it to be the "*fundamental resonant frequency*", Lachet and Bard [25] termed it as "resonance frequency".

However, soil is a highly complex material and as seen from the results provided in Table 14.18, has provided various fundamental frequencies for various earthquake events but within a certain frequency range. As such, the fundamental frequency is best defined in the form of a frequency range termed as "*fundamental frequency band*". Therefore, in this study, a range of frequency is provided which is the frequency band between which the soil site understudy has shown maximum amplification.It can be observed from Table 14.24 that Boko-Palashbari has a fundamental

Table 14.23 Peak amplification from SSR and HVSR

Site	SSR	HVSR
Boko-Palashbari	18.59	5.15
Guwahati-Central	12.16	3.81
Goalpara	33.74	7.6

Table 14.24 Fundamental frequency band

Site	Fundamental Frequency (FF) band (Hz) HVSR	Fundamental Frequency (FF) band (Hz) SSR
Boko–Palashbari	0.80–0.93	0.66–1.89
Guwahati-Central	1.14–2.69	1.69–3.49
Goalpara	0.63–0.82	0.70–1.88

frequency band of 0.80–0.93 Hz obtained by the HVSR method while for the SSR method it is 0.66–1.89 Hz. For Guwahati-Central, HVSR provided a range of 1.14–2.69 Hz while SSR provided a range of 1.69–3.49 Hz. For Goalpara the HVSR reported a frequency range of 0.63–0.82 Hz and SSR reported a range of 0.70–1.88 Hz. It is clearly identified that the fundamental frequency ranges as provided by both the methods compared well, which are in agreement with Pilz et al. [43], Lachet et al. [25], Taber [54], Ergin et al. [13]. Additionally, it can also be seen that the fundamental frequency band, as provided by the SSR method is comparatively wide, when compared to the HVSR method. This observation is in agreement with the observation made by Ibs-Vohn Seht and Wolhenderg that the SSR method is less reliable as compared to HVSR in determining the fundamental frequency of the subsoil. In this study, the fundamental frequency as provided by the HVSR method is considered to be representative of the sites investigated.

14.5 Summary

In this chapter a discussion on the results of the various site response analysis methods employed in this study viz. SSR and HVSR is presented. During the discussion, it is seen that the SSR results were consistently higher than that of the HVSR analysis. Pursuant to the statements made by Beresnev and Wen [3] and Rodriguez and Midorikawa [48] it can be asserted that the SSR method provides a more accurate estimate of site amplification as compared to HVSR. Based on the observations of Beresnev and Wen [3], Rodriguez and Midorikawa [48] and Mucciarelli et al. [36] in their study, it can be summarised that, for the Western Guwahati region, SSR provides a more reliable estimate of the site response.

This finding of this study is also complimentary to the findings of Field and Jacob [18] that, if the SSR estimates are taken as the most reliable, then the HVSR method under predicts the site response. The results provided by HVSR are less than that of the SSR results by a factor of 2–4.

SSR and HVSR analysis is carried out in the frequency domain and does not provide a seismic time history, which is required for dynamic analysis of structures. Further, SSR and HVSR analysis is dependent on the availability of recorded ground motions.

The Northeast part of India falls under seismic Zone V (IS:1893–2002), the highest seismic activity zone. However, there is a lack of sufficient dense seismic arrays in the region to record the seismic activity. Irrespective of the availability of the seismic records, studies related to possible seismic hazards have to be carried out in the region.

References

1. Al Yuncha Z, Luzon F (2000) On the horizontal-to-vertical spectral ratio in sedimentary basins. Bull Seismol Soc Am 90:1101–1106
2. Bard P-Y (1998) Microtremor measurements: a tool for site effect estimation? Proceeding of the second international symposium on the effects of surface geology on seismic motion, Yokohama, Japan 3:1251–1279
3. Beresnev IA, Wen KL (1996) The accuracy of soil estimates using soil-to-rock spectral ratios. Bull Seismol Soc Am 86(2):519–523
4. 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 S-wave, coda, and H/V methods. Bull Seismol Soc Am 87(3):710–730
5. Bour M, Fouissac D, Dominique P, Martin C (1998) On the use of microtremor recordings in seismic microzonation. Soil Dyn Earthq Eng 17:465–474
6. Borcherdt RD (1970) Effects of local geology on ground motion near San Francisco Bay. Bull Seismol Soc Am 60:29–61
7. Castro RR, Mucciarelli M, Pacor F, Petrungaro C (1997) S-Wave site response estimates using horizontal-to-vertical spectral ratios. Bull Seismol Soc Am 87:256–260
8. Chavez-Garcia FJ, Cuenca J (1998) Site effects and microzonation in acapulco. Earthq Spectra 14(1):75–94
9. Delgado J, Lopez CC, Estevez A, Giner J, Cuenca A, Molina S (2000) Mapping soft soils in the Segura river valley (SE Spain): a case of study of microtremors as an exploration tool. J Appl Geophys 45:19–32
10. Dimitriu P, Kalogeras I, Theodulidis N (1999) Evidence of nonlinear site response in horizontal-to-vertical spectral ratio from near-field earthquakes. Soil Dyn Earthq Eng 18:423–435
11. DST (2008) Report on seismic microzonation of Guwahati region. http://www.am.tron.in/microzonation
12. Duval AM (1994) Determination de la reponse d'un site anx seismes al'aide du bruit de fond: evaluation experimentale, PhD thesis, Universite Paris 6, 265
13. Ergin M, Ozalaybey S, Aktar M, Yalcin MN (2004) Site amplification at Avcilar, Istanbul. Tectonophysics 391:335–346
14. Fah D (1997) Microzonation of the city of Basel. J Seismolog 1:87–102
15. Field EH (1994) Earthquake site response estimation, PhD thesis, Columbia University, New York, p 303
16. Field EH, Jacob KH (1993) The theoretical response of sedimentary layers to ambient seismic noise. Geophys Res Lett 20:2925–2928
17. Field EH, Jacob KH, Hough SE (1992) Earthquake site response estimation: a weak-motion case study. Bull Seismol Soc Am 82:2283–2307
18. Field EH, Jacob KH (1995) A comparison and test of various site response estimation techniques, including three that are not reference-site dependent. Bull Seismol Soc Am 85(4):1127–1143
19. Gitterman Y, Zaslavsky Y, Shapira A, Shtivelman V (1996) Empirical site response evaluations: case studies in Israel. Soil Dyn Earthquake Eng 15:447–463

20. Gutierrez C, Singh K (1992) A site effect study in Acapulco, Guerrero, Mexico: comparison of results from strong-motion and microtremor data. Bull Seismol Soc Am 82(2):642–659. https://doi.org/10.1785/BSSA0820020642
21. Hashash YMA, Musgrove MI, Harmon JA, Groholski DR, Phillips CA, Park D (2015) DEEPSOIL 6.1, User manual, p 135
22. Ibs- Von Seth M, Wohlenberg J (1999) Microtremor measurements used to map thickness of soft sediments. Bull Seismol Soc Am 89:250–259
23. Kausel E, Assimaki D (2002) Seismic simulation of inelastic soils via frequency-dependent moduli and damping. J Eng Mech 128(1):34–47
24. Konno K, Ohmachi T (1998) Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components. Bull Seismol Soc Am 88(1):228–241
25. Lachet C, Hatzfeld D, Bard PY, Theodilidis N, Papaioannou C, Savvaidia A (1996) Site effects and microzonation in the city of Thessaloniki (Greece), comparison of different approaches. Bull Seismol Soc Am 86(6):1692–1703
26. Lang DH (2004) Damage potential of seismic ground motion considering local site effects, PhD thesis, Bauhaus-University Weimar
27. Lebrun (1997) Les effects de site: etude experimentale et simulation de trios configurations. In: These de doctorat del Úniversite J. Fourier de Grenoble, France, p 208
28. Lermo J, Chavez-Garcia EJ (1993) Site effect evaluation using spectral ratios with only one station. Bull Seismol Soc Am 83:1574–1594
29. Lermo J, Chavez Garcia FJ (1994) Site effect evaluation at Mexico City: dominant period and relative amplification from strong motion and microtremor records. Soil Dyn Earthq Eng 13:413–423
30. Lermo J, Chávez-García FJ (1994) Are microtremors useful in site response evaluation? Bull Seismol Soc Am 84(5):1350–1364
31. Maresca R, Castellano M, De Matteis R, Saccorotti G, Vaccariello P (2003) Local site effects in the town of Benevento (Italy) from noise measurements. Pure Appl Geophys 160:1745–1764
32. Mittal H, Kamal K, Kumar A, Singh SK (2013) Estimation of site effects in Delhi using standard spectral ratio. Soil Dyn Earthq Eng 50:53–61
33. Mittal H, Kumar A, Ramhmachuani R (2012) Indian national strong motion instrumentation network and site characterization of its stations. Int J Geosci 3:1151–1167
34. Molnar S, Cassify JF, Dosso SE (2004) Site response studies in Victoria, B.C., Analysis of Mw 6.8 nisqually earthquake recordings and shake modelling. In: Proceedings of the 13th world conference on earthquake engineering, Vancouver, B.C., August 1–6, 2004, paper No 2121
35. Mucciarelli M, Gallipoli MR (2001) A critical review of 10 years of microtremor HVSR technique. Bollettino Di Geofisica Teorica Ed Applicata. 42(3–4):255–266
36. Mucciarelli M, Gallipoli MR, Arcieri M (2003) The stability of the horizontal to vertical spectral ratio of triggered noise and earthquake recordings. Bull Seismol Soc Am 93(3):1407–1412
37. Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface. Quarterly Reports of the Railway Technical Research Institute Tokyo 30:25–33
38. Nath SK, Raj A, Sharma J, Thingbaijan KKS, Kumar A, Nandy DR, Yadav MK, Dasgupta S, Majumdar K, Kayal JR, Shukla AK, Deb SK, Pathak J, Hazarika PJ, Paul DK, Bansal BK (2008) Site amplification, Qs, and source parameterization in Guwahati region from seismic and geotechnical analysis. Seismol Res Lett 79(4):526–539
39. Nath SK, Sengupta P, Srivastav SK, Bhattacharya SN, Dattatrayam RS, Prakash R, Gupta HV (2003) Estimation of S-wave site response in and around Delhi region from weak motion data. Proc Indian Acad Sci (Earth Planet Sci) 112(3):441–462
40. Ohmachi T, Nakamura Y, Toshinawa T (1991) Ground motion characteristics of the San Francisco bay area detected by microtremor measurements. Second international conference on recent advances in geotechnical earthquake engineering and soil dynamics, St Louis 2:1643–1648
41. Parolai S, Bormann P, Mikereit C (2002) "New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for the Cologne area (Germany). Bull Seismol Soc Am 92:2521–2527

42. Parolai S (2012) Investigation of site response in urban area using earthquake data and seismic noise. https://doi.org/10.2312/GFZ.NMSOP-2_ch14. www.gfzpublic.gfz-potsdam.de
43. Pilz M, Parolai S, Leyton F, Campos J, Zschau J (2009) A comparison of site response techniques using earthquake data and ambient seismic noise analysis in the large urban areas of Santiago de Chile. Geophys J Int 178(2):713–728. https://doi.org/10.1111/j.1365-246X.2009.04195.x,2009
44. Pitilakis K (2004) "Site Effects", Recent advances in earthquake geotechnical engineering and microzonation, Ansal A (ed). Kluwer Academic Publishers, Springer Science, Netherlands, pp 139–197
45. Raptakis D, Theodulidis N, Pitilakis K (1998) Data analysis of the Euroseistest strong motion array in Volvi (Greece): Standard and horizontal-to-vertical spectral ratio techniques. Earthq Spectra 14(1):203–223
46. Rial JA, Saltzman NG, Ling H (1992) Earthquake-induced resonance in sedimentary basins. Am Sci 80:566–578
47. Riepl J, Bard P-Y, Hatzfeld D, Papaioannou C, Nechstein N (1998) Detailed evaluation of site-response estimation methods across and along the sedimentary valley of Volvi (Euroseistest). Bull Seismol Soc Am 88(2):488–502
48. Rodriguez HS, Midorikawa S (2003) Comparison of spectral ratio techniques for estimation of site effects using microtremor data and earthquake motions recorded at the surface and in boreholes. Earthquake Eng Ans Struct Dyn 32:1691–1714
49. Safak E (1991) Problems with using spectral ratios to estimate site amplification. In: Proceedings of the fourth international conference on seismic zonation, vol. II. EERI, Oakland, pp 277–284
50. Sairam B, Rastogi BK, Aggarwal S, Chauhan M, Bhonde U (2011) Seismic site characterization using Vs30 and site amplification in Gandhinagar region, Gujarat, India. Curr Sci 100(5):754–761
51. Salazar W, Brown L, Mannette G (2013) Surface soil effects studies based on H/V ratios of microtremors at Kingston metropolitan Area, Jamaica. J Civil Eng Architect 7(10) (Serial No. 71):1301–1322
52. Seekins LC, Wennerberg L, Margehereti L, Liu H-P (1996) Site amplification at five locations in San Fransico, California: a comparison of S waves, codas, and microtremors. Bull Seismol Soc Am 86:627–635
53. Steidl JH, Tumarkin AG, Archuleta RJ (1996) What is a reference site? Bull Seismol Soc Am 86:1733–1748
54. Taber JJ (2000) Comparison of site response determination techniques in the Wellington region, New Zealand. In: Proceedings of the 12th world conference on earthquake engineering, New Zealand
55. Theodulidis N, Bard P-Y (1995) Horizontal to vertical spectral ratio and geological conditions: an analysis of strong motion data from Greece and Taiwan (SMART-I). Soil Dyn Earthquake Eng 14:177–197
56. Theodulidis N, Bard PY, Archuleta R, Bouchon M (1996) Horizontal-to-vertical spectral ratio and geologic conditions: the case of garner valley downhole array in Southern California. Bull Seismol Soc Am 86(2):306–319
57. Tokeshi JC, Sugimura Y (1998) On the estimation of the natural period of the ground using simulated microtremors. In: Proceedings of the second international symposium on the effects of surface geology on seismic motion, Yokohama, Japan, vol 2, pp 651–664
58. Tucker BE, King JL (1984) Dependence of sediment-filled valley response on input amplitude and valley properties. Bull Seismol Soc Am 74:153–165
59. Tucker BE, King JL, Hatzfeld D, Nersesov IL (1984) Observations of hard-rock site effects. Bull Seismol Soc Am 74:121–136
60. Wakamatsu K, Yasui Y (1996) Possibility of estimation for amplification characteristics of soil deposits based on ratio of horizontal to vertical spectra of microtremors. In: Proceedings of the 11th world conference on earthquake engineering. Acapulco, Mexico