Estimation of S-wave site response in and around Delhi region from weak motion data

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Site response in and around Delhi is studied using digital seismograms recorded by a thirteen-station VSAT-based 24-bit digital Delhi telemetry network of the India Meteorological Department. Nine local ($M_l \geq 2.3$) and nine regional ($M_l \geq 3.9$) earthquakes are selected for the estimation of site amplification factor using the classical standard spectral ratio for regional events (Ridge Delhi Observatory being the reference station), normalized standard spectral ratio for local events, horizontal-to-vertical spectral ratio or receiver function and the generalized inversion techniques in the frequency range of 0.5 to 7.5 Hz. Site response curves at all the thirteen stations exhibit station to station variation of the site amplification factor reflecting the changes in geologic/geotectonic/soil conditions. A comparison of the site response values obtained by the generalized inversion with those computed using receiver function technique shows a large scatter even though the pattern of the curves remain more or less similar. However, the site effects computed by generalized inversion and standard spectral ratio exhibit a good 1:1 correspondence. The peaks yielded by all the methods have been observed to occur at the same frequencies. It is evident that the softer fluvial deposits of the newer alluvium of the east Yamuna sector show steeper site amplification gradient at lower frequencies, while the greater Delhi experiences moderate site amplification. The variation of site response corroborates the abrupt changes in intensity from one location to another due to local site condition.

1. Introduction

The relative velocity of the Indian plate with respect to the Eurasian plate near Delhi is about 50 mm/yr in the direction of N13°E (DeMets *et al* 1994). The collision of these continental plates results in a crustal shortening along the northern edge of the Indian plate. This process has given rise to the major thrust planes: the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) (Gansser 1964; Molnar and Chen 1982). The region has experienced several great earthquakes in the past 100 years or so. The Himalayan geodynamics and the occurrence of great earthquakes are well

summarized by Seeber and Armbruster (1981); Khattri (1999); and Bilham and Gaur (2000). A 750-km long segment, called the central seismic gap (figure 1), continues to be under high strain. A large earthquake in the central seismic gap is likely to cause great loss of life and property and severe damage to construction in and around the epicentral zone. Delhi, a city of more than 10 million inhabitants, lies approximately 200 km from MBT and 300 km from MCT (figure 1). The city, now extends over swamps and recent fluvial deposits on the banks of the Yamuna river. As a result there is an increasing concern about the seismic hazard in the capital especially after the Bhuj earthquake of 26th January 2001 (M_w 7.6)

Keywords. Site response; classical and normalised standard spectral ratio; receiver function, site effects by generalised inversion; local site condition; Delhi telemetry network.

Figure 1. Tectonic map of the region (modified from Seeber and Armbruster 1981). The segment between the rupture areas of the 1905 and 1934 earthquakes is known as the central seismic gap.

that caused severe damage and destruction to the city of Ahmedabad situated approximately 300 km from the epicentral zone. Two moderate earthquakes have occurred in the western part of the central seismic gap, the Uttarkashi earthquake of 19th October 1991 (M_w 6.8) and the Chamoli earthquake of 28th March 1999 (M_w 6.5) in the Garhwal Himalaya. The Chamoli earthquake and its aftershocks were also felt and recorded in Delhi. Considering a shortening rate of 20 mm/year across the Himalayas (Lyon-Caen and Molnar 1985; Avouac and Tapponnier 1993; Gahalaut and Chander 1997; Bilham *et al* 1998), Khattri (1999) has estimated the probability of the occurrence of a great M_w 8.5 earthquake in the central seismic gap in the next 100 yr to be 0.59. Therefore, an assessment of seismic hazard has become an important issue necessitating estimation of site amplification factor, resonance frequency and other seismological attributes for the eventual microzonation of Delhi city.

Numerous studies on devastating earthquakes amply demonstrated large concentrations of damage in specific areas due to site-dependent factors related to surface geologic conditions and local soils altering seismic motions (Borcherdt 1970; Field *et al* 1992; Nath *et al* 2000, 2002a, b) and hence the engineering designs. The observed important effects include predominant periods of vibration of soil *in situ*, large amplification of ground motion in the form of site factors in certain frequency ranges, semi-resonance or resonance of certain building types and consequent deformations or collapses of structures, etc.

To evaluate site response several techniques have been utilized and compared in recent studies (Field and Jacob 1995). Two of the proposed methods, the standard spectral ratio (SSR) (Borcherdt 1970) and the receiver function technique (HVSF) (Langston 1979; Lermo *et al* 1993; Nath *et al* 2000, 2002a, b) are based on a spectral ratio scheme. In both these techniques the source and path contributions are removed from the seismic recordings by means of a deconvolution operation using a function free of site effects.

An alternative method to calculate site response is the generalized inversion technique (GINV) (Andrews 1986; Castro *et al* 1990; Boatwright *et al* 1991; Hartzell 1992) to compute site response by solving data of a number of recorded events for all source/path effects and site effects simultaneously.

In this article we report the results obtained on site amplification factor (SAF) in and around Delhi by classical standard spectral ratio for 9 regional events, normalized standard spectral ratio for 3 local events, receiver function and generalized inversion for 9 local and 9 regional events recorded

by the 13 VSAT-based digital telemetry network of the India Meteorological Department.

2. Data source

India Meteorological Department (IMD) is operating a network of 13 stations of VSAT based digital telemetry systems around Delhi as shown on the base map in figure 2. Ridge observatory has a 3-component, broadband (CMG-40T) system with a 24-bit digitizer at 20 samples per second. The other telemetry systems have 3-component sensors (S-13, short period) with 24-bit digitizer at 50 samples per second. Nine local and nine regional events enlisted in table 1 are used for the proposed site amplification study in and around Delhi. Figure 2 also displays the epicentral location of the local events.

3. Data processing and site factor estimation

The seismograms of the selected events were first corrected for the system response. Next the *S*-wave packets recorded by the seismographs were windowed with a window width containing the maximum amplitude. The window length was selected following the results of Seekins *et al* (1996). A Hanning taper is applied to the time windowed data and then Butterworth bandpass filtered between 0.5 and 10 Hz before the amplitude spectra were computed. The filtered seismograms at the stations Sohna (SONA), Ridge New Delhi (NDI) and Kurukshetra (KKR) are presented in figures 3(a, c and e) for the local event 05112000 ($M_l = 2.3$) together with the Fourier spectra of the respective *S*-envelope in figures 3(b, d and f) in log-log scale.

Let the *S*-wave spectral amplitude and that of the background noise be $O(r_{ij}, f_k)$ and $B(r_{ij}, f_k)$ respectively at the hypocentral distance r_{ij} . Then the signal amplitude spectrum at the frequency f_k can be expressed as,

$$A(r_{ij}, f_k) = O(r_{ij}, f_k) - B(r_{ij}, f_k). \quad (1)$$

The corrected spectra are smoothed in order to reduce the data variance using a five-point smoothing window and a spline interpolator at 0.1 Hz interval from 0.5 to 7.5 Hz.

Suppose the network has recorded I events by J stations. The amplitude spectrum of the i th event recorded at the j th station for the k th frequency, $A(r_{ij}, f_k)$ can be written in the frequency domain as a product of a source term $SO_i(f_k)$, a propagation path term $P(r_{ij}, f_k)$, and a site effect term $SI_j(f_k)$, (Lermo *et al* 1993):

$$A(r_{ij}, f_k) = SI_j(f_k) \cdot P(r_{ij}, f_k) \cdot SO_i(f_k) \quad (2)$$

Figure 2. Telemetry network and local events on the base map of greater Delhi.

Table 1. Local and regional events used in the site amplification factor estimation.

Local Events

Sl.No.	Date	Origin time	Epicentre	Magnitude	Region
1.	05.11.2000	04:05:01.9	28.72°N/76.73°E	2.3	Haryana
2.	05.12.2000	21:47:48.7	28.90°N/77.40°E	2.6	Delhi-U.P.-Haryana Border
3.	20.02.2001	08:42:10.1	31.10°N/78.00°E	3.8	H.P.-Uttanchal Border
4.	23.02.2001	15:17:19.2	29.80°N/77.20°E	2.9	Haryana-U.P. Border
5.	28.02.2001	02:41:49.7	28.60°N/76.20°E	4.0	Haryana Near Charkhi Dadri
6.	28.04.2001	03:06:26.0	28.80°N/77.20°E	3.8	Haryana Near Sonapat
7.	17.05.2001	12:08:16.1	29.10°N/77.00°E	2.9	District - Sonapat (Haryana)
8.	23.06.2001	02:33:31.0	30.30°N/77.60°E	3.4	Haryana-U.P. Border
9.	17.07.2001	06:35:08.0	28.96°N/77.53°E	2.5	U.P. - Haryana Border

Regional Events

Sl.No.	Date	Origin time	Epicentre	Magnitude	Region
1.	26.01.2001	03:16:42.9	23.40°N/70.28°E	$M_t = 6.9$	Rann of Kutch, Gujrat
2.	26.01.2001	03:33:35.3	23.40°N/70.18°E	$M_t = 5.5$	Rann of Kutch, Gujrat
3.	25.02.2001	02:21:37.0	36.50°N/70.60°E	$M_b = 6.7$	Afghanistan-Tazikistan Border
4.	15.04.2001	08:36:38.0	29.00°N/81.40°E	$M_t = 3.9$	Nepal
5.	28.04.2001	10:37:58.4	28.40°N/87.10°E	$M_b = 5.2$	Nepal - Tibet Border
6.	16.05.2001	11:00:08.0	30.70°N/68.90°E	$M_b = 5.0$	Pakistan Near Quetta
7.	30.06.2001	11:48:37.0	30.97°N/69.95°E	$M_b = 5.0$	Pakistan
8.	16.07.2001	16:07:18.0	32.80°N/72.90°E	$M_t = 5.0$	Pakistan
9.	16.07.2001	16:12:48.2	28.13°N/84.72°E	$M_t = 5.4$	Nepal

3.1 Site amplification factor by horizontal-to-vertical-spectral ratio (HVSr) or receiver function technique

The receiver function $HVSr_{ij}(f_k)$ can be computed at each j site for the i th event at the central frequency f_k from the root mean square average of the amplitude spectra as,

$$HVSr_{ij}(f_k) = \frac{\frac{1}{\sqrt{2}} \sqrt{|absH_{ij}(f_k)|_{NS}^2 + |absH_{ij}(f_k)|_{EW}^2}}{|absV_{ij}(f_k)|} \quad (3)$$

where,

- $H_{ij}(f_k)|_{NS}$ - Fourier spectra of the NS component,
- $H_{ij}(f_k)|_{EW}$ - Fourier spectra of the EW component and
- $V_{ij}(f_k)$ - Fourier spectra of the vertical component.

Finally the event average receiver function $HVSr_{ijj}^{ave}(f_k)$ (Field and Jacob 1995) is computed at each j site for the k th frequency to consider the contribution of all the seismic events recorded at that station.

3.2 Site amplification factor through generalized inversion (GINV)

In equation (2) the propagation path term can be expressed as,

$$P(r_{ij}, f_k) = G(r_{ij}) e^{\frac{-(\pi f_k r_{ij})}{Q_s(f_k)\beta}} \quad (4)$$

where $G(r_{ij})$ accounts for geometrical spreading, $Q_s(f_k)$ and β are S -wave frequency-dependent quality factor and velocity, respectively. We assumed $\beta = 4.06$ km/sec as an average shear-velocity on the basis of the velocity models for the Garhwal Himalaya assuming $\alpha/\beta = 1.73$ (IMD, 2000), where α is the P -wave velocity. Following Ordaz and Singh (1992) and others, we considered,

$$G(r_{ij}) = \frac{1}{r_{ij}} \quad \text{for } r < 100 \text{ km}$$

or,

$$G(r_{ij}) = (r_{ij}^* 100)^{-0.5} \quad \text{for } r > 100 \text{ km} \quad (5)$$

to take into account possible arrival of surface waves in the windowed data.

We have treated Q_s as predetermined in the inversion procedure. The relation used is,

Figure 3. (Continued)

Figure 3(a-f). The local event 05112000 ($M_l = 2.3$) as recorded by the sites SONA (EW component), NDI (EW component) and KKR (vertical component) and the corresponding Fourier spectra of the S-wave envelopes.

Figure 4. Regression analysis for the Q -factor estimation from the direct S -wave envelope.

$$Q_s(f) = 58.79f \pm 6.72. \quad (6)$$

As displayed in figure 4 the equation (6) has been obtained by the regression analysis on the S -wave envelope of the weak motion data of the local and regional events used in this study.

The equation (2) can further be written as,

$$SO_i(f_k) SI_j(f_k) = \frac{A(r_{ij}, f_k)}{P(r_{ij}, f_k)} = A'(r_{ij}, f_k) \quad (7)$$

where $A'(r_{ij}, f_k)$ is the spreading and attenuation corrected amplitude spectrum. Taking the natural logarithm on both the sides of equation (7) and multiplying by σ_{ijk} (Hartzell 1992), we can write,

$$S_i(f_k) + R_j(f_k) = D_{ij}(f_k), \quad (8)$$

where, for the k th frequency f_k , $S_i = \sigma_{ijk} \ln SO_i(f_k)$, $R_j = \sigma_{ijk} \ln SI_j(f_k)$ and $D_{ij} = \sigma_{ijk} \ln A'(r_{ij}, f_k)$. σ is a weighted factor and an estimate of the standard deviation of the data given by the ratio of the signal spectrum to a noise sample spectrum, $N_{ij}(f_k)$. The algorithm for estimating σ tried in this study is,

$$\sigma_{ijk} = \max(\min(A(r_{ij}, f_k)/N(r_{ij}, f_k), 5.0), 1.0)/5.0, \quad (9)$$

where σ is normalized and limited to the range of 1.0 to 0.2. This imposes a balance in the quality of the data with the need to include as many observations as possible to average out radiation-pattern and source-directivity effects. $N_{ij}(f_k)$ is obtained from a 2.0-sec or less duration noise sample immediately preceding the shear-wave arrival. Equation (8) is written in the matrix form follow-

ing the notation of Menke (1989) and solved by generalized inversion scheme using singular value decomposition (Nath et al 2002b). The method requires a reference site with known response value in the frequency range of interest to minimize the trade-off between the source and site parameter values as observed by Andrews (1986). Ridge-New Delhi (NDI) observatory installed on the Alwar quartzite is selected as the reference site on the basis of the available geological information and after calibrating its own site response through receiver function analysis to be discussed in the subsequent paragraphs in detail.

3.3 Reference station spectral ratio (SSR) estimate of site amplification factor

The traditional spectral ratio is estimated with respect to a 'reference site'. Suppose, we have a reference site ($j = R$) that is assumed to have a negligible site response ($\ln S_R = 0$) and if the inter-station spacing is too small compared to the epicentral distances, so that $P(r_{ij}, f_k) \approx P(r_{iR}, f_k)$, then the site response at each seismological station can be estimated from,

$$\begin{aligned} \ln S^{SR}(r_{ij}, f_k) &= \frac{1}{I} \sum_{i=1}^I \ln \left(\frac{A(r_{ij}, f_k)}{A(r_{iR}, f_k)} \right) \\ &= \frac{1}{I} \sum_{i=1}^I (\ln A(r_{ij}, f_k) - \ln A(r_{iR}, f_k)). \end{aligned} \quad (10)$$

Equation (10) constitutes the geometric average spectral ratio. If the reference site has a non-negligible site response, then the spectral ratios

Figure 5. (a) Site amplification factor at New Delhi (NDI) estimated by generalised inversion (GINV) and receiver function (HVSR) from the horizontal amplitude spectra of the seismograms recorded for the regional and local earthquakes. The solid straight line parallel to frequency axis at SAF 1.0 represents spectral amplification for a reference site. (b) Vertical spectral amplification by GINV for regional and local events at New Delhi (NDI).

become relative site-response estimates or site amplification factor. In the present study Ridge-New Delhi (NDI) is considered to be the reference

site. In the classical spectral ratio method, the source and path effects are considered identical for every site and the reference one only when the epi-

Figure 6. (Continued)

Figure 6(a-f). Site amplification factor at Kalagarh (KALG) by (a) Generalized inversion (GINV) of the horizontal and vertical amplitude spectra of the seismograms recorded for the local and regional events. (b) SAF value scatter with frequency for the horizontal spectra by GINV for local and regional events. The shaded areas represent ± 1 standard deviation (SD) from the mean. (c) Standard spectral ratio estimate (SSR) for the regional events and the normalized spectral ratio estimate for local events using horizontal and vertical amplitude spectra. (d) SAF value scatter with frequency for the horizontal spectra by SSR for local and regional events. The shaded areas represent ± 1 standard deviation (SD) from the mean. (e) The receiver function estimate (HVSr) of the site amplification factor for the local and regional events. (f) The scatter of site amplification factor by HVSr with frequency for the local and regional events.

Figure 7. SSR, GINV, HVSR estimates of the site response for the local events at (a) SONA and (b) AGRA.

central distance is appreciably larger compared to the interstation spacing. As a result the normalized SSR method is expected to perform better for the regional events. In the present context the standard

spectral ratio technique is applied for SAF estimation using 9 regional events only. For the local events, however, a normalized SSR technique is evolved for the earthquakes with the network

azimuthal coverage of 270° or more. For each central event, the station spectral amplitudes are normalized to a 50 km epicentral distance through equation (4) and (5). This gives weighted path effect calibrated spectral amplitude at every station to a 50 km epicentral distance. Referring to figure 2, the events 2, 6 and 9 are selected for the normalized SSR computation in the present study. Considering the local sources to be random, the multiple event normalized amplitude spectra at each station are stacked for the elimination of the source effect. The spectral ratio is then determined from the stacked amplitude with respect to the reference site (NDI here) through equation (10).

To analyse the reference site condition at Ridge-New Delhi (NDI) observatory, its site response is computed using receiver function and generalized inversion techniques for the local and regional earthquakes. In figure 5 the variation of SAF with frequency as computed by HVSR and GINV of horizontal (H) and vertical (V) component spectra for the local and regional events are displayed. All the curves in figures 5(a and b) for the horizontal and vertical components exhibit a minimum of 0.32 at 0.5 Hz and 1.5 at 7.5 Hz, a mild departure from the mean value 1.0, the expected site amplification for a competent bedrock site. As a result NDI can be used as the reference site for the SAF determination at all the stations of the network.

The representative site response curves at KALG, SONA and AGRA are presented in figures 6 and 7(a and b) respectively. A detailed analysis for KALG is presented in figure 6, wherein the SAF curves by GINV and SSR for the horizontal and vertical component seismograms of regional events, HVSR for local and regional earthquakes are displayed together with the data scatter.

It is evident from the diagrams that GINV estimated horizontal component SAF from the regional events follow those using the local events (figures 6a and b). The vertical components also show a similar trend for both the local and regional events (figure 6a), with reduced amplification compared to the horizontal ones. The GINV estimated SAF for the local and regional earthquakes exhibit mild scatter as depicted in figure 6(b), the shades indicating ± 1 standard deviation of the mean. The SSR estimated site response values at KALG from the horizontal component seismograms of the regional events presented in figure 6(c) closely follow those by the normalized SSR using horizontal component seismograms of the local events 2, 6 and 9 (ref: table 1). The vertical spectral amplification by SSR method from the local and regional events show a trend following the horizontal ones but with defused amplification. The site response values from regional events by standard spectral ratio and local events by normalized standard spec-

tral ratio also exhibit a mild scatter as depicted in figure 6(d) with ± 1 standard deviation from the mean. The HVSR computed SAF from regional and local events together with the shaded scatter for ± 1 standard deviation displayed in figures 6(e and f) follow the trend of the curves by GINV and SSR. The predominant frequency at Kalagarh is 5 Hz. Similar analysis is performed at all the sites before calculating the average SAF values. Incidentally SONA and AGRA recorded only local events. Their site amplification by generalized inversion and normalized standard spectral ratio from the horizontal and vertical component amplitude spectra and receiver function is presented in figure 7(a and b) respectively. SONA has a predominant frequency of 3.5 Hz while at AGRA it is 1 Hz. The GINV and SSR curves exhibit a good similarity being in the close proximity of each other. The vertical spectral amplification by GINV and SSR is appreciably less compared to the horizontal ones. HVSR generated SAF curves at both SONA and AGRA seem to be following the GINV estimated horizontal amplification curves as well.

The GINV computed site amplification factors for the horizontal component spectra at the central frequencies 1.5, 4 and 6.5 Hz at all the 13 stations are enlisted in table 2. Unless otherwise mentioned, the site amplification SAF will mean those computed using SSR (standard or normalized) and GINV from horizontal component amplitude spectra only.

4. Results and discussion

The recent sequence of earthquakes has highlighted the level of seismic hazard and vulnerability of the

Table 2. Comparison of SAF values at 13 sites in and around Delhi at the central frequencies 1.5, 4 and 6.5 Hz as estimated by GINV.

Stations	1.5 Hz (0.5–2.5 Hz)	4 Hz (3–5 Hz)	6.5 Hz (5.5–7.5 Hz)
SONA	2.28	3.18	2.48
KALG	4.65	4.68	2.81
AGRA	5.17	4.78	3.21
AYAN	1.88	1.68	2.56
KKR	2.93	4.26	6.44
ASR	2.31	3.44	6.51
RTK	5.65	6.09	1.67
BIS	3.22	2.842	4.52
BHGR	1.96	2.86	5.52
UGON	0.53	0.58	1.51
RTUL	1.89	2.21	3.31
KUDL	3.76	4.51	2.62
NDI	1.00	1.00	1.00

built-up regions in India for damage and destruction. This calls for a multi-disciplinary effort on the part of scientists and engineers to create a seismic hazard map through microzonation by incorporating a variety of factors including geology, topography, sub-soil condition, building morphology, earthquake ground motion amplification, etc.

Microzonation map helps discriminating between soft soil and hard rock sites depending on the respective site response values. However, the damage caused to buildings depends also on the strength of the structure, that has to be evaluated from the zones with high site response values. These values depend on the soil susceptibility towards compaction and liquefaction. In greater Delhi and its surroundings, all the stations (except UGON) exhibit site amplification except NDI at all frequencies. As discussed in the preceding section the site amplification values estimated by standard spectral ratio for the regional events, normalized standard spectral ratio for the local events, generalized inversion and receiver function are highly comparable. The horizontal component spectral amplification is more pronounced than the vertical ones as evident in figures 6 and 7 for the sites KALG, SONA and AGRA. This is true for all the sites. The variation of the vertical site amplification factor with frequency indicates that all the components are influenced by the near surface inhomogeneity in soil conditions. The site amplification at KALG at the resonance frequency (5 Hz) is 6.45, while at SONA it is 5.75 at 3.5 Hz. At AGRA the SAF value at the resonance frequency 1 Hz is 6.47. The GINV estimated vertical spectral amplification (figure 7b) shows a peak at 1.5 Hz while the resonance frequency of the basin is 1 Hz (SSR, HVSR, GINV_H all peaking at 1 Hz). This may be attributed to a local optimization problem associated with the generalized inversion scheme and hence a numerical anomaly. The scatter plot between the site amplification factors computed by SSR and GINV as depicted in figure 8(a) shows a good 1:1 correspondence. Since the vertical components are not free from the near surface influences, the HVSR estimated site amplification factors show a large scatter with respect to the GINV estimated site response as shown in figure 8(b).

Because detailed geological, geotechnical, and geophysical information relevant to the soil column underlying the considered stations are not available, we do not attempt to correlate soil characteristics with calculated site response, but make a subjective interpretation based on the values yielded by generalised inversion technique. As listed in table 2, at 1.5 Hz an appreciable site response (≈ 5.17) is computed at station AGRA,

while KALG exhibited a value of 4.65. AGRA again shows higher response (≈ 4.78) at 4 Hz, while RTK exhibited the highest response of 6.09. At 6.5 Hz a high response (≈ 6.51) is estimated at ASR and KKR (≈ 6.44). At BHGR the site response is 5.52, while at BIS it is 4.52. Using the estimated site response at the central frequencies 1.5, 4 and 6.5 Hz we prepared the contour maps as shown in figures 9(a, b and c) in order to have a broader perspective of the regional site response variation. At 1.5, 4 and 6.5 Hz we observe two low site amplification zones – one at New Delhi and the other at Oonchagaon. At all the central frequencies, the site amplification is higher in the greater Delhi region as shown in the zoomed site contour maps of greater Delhi in figures 10(a, b and c). However, the site response gradient is steeper towards east Yamuna sector on the fluvial deposits at 1.5 Hz. At higher frequencies, the SAF gradient is mild. This subjective interpretation, even though very preliminary, definitely yields an amplification trend and calls for detailed investigation using dense network in and around Delhi using both weak and strong motion stations.

5. Conclusion

The standard spectral ratio, receiver function and generalised inversion methods are well established, and revealed interesting results in and around Delhi region. The normalized reference site spectral ratio technique is developed as a part of this work to handle local events with epicentral distances comparable to the interstation spacing. Only three local events (2, 6 and 9) are considered in the present analysis for the estimation of site amplification by normalized SSR due to good network azimuthal coverage (weighted to 50 km epicentral distance). The site response computed by SSR and GINV shows good resemblance. Since the vertical component also exhibits amplification, the site response yielded by HVSR shows scatter with respect to those computed by GINV.

Calculation of spectral ratios at different sites with higher station distribution and a large catalogue of earthquake can certainly make it possible to determine areas of different amplification levels irrespective of the magnitude of an earthquake. The inherent relationship of the site response with soil compaction and liquefaction, the frequency response characteristics of the spectral-ratio and generalised inversion estimate defining the resonance amplification of the basin, go a long way in identifying fail-safe corridor for the Delhi region in planning its building size and hence proper urbanization. Settlements developed on alluvial terraces suffered damages during the Chamoli earthquake,

Figure 8. The comparison of site amplification factor calculated by GINV versus those obtained from (a) the SSR method and (b) the HVSR technique. The diagonal line indicates 1:1 correspondence.

(a)

Figure 9. (Continued)

(b)

Figure 9. (Continued)

Figure 9(a–c). Site response contour maps in and around Delhi at the central frequencies: (a) 1.5 Hz, (b) 4 Hz and (c) 6.5 Hz.

Figure 10. (*Continued*)

(b)

Figure 10. (Continued)

(c)

Figure 10(a–c). Site response contour maps in the greater Delhi region at: (a) 1.5 Hz, (b) 4 Hz and (c) 6.5 Hz.

while the intervening regions on relatively harder rocks suffered little or no damage. Site amplification could be one of the probable reasons for wider damages during the 1991 Uttarkashi earthquake also.

This is our first attempt to make site response study in and around Delhi. This study needs to be extended using close-spaced digital network data.

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