Nat Hazards (2016) 82:1123–1146
DOI 10.1007/s11069-016-2236-x

ORIGINAL PAPER

Stochastic finite modeling of ground motion for March 5, 2012, Mw 4.6 earthquake and scenario greater magnitude earthquake in the proximity of Delhi

Himanshu Mittal[1] · Yih-Min Wu[1] · Da-Yi Chen[2] · Wei-An Chao[1]

Received: 21 October 2015 / Accepted: 5 February 2016 / Published online: 19 February 2016

Abstract In present work, seismic hazard from future earthquake is worked out for Delhi region in terms of different strong motion parameters such as peak ground acceleration (PGA), characteristics frequency and spectral acceleration (Sa). The earthquake of March 5, 2012, is taken as key earthquake for synthesis. Stochastic finite modeling technique based on dynamic corner frequency initially is used to produce and match the ground motion histories where 2012 earthquake was recorded. The matching is attained in terms of PGA, response spectra and duration. Once a good match is found, the ground motion is estimated for higher magnitude earthquakes (i.e., Mw 6.0 and Mw 6.5). Our work demonstrates that a Mw 6.0 magnitude earthquake in proximity of Delhi will deliver PGA estimations of 20–209 gal (1 cm/s^2 = 1 gal), the lower values occurring at hard rock sites like NDI (IMD) and DJB. Similarly Mw 6.5 earthquake may produce PGA values ranging between 30 and 323 gal. Finally seismic hazard in Delhi and surrounding regions is estimated from Mw 6.5 magnitude earthquake in terms of PGA, Sa and predominant period. Our computation specifies that at short period, the small structures toward eastern and north-western part of Delhi city may be affected by the earthquakes. For a case of 0.5 s period, Sa values are distributed uniformly at all the places in Delhi, indicating that the buildings with five floors or so may be in danger from future higher magnitude earthquakes. The Sa maps acquired in this study can be utilized to survey the seismic danger of the region and identify vulnerably susceptible areas in and around Delhi from future higher magnitude earthquake.

Keywords Stochastic · Seismic hazard · Peak ground acceleration · Spectral acceleration

✉ Himanshu Mittal
himanshumitt10@gmail.com

[1] Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan

[2] Central Weather Bureau, Taipei, Taiwan

1 Introduction

Earthquakes are the most deadly event of all natural disasters. Large earthquakes may cause heavy damages to mankind in terms of fatalities, injuries and destruction of infrastructure. These losses can be avoided if it is possible to predict the future earthquake in terms of its location and size. But till date, prediction of future earthquake is impossible. However, the hazard from future earthquake can be worked out if a lot of earthquake recordings from different magnitude earthquakes are available. These earthquakes recordings having same source, site and path effects can be combined to produce the hazard. The strong ground motions are looked after both by seismologists and engineers. Seismologists use them for studying source characteristics, whereas and the engineers use them for structural design, urban planning and management. In a country like India where too much strong motion recordings are not available, some other method needs to be investigated. This demands generating synthetic ground motion using site-specific ground motion parameters or by using region-specific ground motion prediction equations (GMPE). Many techniques are available for synthesis of ground motion. These are empirical Green's function technique (Hartzell 1978; Ordaz et al. 1995); composite source model (Khattri et al. 1994; Yu et al. 1995); envelope technique (Joshi et al. 1999) and stochastic technique (Boore, 1983; Chopra et al. 2012, 2013; Mittal and Kumar 2015). Empirical Green's function technique has been used by many researchers previously in many environments (e.g., Singh et al. 2002; Mittal et al. 2013a, 2015).

Indian region experienced many major earthquakes in past. Some of these earthquakes are: Gujarat earthquake (1819), $M = 8.0$; Assam earthquake (1897), $M = 8.7$; Himachal earthquake (1905), $M = 8.0$; Nepal–Bihar earthquake (1934), $M = 8.3$; Assam earthquake (1950), $M = 8.5$ and Gujarat earthquake (2001), $M = 7.9$. Lot many persons in India, living in Himalayan area and abutting fields, are at danger from seismic tremors. The recent Nepal earthquake of April 25, 2015 ($M = 7.8$) and May 15, 2015 ($M = 7.3$) witnessed this risk by killing around 9000 people and injuring 25,000 people in Nepal. Two regions of India namely Uttar Pradesh and Bihar of India were badly affected by these Nepal earthquakes. In the seismic zonation map of India, most of the parts of Himalayas are mapped as either seismic zone IV or V, the two most seismically active zones (BIS 2002).

Delhi, the nation capital of India, falls in the seismic zone IV as per Bureau of Indian Standards (BIS 2002). It is situated near to two seismically active faults of the Himalayas namely Main Boundary Thrust (MBT) and Main Central Thrust (MCT) (Seeber and Armbruster 1981). Several earthquakes in magnitude range from 3.0 to 7.4 (locally as well as from Himalayas) have been observed in and around Delhi and caused severe damage. As discussed earlier, most recent earthquakes of Nepal were also felt in Delhi. Because of fast development in populace, urbanization has quickly expanded prompting ascents in the quantity of elevated structures, which is helpless against high seismic hazard even because of moderate size tremors. So, fundamental seismic elements ought to be mulled over for urban arranging, industrialization, outlining and development of structural designing structures. Several publications are there from various researchers regarding the seismic hazard and microzonation of Delhi city. The basic thing that comes in mind is that what will be the ground motion in Delhi from local earthquakes as well as earthquakes occurring in Himalayas, since so many recorded ground motion histories are not there. In present work, we synthesize ground motion at 22 sites in Delhi using stochastic simulation approach, where March 5, 2012, earthquake was recorded. The synthesis at soil sites is performed by incorporating site effects, estimated using horizontal-to-vertical (H/V) spectral ratio technique (Nakamura 1989). The synthesized ground motion histories are compared with recorded one in terms of PGA, Fourier spectra, duration and response spectra. Once a good comparison is found, seismic hazard in city is presented from scenario Mw 6.0 and Mw 6.5 earthquakes using stochastic simulation. In total, 53 sites are used for generating scenario earthquakes time histories. Out of these 20 sites are strong motion sites (Kumar et al. 2012; Mittal et al. 2012), while at remaining sites data was collected by Wadia Institute of Himalayan Geology during a period of 3 months during which they recorded 11 earthquake events at different stations.

2 Geology and seismotectonics of region

The Delhi region lies between 28°24′17″N to 28°53′00″N latitude and 76°50′24″E to 77°20′37″E longitude. The National Capital Territory (NCT) of Delhi (area $\approx$ 1600 sq. km) has experienced major earthquakes in historic times as it lies in Seismic Zone IV of the Indian Seismic code (BIS 2002).

The terrain of Delhi is generally flat except for a low NNE–SSW trending ridge (Sharma et al. 2003). Several lineaments and faults like the Rajasthan Great Boundary Fault (RGBF), Sohna Fault, Delhi–Hardwar Ridge, Mathura fault and Moradabad Fault are reported in literature (Srivastava and Somayajulu 1966; Srivastava and Roy 1982). Mahendragarh–Dehradun Fault (MDF) and Aravalli–Delhi fold axes are believed to be two main features responsible for adequate seismicity in Delhi. The tri-junction of Delhi–Haridwar ridge, Delhi–Lahore ridge and Aravalli–Delhi fold ranges are seismically dynamic areas (Shukla et al. 2007). Delhi–Haridwar ridge having NE–SW trend is primarily responsible for seismicity around Delhi (Sharma et al. 2003). However, it is quite scattered and difficult to assign seismicity to a particular structure (Fig. 1).

Great Boundary Fault (GBF) is the most noticeable among the faults. Repeated activity is observed along GBF and the migration of Chambal and Yamuna River course are the result of movements along this fault system (GSI 2000). The general trend of Moradabad fault zone is along NE–SW direction. This tectonic mark is perceptible on to the shield area as a tectonic border between the Delhi folder belt and the Vindhyans (Ramakrishnan and Vaidyanathan 2008).

Delhi–Moradabad tectonic province is surrounded by Delhi-Hardwar ridge in the northwest and Moradabad fault zone in the southeast. The main trend of the Moradabad fault zone is found to occur along northeast extension of RGBF. Srivastava and Somayajulu (1966) postulated that Srivastava and Somayajulu (1966) stated that Mathura fault zone having NNW–SSE direction runs from Mathura in south to north. RGBF zone is a well-characterized fault that runs for around 400 km as a foremost disruption zone in Rajasthan (Sharma et al. 2003).

On the basis of satellite image (remote sensing) studies, it has been seen that some of major geological features viz., Lahore–Delhi ridge, Delhi axis of folding, Delhi–Hardwar ridge and the Himalayan frontal folded zone are clearly following the regional trends (Srivastava and Roy 1982). Criss-cross lineaments near Delhi show the complexity of the region probably due to conjoining of the above-mentioned geological features. Geological Survey of India mapped Sohna fault running in N–S direction from Sohna to the west of Delhi.

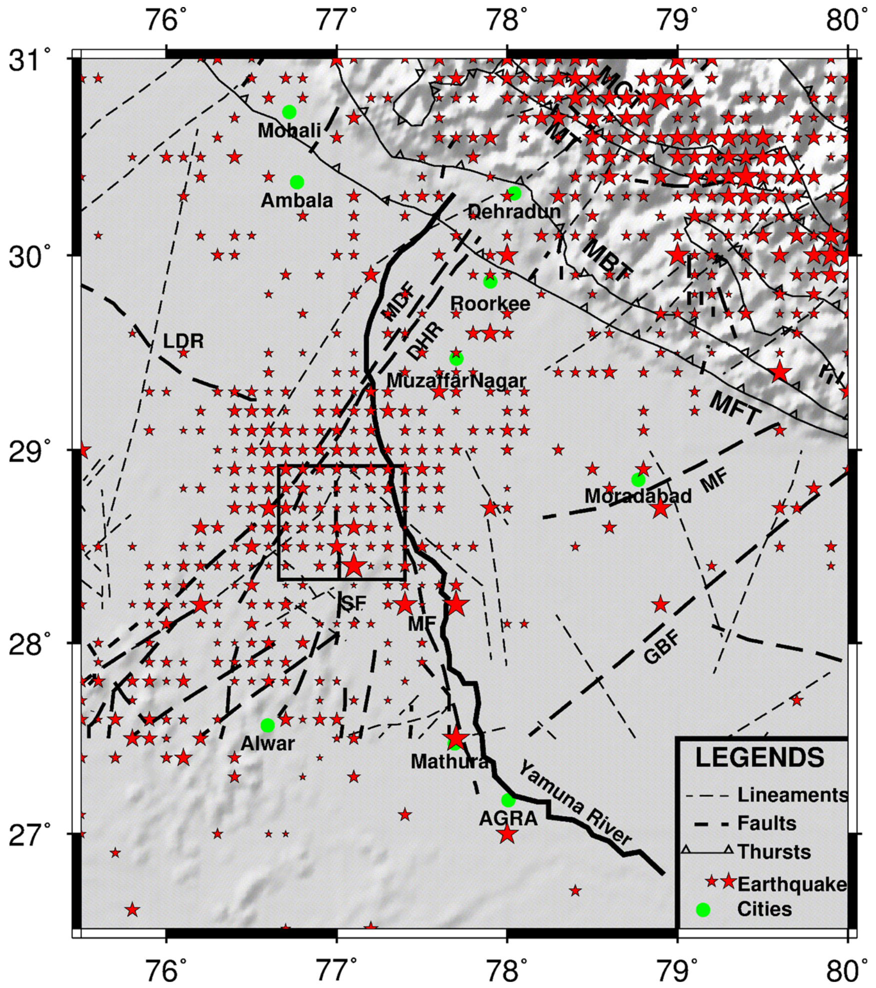

Fig. 1 Seismotectonic map showing different prominent structural features near Delhi region in square. The earthquakes are plotted as stars according to size. Important Himalayan tectonic features like Main Boundary Thrust (MBT), Main Central Thrust (MCT), Main Frontal Thrust (MFT) are plotted along with others regional features like Mahendragarh–Dehradun Fault (MDF), Delhi–Haridwar Ridge (DHR), Moradabad Fault (MF), Sohna Fault (SF), Mathura Fault (MTF) and Great Boundary Fault (GBF). Important cities are shown in *green color*. The historical earthquakes near Delhi are also plotted. The earthquake data are collected from Indian Meteorological Department (IMD), India

In the area near Delhi and southward, outcrops of highly joined and folded Alwar quartzites, unconformably covered by sediments of various thickness are observed. A plot of major geological features in and around Delhi region is shown in Fig. 2. The study area is mostly covered with quaternary alluvium and pre-Cambrian metasediments of Delhi System. The soils are sand to loamy sand in sandy plain areas. Thickness of the alluvium in either direction (East or West) plays an important role in evaluating site amplification.

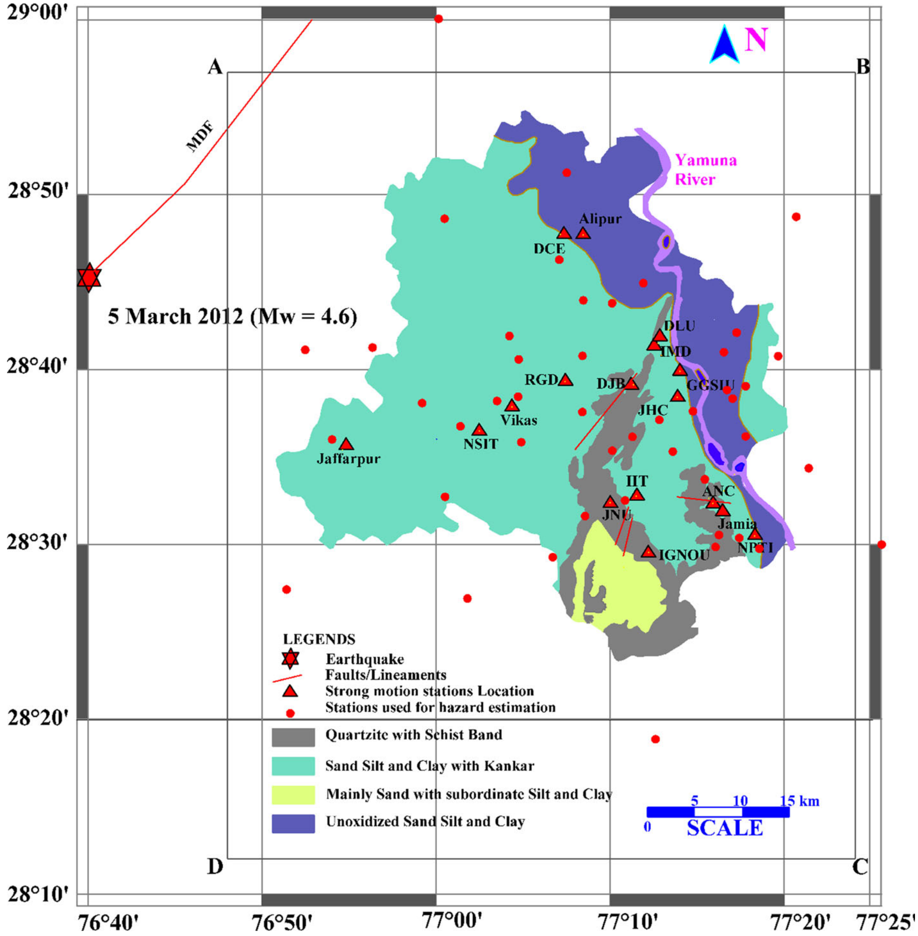

Fig. 2 A map showing the different geological formations in Delhi March 5, 2012, earthquake is also shown. The strong motion instruments in Delhi which have recorded 2012 earthquake are shown as *triangle*. *Circles* are the sites which will be included along with strong motion sites to estimate hazard from scenario earthquakes. The *rectangle* ABCD will be used to mark hazard in city in terms of different ground motion parameters

3 Methodology

In present work, synthesize of the accelerograms of the March 2012 earthquake is carried out using modified stochastic model based on dynamic corner frequency proposed by Motazedian and Atkinson (2005). In this simulation method, a large fault is separated into a number of small sub-faults. The ground motions contributed by each sub-fault can be computed by using stochastic point-source method. Quality factor (Q), between the source region and Delhi and the stress drop ($\Delta\sigma$) of present earthquake are estimated by studying recording spectra. The methodology is described in detail in Mittal and Kumar (2015).

The Fourier acceleration spectral amplitude, $A(f, R)$, can be written as (Boore 1983)

$$A(f,R) = \frac{CS(f)e^{\frac{-\pi fR}{\beta Q(f)}}}{G(R)} \tag{1}$$

$$C = \frac{R_{\theta\emptyset}\mathrm{FP}(2\pi)^2}{(4\pi\rho\beta^3)} \tag{2}$$

$$S(f) = f^2\dot{\mathrm{M}}_0(\mathrm{f}) \tag{3}$$

$$S(f) = \frac{f^2 f_c^2 M_0}{(f^2 + f_c^2)} \tag{4}$$

$$f_c = 4.9 \times 10^6 \times \beta\left(\frac{\Delta\sigma}{M_0}\right)^{\frac{1}{3}} \tag{5}$$

$$\log A(f,R) + \log G(R) - \log C = \log S(f) - 1.36fR/\beta Q(f) \tag{6}$$

$$A(f,R) = \frac{R_{\theta\emptyset}\mathrm{FP}}{(4\pi\rho\beta^3)} \cdot \frac{(2\pi)^2 f^2 f_c^2 M_0}{(f^2 + f_c^2)} e^{-\pi kf} e^{\frac{-\pi fR}{\beta Q(f)}}.G(R) \tag{7}$$

$\dot{\mathrm{M}}_0(f)$ is the moment rate spectrum and $\dot{\mathrm{M}}_0(f) \rightarrow M_0$ as $f \rightarrow 0$, ρ is density $(2.9\ \mathrm{g/cm^3})$, $R_{\theta\emptyset}$ is average radiation pattern (0.55), β is shear-wave velocity (3.8 km/s), $Q(f)$ is quality factor, and F is Free surface amplification(2.0). P accounting for the partitioning of energy in the two horizontal components is taken as $(1/\sqrt{2})$. $G(R)$ is the geometrical spreading term, which is taken as $1/R$ (Singh et al. 1999). κ is spectral decay parameter called kappa, a value of near-surface attenuation, which controls the path independent high-frequency decay of the spectrum (Anderson and Hough 1984).

Equation (6) was solved to obtain the value of $\log(f^2\dot{\mathrm{M}}_0(f))$. The source spectra are shown in Fig. 3. The hard-site spectra are interpreted by an ω^2-source model to obtain an estimation of the seismic moment (M_0) and corner frequency (f_c). Both low- and high-frequency levels of the spectrum are well fitted by ω^2-source model with $M_0 = 8.5 \times 10^{22}$ dyne cm and $f_c = 1.78$ Hz (with a stress drop, $\Delta\sigma$, of 124 bars).

Stochastic procedure to large faults was extended by Beresnev and Atkinson (1997) by dividing it into small sub-faults and considering them as a point source. A complete methodology about stochastic procedure is discussed by Motazedian and Moinfar (2006). The ground motion from sub-faults is summed with a proper time delay so as to obtain the ground motion acceleration from the entire fault as

$$a(t) = \sum_{i=1}^{nl}\sum_{j=1}^{nw} a_{ij}(t + t_{ij})$$

where nl and nw are the number of sub-faults along fault strike and dip, respectively. t_{ij} is the relative delay time taken from the ijth sub-fault to observation point. The $a_{ij}(t)$ is the acceleration of the ijth sub-fault at the observation point, calculated by the stochastic point-source method (Boore 1983; Motazedian and Atkinson 2005).

Motazedian and Atkinson (2005) established the idea of dynamic corner frequency by stating that the corner frequency decreases as ruptured area increases and considered it as a function of time. The dynamic corner frequency of the ijth sub-fault, f_{cij} (t), is given by

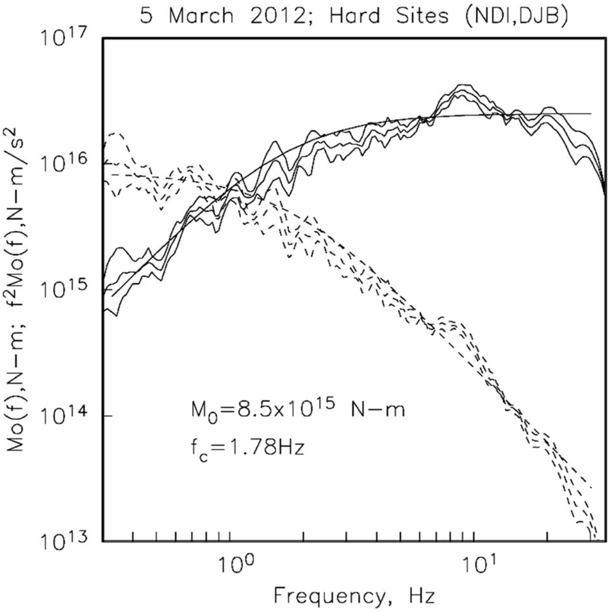

Fig. 3 Source displacement (*continuous curves*) and acceleration spectra (*dashed curves*), $\dot{M}_0(f)$ and $f^2\dot{M}_0(f)$ of March 5, 2012, earthquake. Median and ± one standard deviation curves are shown. Data from stations NDI and DJB, two hard site in Delhi. The spectra are reasonably well fit by an ω^2-source model with $M_0 = 8.5 \times 10^{15}$ Nm and a corner frequency of 1.78 Hz

$$f_{cij} = \frac{4.9 \times 10^6 \beta}{N(t)^{\frac{1}{3}}} \left(\frac{\Delta\sigma}{M_{0\mathrm{ave}}} \right)$$

where $M_{0ave} = M_0/N$ is the average seismic moment of sub-faults, N is the number of sub-faults, $N(t)$ is the cumulative number of ruptured sub-faults at time t.

For $t = t_{\mathrm{end}}$, the number of ruptured subfaults, N_R $(t = t_{\mathrm{end}}) = N$. The corner frequency at the end of rupture is rewritten by

$$f_{cij(t_{\mathrm{end}})} = \frac{4.9 \times 10^6 \beta}{N(t_{\mathrm{end}})^{\frac{1}{3}}} \left(\frac{\Delta\sigma}{M_{0\mathrm{ave}}} \right)$$

A scaling factor H_{ij} was applied by Motazedian and Atkinson (2005) to conserve the high-frequency spectral level of sub-faults. The factor is given as:

$$H_{ij} = \left(\frac{N \sum \left\{ f^2 / \left[1 + f/f_c^2 \right] \right\}^2}{\sum \left\{ f^2 / \left[1 + f/f_{cij}^2 \right] \right\}^2} \right)^{\frac{1}{2}}$$

Another concept of pulsing area is also put forward in the stochastic model by Motazedian and Atkinson (2005) to accommodate the slip behavior of earthquake ruptures. This method omits the restriction of sub-fault size (Motazedian and Moinfar 2006). Same approach is used in present work to synthesize ground motion for Mw 4.6 earthquake at different sites.

4 Ground motion synthesis

March 5, 2012, Delhi earthquake was recorded by 24 stations of strong motion network of IITR network. Mostly recordings are available within an epicentral distance of 30–100 km. The earthquake location was reported by Indian Meteorological Department (IMD), India. However, modified location and fault plane solution for the same are available from Bansal and Verma (2012). The epicenter of the earthquake is at 28.75°N and 76.65°E, with a focal depth of 14 km from IMD catalogue (Bansal and Verma 2012; Table 1). A best double couple solution of NP1: 348°/48°/131° (strike/dip/rake) and NP2: 115°/56°/54° was determined by Bansal and Verma (2012). We also estimated the source

Table 1 Range of different ground motion parameters used in synthesis and final adopted parameters based on minimum RMS error

Parameter	Parameter values by different researchers	Final parameters adopted in synthesis
Latitude, longitude	28.75°N, 76.65°E	28.75°N, 76.65°E
Fault orientation (strike, dip)	348°, 48° (Bansal and Verma 2012)	348°, 48° (Bansal and Verma 2012)
Fault length and width (km)	3.2 (Wells and Coppersmith 1994)	3.2 (Wells and Coppersmith 1994)
Subfault length and width (km)	0.5, 0.5	0.5, 0.5
Depth of the hypocenter (km)	14	14
Moment magnitude (Mw)	4.6	4.6
Q(*f*)	$Q_c = 142f^{1.04}$ (Mohanty et al. 2009) $Q_c = (158 \pm 9)f^{(0.97\pm.08)}$ (Sharma et al. 2015) $Q = 800f^{0.42}$ (Singh et al. 2004)	$Q = 800f^{0.42}$ (Singh et al. 2004)
Distance-dependent duration	0 ($R < 10$ km), (Beresnev and Atkinson 1999) 0.16R ($10 < R < 70$ km), −0.03R ($70 < R < 130$ km), 0.04R ($R > 130$ km)	0 ($R < 10$ km), (Beresnev and Atkinson 1999) 0.16R ($10 < R < 70$ km), −0.03R ($70 < R < 130$ km), 0.04R ($R > 130$ km)
Kappa (κ, s)	0.03–0.07	0.04
Crustal shear-wave velocity (km/s)	3.7	3.7
Crustal density (g/cm^3)	2.8	2.8
Geometric spreading	$1/R$ ($R \le 100$ km) $1/R^{0.5}$ ($R > 100$ km) (Singh et al. 1999)	$1/R^{1.1}$ ($R \le 100$ km) $1/R^{0.5}$ ($R > 100$ km) (Singh et al. 1999) with little change
Stress parameter (bars)	124, 50, 100	124 bars
Pulsing percentage	50 %	50 %
Windowing function	Saragoni-Hart	Saragoni-Hart
Rupture velocity/shear-wave velocity	0.8	0.8
Crustal amplification	Western North America generic rock site (Boore and Joyner 1997)	Western North America generic rock site (Boore and Joyner 1997)
Fault-slip distribution	Random slip for all sub-faults	Random slip for all sub-faults

parameter of earthquake using strong motion data and found location and other parameters to comply with Bansal and Verma (2012) other than stress drop and magnitude. We found stress drop and magnitude of earthquake to be $\Delta\sigma = 124$ bars and Mw = 4.6, respectively. The stress drop plays an important parameter in controlling the high-frequency content and level. The ground motion is synthesized at all the sites where recorded ground motion histories are available. The root mean square (RMS) of each simulation utilizing specific arrangement of parameters is determined. At last, the parameters with least RMS were chosen to be utilized for assessing ground movements for great scenario earthquake.

The nodal plane NP1 is selected as fault plane for modeling ground motion which seems to be reasonable as per geological structure. Fault dimension is selected using Wells and Coppersmith (1994) after comparing with Leonard (2010) and Hanks and Bakun (2008).

The modified stochastic finite modeling technique requires region-specific path and site effects for synthesis. Path effect is expressed as a combination of dimensionless quantity called quality factor Q, which expresses the decay of wave amplitude during its propagation in the medium (Knopoff 1964) and geometrical spreading $G(R)$. We have three different values of Q available to us in the study region, i.e., $Q_c = 142f^{1.04}$ from Mohanty et al. (2009); $Q_c = (158 \pm 9)f^{(0.97\pm0.08)}$ from Sharma et al. (2015) and $Q = 800f^{0.42}$ of Singh et al. (2004) for Indian shield region. Although the stress drop is considered to be 124 bars, but the simulations are also performed using other standard values like 50 and 100 bars. The near-surface attenuation of upward propagating seismic waves is represented by kappa factor (κ). The shape of the Fourier spectra at the high-frequency end is controlled by κ value, which depends on the shear-wave velocity at shallow depth. No reported value of κ exists in study region, so distinctive estimations of κ were worked beginning from 0.03 to 0.08 in little strides of 0.01, and the best fit was found for 0.04. Local site conditions beneath the site of interest, play an important role in modifying the amplitude, frequency and duration of waves. In our study, site effects are estimated at all sites using H/V spectral ratio method (Nakamura 1989). Utilizing every single conceivable blend of Quality factor, kappa, stress drop and site amplification, a sum of 130 simulations have been done at 22 sites where recorded strong ground motion data is accessible. For every simulation, RMS error is checked between simulated and recorded one. Finally, the combination of parameters providing minimum RMS is selected for simulation. Table 1 gives the range of values for different parameters used in synthesis as well as final chosen.

5 Amplification

It is understood that there can be huge irregularity in nearby site conditions, and subsequently the ground motion at the surface can be completely not the same as that at the underlying rock layer. So local site effects must be studied carefully in seismic hazard studies.

Delhi is a city where soil varies at few meters. In order to have a precise knowledge of ground motion from future earthquake at soil sites, site effects must be found as close as possible. Many approaches are accessible in literature to gauge site effects due to local site conditions (Borcherdt 1970; Andrews 1986; Lermo and Garcia 1993; Iwata and Irikura 1986; Tinsley et al. 2004). The best technique to access site effects is to divide the Fourier spectrum of soil site by that of rock site, so-called standard spectral ratio (SSR) technique (Borcherdt 1970). Site effects in Delhi, using this technique has been worked out by many researchers in past (e.g., Singh et al. 2002; Mittal et al. 2013b, c). Moreover, this technique also requires the simultaneous recording of ground motion at two sites, i.e., soil site and hard rock site (reference site). There are few earthquake recording in Delhi which are not available at reference sites. Thus they cannot be used to access site effects using SSR. Another technique to estimate site effect is the horizontal-to-vertical spectral ratio (HVSR) method proposed for microtremors (Nakamura 1989). Later this technique was successfully applied to strong motion studies (e.g., Lermo and Garcia 1993). In this technique Fourier spectrum of horizontal component is divided by that of Fourier spectrum of vertical component of same site. Nowadays, average shear-wave velocity to 30 m depth (VS30) is being used all over the world as an alternative for site classification. The limitation of site classification based on VS30 is that they do not capture the sediments thickness (Steidl 2000) nor the predominant period of the site. The ground motion predictions based on VS30 are overestimated at short periods and under-estimated at longer periods (Park and Hashash 2004). Ideally, geotechnical investigations amalgamated with geophysical investigations examinations must be done to portray the sub-surface. But such methods are very expensive and time consuming as well. In the present study, the H/V spectral ratios are estimated using the S-wave portions of recording of 5th March 2012 and some other different magnitude earthquakes at different stations.

The acceleration time histories are windowed for a window length of 10–15 s. Depending on availability, we tried to use as many as earthquakes at each site for analysis. The time window was selected following S-wave arrival time, and a 5 % Cosine taper was applied. Windowed time series is transformed into frequency domain using fast Fourier transform algorithm. The obtained Fourier spectra between 0.25 and 25 Hz are smoothed using the windowing function of Konno and Ohmachi (1998) with smoothing constant = 40. Figure 4 show average H/V spectral ratio at all stations.

6 Results

Ground motion is synthesized at all the locations where March 5, 2012, earthquake was recorded using final adopted parameters base on minimum RMS error. It is found that synthesized ground motion matches well with recorded one at most of the sites in terms of PGA, Fourier spectra, Response spectra, predominant period and duration. A comparison of synthesized time histories with recorded one is shown in Fig. 5. This comparison in terms of PGA and predominant period is summarized in Table 2. From here it can be observed that the synthesized PGAs are in close agreement at most of the stations. The comparison somewhat deviate at four sites namely Jaffarpur, IIT, Alipur and NPTI, which may be attributed to variable site effects. In terms of predominant period, comparison is very fair. The rate of decay of PGA with distance in synthesized time histories is found to be same as that of observed ones.

The 5 % damping response spectra are estimated from synthesized acceleration time histories. These response spectra are compared with response spectra of actual ground motion. The comparison of response spectra at some of the sites is shown in Fig. 6. The response spectra matches very well at sites namely Alipur, ANC, DCE, DLU, RGD, IIT, DJB, IMD, and GGSIU. A fair agreement is seen between the response spectra at JNU, JHC, NPTI, NSIT, VIKAS, Sonipat and Noida. At other sites namely Kaithal, Roorkee,

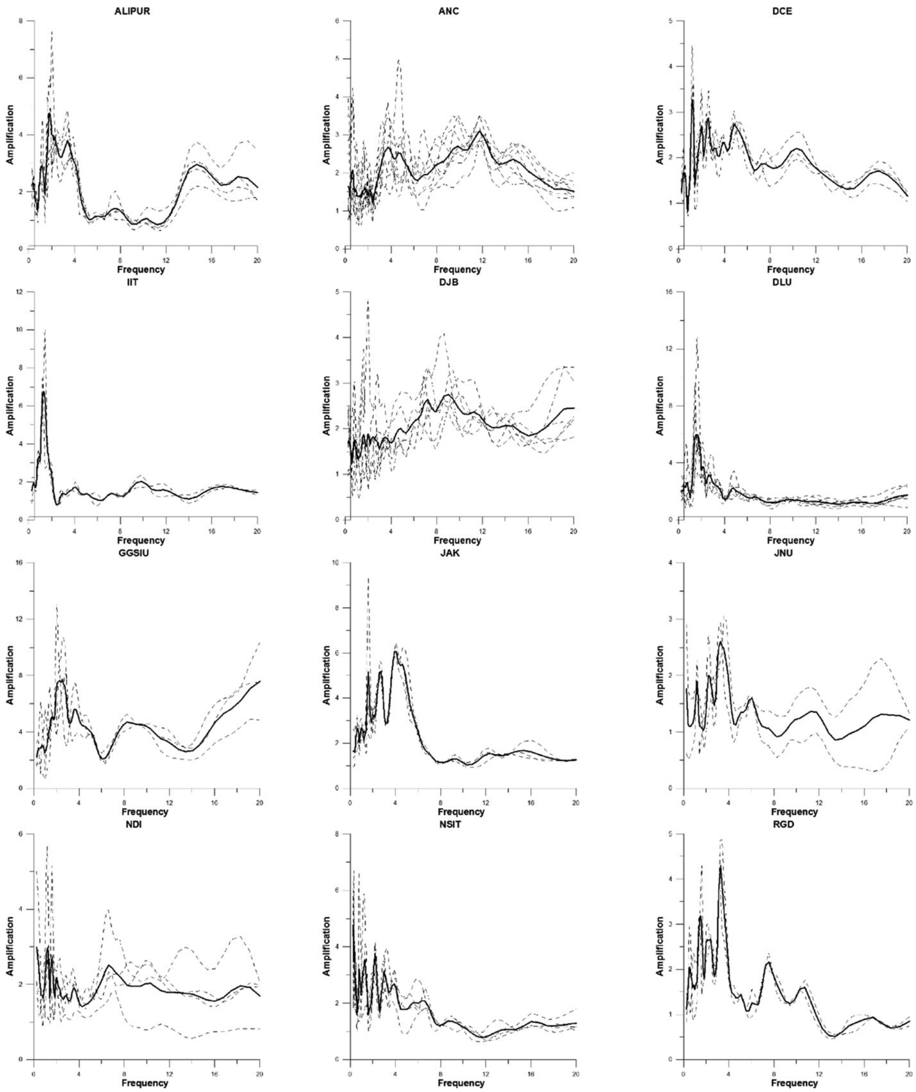

Fig. 4 H/V ratio at few stations where March 5, 2012, earthquake was recorded. Only some of the sites are shown. At each site at least 2–3 different magnitude earthquakes are considered for estimation of amplification. *Dotted lines* at each site show H/V ratio from different magnitude earthquakes, while *solid line* show the average H/V ratio

Palwal, Baraut, Gurgaon and Jaffarpur, some difference in response spectra either at low period or high period is observed.

The overall matching of essential ground motion parameters proves the applicability of modified stochastic method based on dynamic corner frequency in estimating ground motion from future earthquake in Delhi region where recording from large earthquakes are inadequate. The region-specific parameters found in our work are used to find seismic hazard from future earthquake in Delhi region.

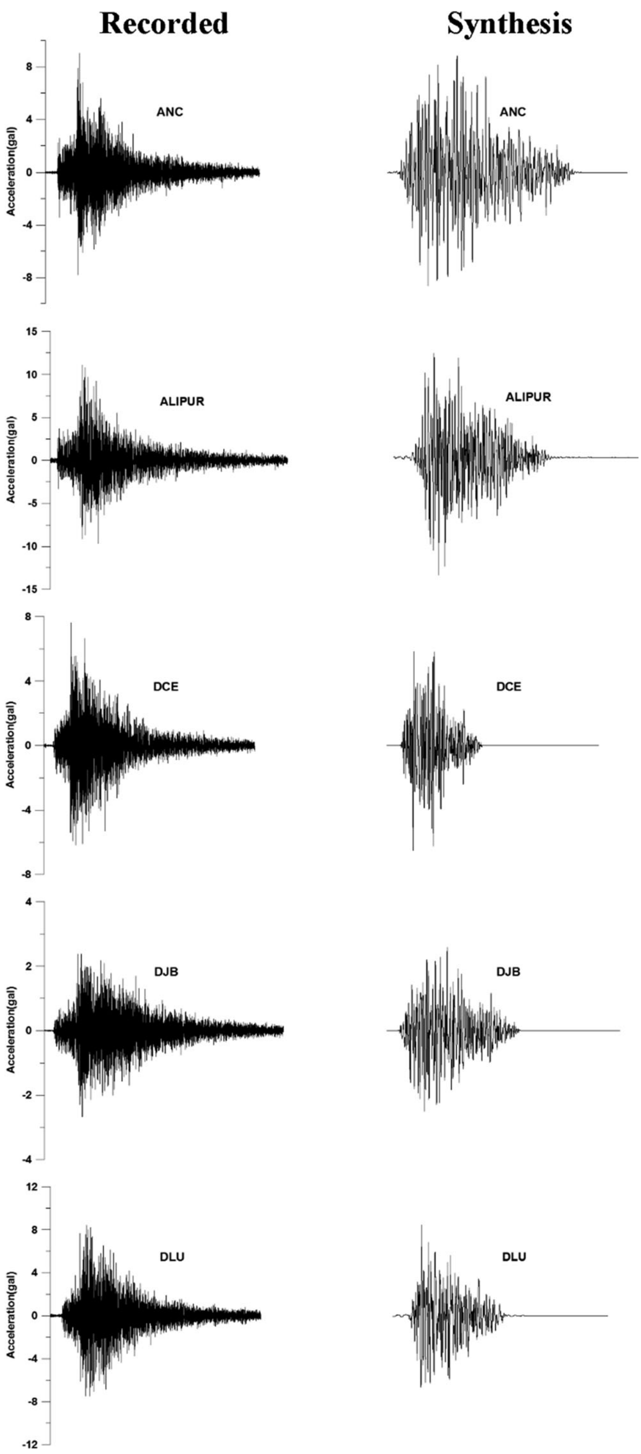

Fig. 5 A comparison of synthesized time histories with recorded ones

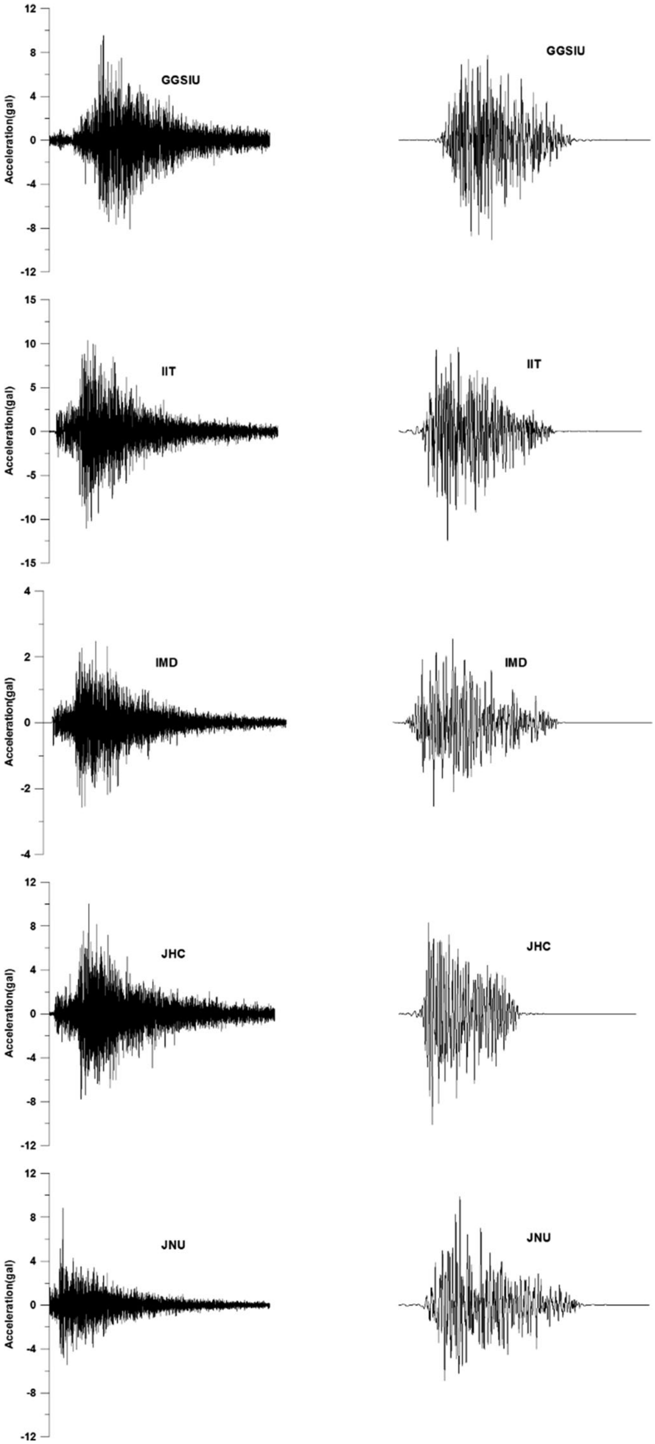

Fig. 5 continued

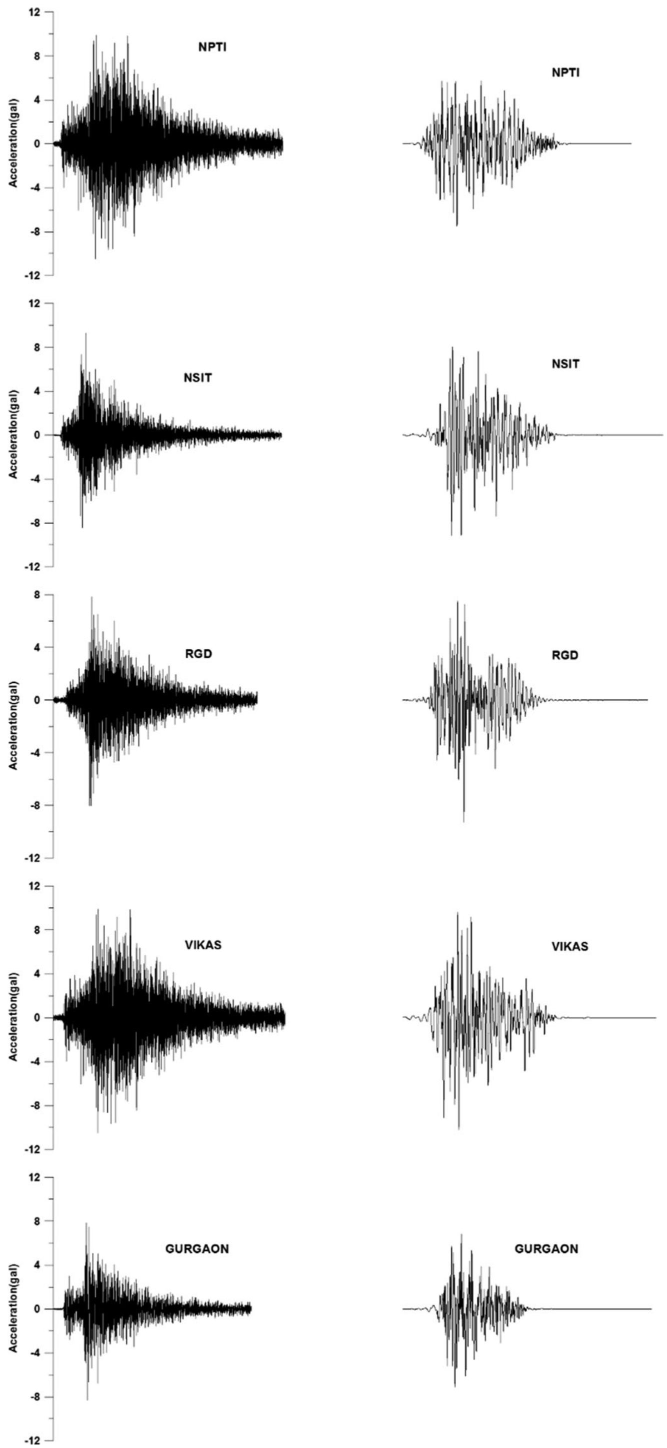

Fig. 5 continued

Table 2 Comparison of synthesized ground motion with observed one in terms of PGA and predominant period

Epicentral distance (km)	Station	Station code	PGA (cm/s^2)		Predominant period	
			Observed	Synthesized	Observed	Synthesized
36	Jaffarpur	JAF	35.60	28.90	0.08	0.16
47	NSIT	NSIT	8.92	9.16	0.14	0.16
49	Vikaspuri	VIK	10.50	10.20	0.13	0.15
50	Sonipat	SON	22.36	19.20	0.13	0.17
52	Technical Uni.	DCE	7.62	6.50	0.13	0.14
53	Raja Garden	RGD	8.03	9.29	0.13	0.13
54	Alipur	ALP	13.40	11.00	0.07	0.07
54	Gurgaon	GUR	6.71	7.11	0.19	0.19
59	Delhi Jal Board	DJB	2.67	2.50	0.07	0.07
61	Delhi Uni.	DLU	8.42	6.88	0.07	0.07
61	IMD	IMD	2.58	2.55	0.12	0.13
61	JNU	JNU	8.85	9.87	0.13	0.13
62	IIT	IIT	15.50	11.00	0.07	0.07
63	Jakir Hussain	JHC	10.00	10.10	0.13	0.19
63	Kashmiri gate	GGSIU	9.55	9.08	0.13	0.14
74	NPTI	NPTI	10.50	7.49	0.14	0.14
76	Baraut	BRT	5.00	6.73	0.25	0.25
78	KalkaJi	ANC	9.03	8.82	0.13	0.09
90	Noida	NOI	7.84	6.34	0.25	0.19
99	Palwal	PAL	5.22	6.05	0.21	0.22
120	Kaithal	KAI	8.85	7.92	0.15	0.17
177	Roorkee	ROO	2.02	1.65	0.19	0.19

GMPEs are generally used to produce strong ground motion data where too much recorded one are not available. We tried to check for validity of GMPEs in Delhi region. A number of attenuation relationships have been derived for Indian region using actual strong ground motion data (e.g., Aman et al. 1995; Singh et al. 1996; Sharma 1998; Sahoo et al. 2000; Parvez et al. 2001; Iyengar and Ghosh 2004; Raghukanth and Kavitha 2014 to name a few). All of these relations have proposed general ground motion estimation in active Himalayan region. Only some of these relations look valid for Delhi region. Iyengar and Ghosh (2004) derived attenuation relationship for PGA in Delhi based on strong motion data from earthquakes recorded in Himalayan belt. Previously Sharma (1998) and Singh et al. (1996) derived attenuation relation in Himalayan region using some of the earthquakes. Figure 7 shows PGA for Mw 4.6 earthquake computed from different researchers along with recorded PGA. It is seen clearly that the all relations generally greatly overestimate the PGAs in comparison to recorded during 2012 event. The only relation that looks somewhat reasonable is Sharma (1998), which is in small agreement with recorded PGA at some places. From here it can be conclude that attenuation relations may not be appropriate for PGA estimation in Delhi.

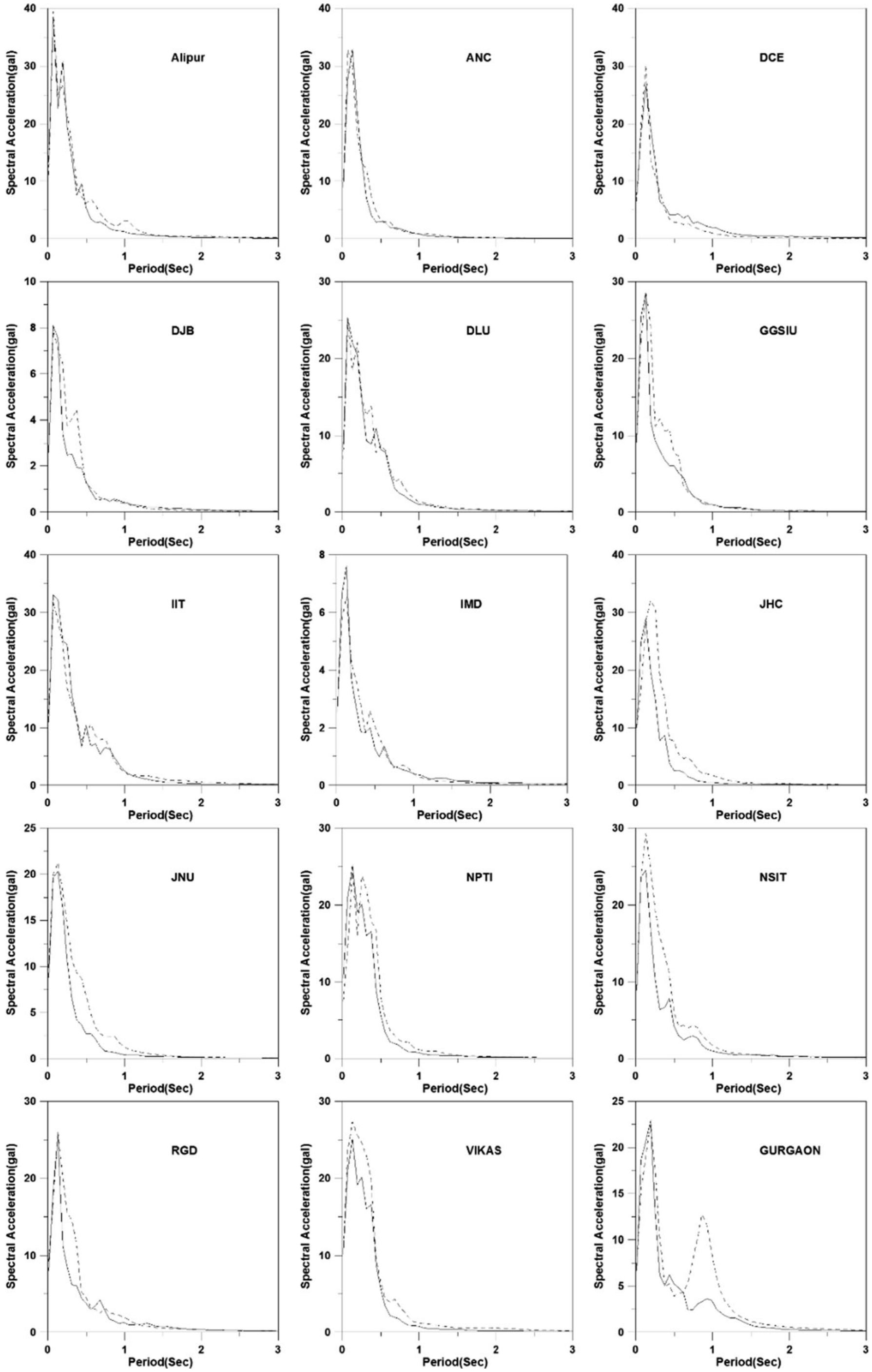

Fig. 6 Comparison of response spectra of observed (*solid line*) with synthesis (*dotted line*). The comparison is in agreement at most of the stations

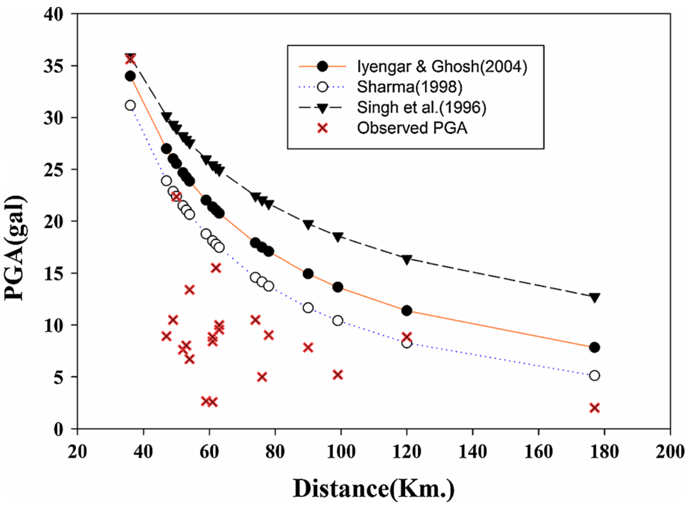

Fig. 7 PGA as a function of hypocentral distance, *R*, for the 2012 Delhi earthquake (Mw 4.6). The figure also shows the predicted PGA for Mw 4.6 earthquake from attenuation relation given by different researchers

Table 3 Significant earthquakes in and around Delhi recorded by strong motion network

Date	Lat (°N)	Long (°E)	Magnitude	Region	Distance from Delhi (km.)
25/11/2007	28.57	77.10	4.2	Delhi Metropolitan	17
24/02/2010	28.60	76.90	2.5	Rohtak, Haryana	32
26/01/2011	29.00	77.20	3.2	Haryana–Delhi border	36
18/02/2011	28.60	77.30	2.3	Delhi	12
07/09/2011	28.60	77.00	3.9	Haryana–Delhi border	23
05/03/2012	28.75	76.65	4.6	Haryana–Delhi border	61
12/03/2012	28.90	77.30	3.5	Baghpat, Uttar Pradesh	26
10/04/2013	29.00	76.60	3.5	Haryana–Delhi border	70
11/10/2013	28.80	76.70	3.3	Haryana	52
11/11/2013	28.60	77.20	3.1	Delhi	9
11/11/2013	28.60	77.20	3.3	Delhi	9
11/11/2013	28.60	77.20	2.5	Delhi	9
11/11/2013	28.60	77.10	2.8	Delhi	14
04/09/2014	29.30	77.20	3.5	Uttar Pradesh–Haryana border	69
14/01/2015	28.90	77.00	3.3	Sonipat, Haryana	32

All distances are taken from IMD (NDI) site

7 Ground motion from future earthquake

The occurrence of an Mw 4.6 event on March 5, 2012, at Delhi–Haryana border is a reminder about the active nature of different tectonic sources in and around Delhi. The earthquake of March 5, 2012, was found to occur on MDF in the proximity of Delhi

(Fig. 2). This earthquake was widely felt in Delhi, Haryana and other states; however, no damage was reported. Delhi has also experienced several lower magnitude earthquakes in the past from faults surrounding Delhi. The occurrence of these lower magnitude earthquakes in the proximity of Delhi calls for the seismic hazard scenario of city from future higher magnitude earthquake. Table 3 depicts some of the recent lower magnitude earthquakes occurred in proximity of Delhi.

In addition, Delhi and its neighborhood has experienced slight to moderate intensity earthquakes based on historical and instrumentally recorded data. At least 5 moderate earthquakes which have affected the region are the earthquake of July 15, 1720 ($M = 6.5$ on Richter scale) near Delhi; the earthquake of September 1, 1803 ($M = 6.7$) near Mathura (Uttar Pradesh); the earthquake of October 10, 1956 ($M = 6.4$) near Bulandshahr; the earthquake of August 27, 1960 ($M = 6.0$); near Delhi (Gurgaon); the earthquake of August 15, 1966 ($M = 5.6$) near Moradabad.

Delhi earthquake of August 27, 1960, is reported to have a magnitude 6.0 with focal depth of 109 km. But recently, Singh et al. (2013) reviewed this earthquake and found moment magnitude to be 4.8 occurring at shallow depth, i.e., ≤30 km. October 10, 1956, earthquake is considered to be the main recorded earthquake near Moradabad fault. The earthquake of August 15, 1966 ($M = 5.6$) may also be attributed to Moradabad fault. Oldham (1883) mentioned July 15, 1720, earthquake as a terrible earthquake in which much destruction was caused. The earthquake of August 31, 1803, near Mathura is associated with this RGBF zone in addition to its association with the Mathura fault zone.

Occurrence of these earthquakes suggests the possibility of M 6.5 magnitude in the proximity of Delhi, but it does not mean that such event may occur in a certain return period. Also an earthquake of magnitude 7.0 on the Richter scale, that was once considered hypothetical, is today a very real possibility (BIS 2002).

In past few researchers worked out for seismic hazard of the city from future earthquake. Singh et al. (2002) estimated ground motion in the city from greater M 8 and 8.5 magnitude earthquakes located in Himalayas. They estimated ground motion in city at four different sites. Bansal et al. (2009) estimated hazard from future Mw 5.0 earthquake at 9 strong motion sites in the city using Empirical Green's function technique. They claimed the hazard to be valid if future earthquake occurs at same focus of smaller earthquake used in synthesis. Mittal et al. (2013a, 2015) estimated hazard from future M 5.5 and 6.0 magnitude earthquakes in the city using empirical Green's function approach. Although they estimated ground motion at 55 sites, but they also claimed ground motion to be valid if earthquake occurs at same location of elementary earthquake. Chopra et al. (2012) estimated ground motion in Delhi from future large magnitude earthquake located in Himalayas. In their analysis, they considered Delhi to be one site only.

Following the above seismic features in the region, ground motion is estimated from future Mw 6.0 and 6.5 magnitude earthquakes by considering source in four regions. The fault dimensions are selected using Wells and Coppersmith (1994) after verifying with Leonard (2010) and Hanks and Bakun (2008). For a case of Mw 6.0 the fault dimensions are 12×8 km, while for Mw 6.5 these are 25×12 km. The considered regions are MDF, GBF, Mathura fault and Moradabad Fault. The PGA values are found to be maximum when the source is placed in MDF zone near to Delhi–Haridwar ridge, which is considered to be primarily responsible for modern seismicity in Delhi. The PGA values for Mw 6.0 ranges between 20 and 209 gal, while for Mw 6.5 these are found to be between 30 and 323 gal, of course the lower values occurring at rock sites like DJB and IMD (NDI). The PGA values are found to occur higher on both sides of Yamuna River, which may be attributed to local site effects. The contours of PGA value for Mw 6.5 are shown in Fig. 8.

On basis of PGA, it is worth to say that hazard may be maximum in eastern and North-Western part of city and moderate in other parts. The characteristic frequency (predominant period) corresponding to highest spectral acceleration is estimated and plotted (Fig. 9). As expected, characteristics frequency is found be less along Yamuna River, which may be due to heavy sedimentation along the river. Characteristics frequency is found to be maximum, i.e., ≥4 Hz along quartzite formation.

The response of a structure to an earthquake motion is commonly evaluated using response spectra, which are defined as the graphic relationship between the maximum responses of single-degree-of-freedom (SDOF) systems and their natural periods. Different period waves (short-period and high-period waves) affect different kind of buildings (small buildings and taller buildings). Resonance as a result of matching of structure natural frequency with incoming wave natural frequency causes structure to vibrate rigorously.

So keeping these points in mind, seismic hazard in Delhi is estimated in terms of response spectra (5 % damping) from simulated accelerograms at four different periods. The contours of spectral acceleration are plotted at four periods, i.e., 0.1 s (small structure),

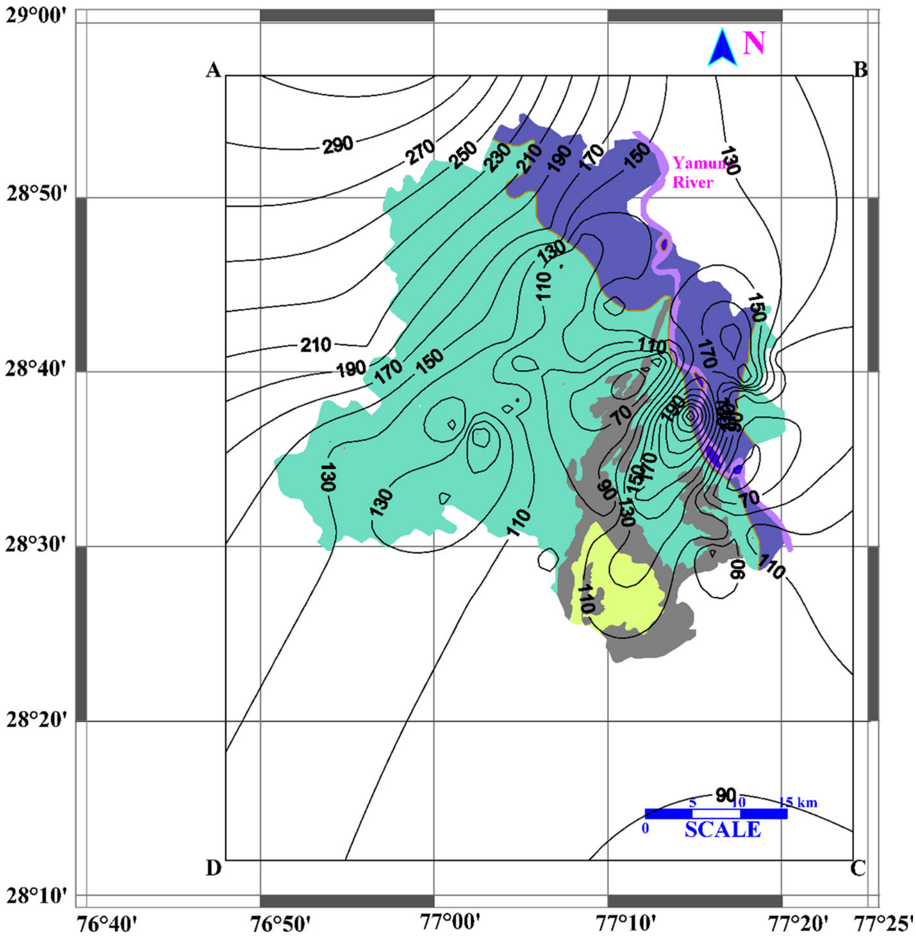

Fig. 8 Contour map of synthesized PGA for Mw 6.5 at different sites in Delhi

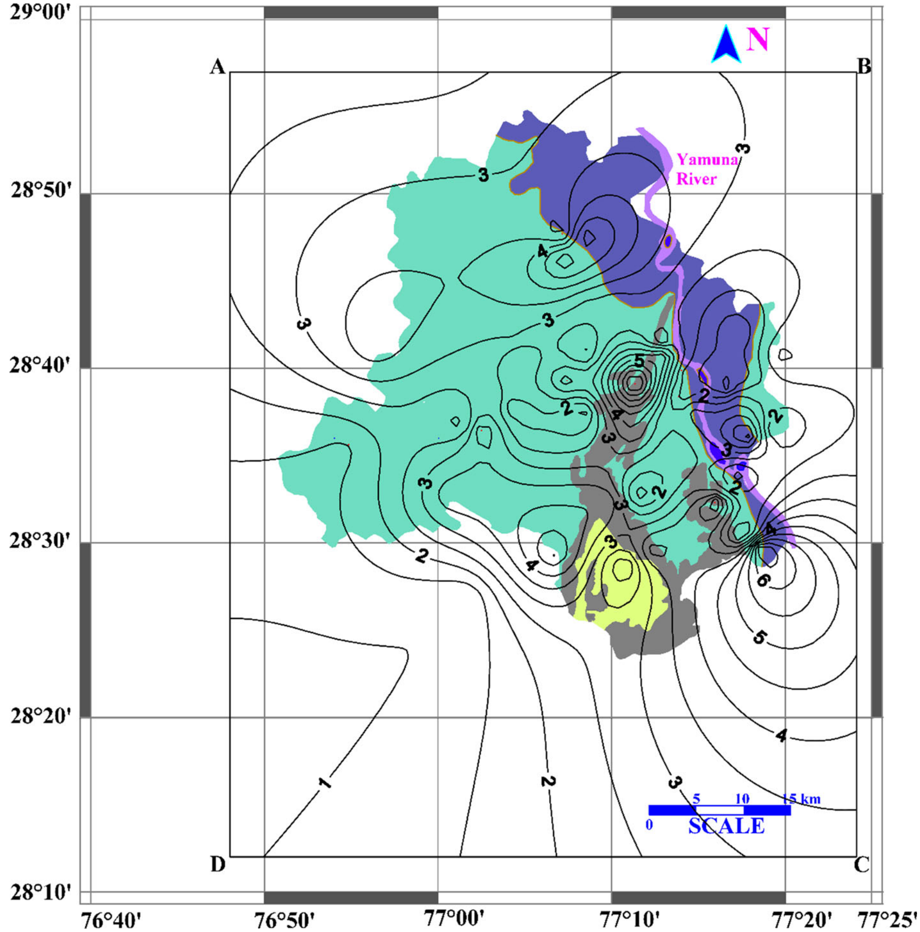

Fig. 9 Contour map showing the spatial distribution of characteristics frequency in different parts of the city

0.3 s (2–3 story buildings), 0.5 s (4–5 story buildings) and finally 1 s (taller buildings). These contours are shown in Fig. 10a–d.

For a case of 0.1 s, Sa values range between 50 and 516 gal, while for 0.3 s, these values range from 60 to 1050 gal. At short periods, higher Sa values are found to occur on eastern and western side as well as joining of geological formations. This means the short story buildings in these areas are going to be affected by incoming high frequency (short-period waves). Maximum care should be taken while constructing new small structures in these areas. Also the existing structures should be strengthened to withstand ground vibrations. For 0.5 s, spectral acceleration values vary from 47 to 850 gal. Although Sa values at some places for 0.5 s are less as compared to 0.3 s, but these are uniformly distributed. Sa values for 0.1 and 0.3 s were observed to be maximum toward eastern and north-western parts of Delhi, but for 0.5 s these look to be generally more than 200 gal at all the places in Delhi. So it can be informed that 5 story structures or thereabouts in all aspects of Delhi may be under danger from higher magnitude earthquakes in proximity of Delhi.

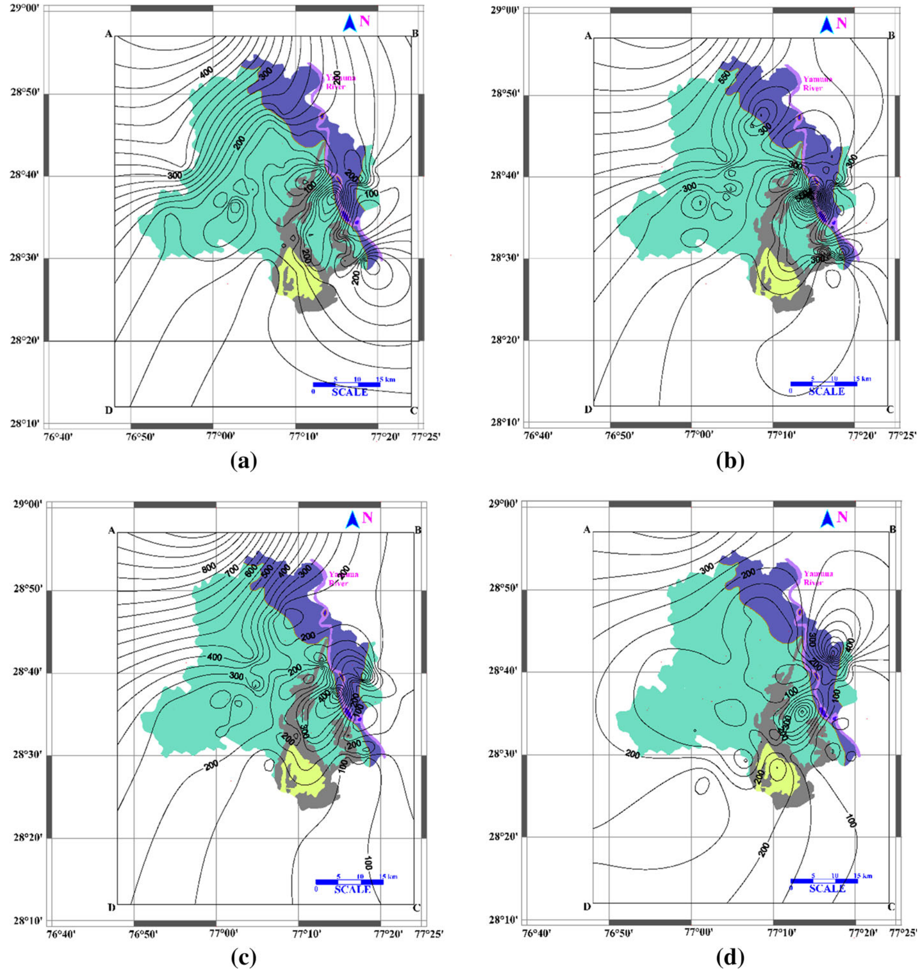

Fig. 10 **a–d** Figure showing the distribution of spectral acceleration values at different periods. **a** 0.1 s, **b** 0.3 s, **c** 0.5 s, **d** 1.0 s

For a case of 1 s, Sa values vary from 45 to 700 gal, maximum toward the eastern side of city. At other places other than eastern side, Sa values are less. Thus high rise building in eastern part of the city should be strengthened enough to withstand ground motion from earthquakes.

8 Conclusions

Delhi the city of twelve million people is susceptible for earthquake related injuries in the future. The city has experienced some of the historical earthquakes in the past. In recent time also many lower magnitude earthquakes got recorded in Delhi. Many seismic sources are responsible for this kind of seismic activity in or near Delhi. In addition, Delhi also gets threat from seismic activity in Himalayas. Himalayas are only 250–300 km away from

Delhi. In view of this, seismic activity in Delhi may be attributed to local geological faults and active Himalayan faults. Although in recent time, no higher magnitude earthquake occurred in Delhi, but its occurrence cannot be denied.

Seismic hazard assessment is the process of evaluating the design parameters of earthquake ground motion at any site. In present work, seismic hazard from future earthquake is being worked out for Delhi region. The hazard is computed in terms of different strong motion parameters like PGA, characteristics frequency and Sa.

Stochastic finite modeling technique based on dynamic corner frequency initially is used to produce the ground motion for greater magnitude earthquakes using region specified parameters. Our predictions show that an Mw 6.0 earthquake will produce PGA $\sim$20–209 gal, the lower values occurring at hard rock sites like IMD and DJB. Similarly Mw 6.5 earthquake may produce PGA $\sim$30–323 gal. On basis of PGA, it is worth to say that hazard may be maximum in eastern and North-Western part of city and moderate in other parts. As expected, characteristics frequency is found be less along Yamuna River, which may be due to heavy sedimentation along the river. Characteristics frequency is found to be maximum, i.e., $\geq$4 Hz along quartzite formation. At low periods, higher Sa values are found to occur on eastern and western side as well as joining of geological formations. This means the short story buildings in these areas are going to be affected by incoming high frequency (low-period waves). For intermediate period, i.e., 0.5 s Sa values look to be generally more than 200 gal at all the places in Delhi. Thus, it may be concluded that five story structures or thereabouts in all aspects of Delhi may be under danger from higher magnitude earthquakes in proximity of Delhi. Proper care must be taken to design these kind of structures so as to withstand ground motion from higher magnitude earthquakes.

The Sa maps acquired in this study can be utilized to survey the seismic danger of the region and identify vulnerably susceptible areas in and around Delhi. The hazard maps displayed here give a suitable premise to reinforce the manufactured environment in Delhi to so as to decrease the normal misfortunes extensively.

Acknowledgments The authors are profusely thankful to Ministry of Science and Technology of Republic of China for funding the project, under which this study was carried out. The authors really acknowledge www.pesmos.in for providing strong motion data to be used in study. Authors are really thankful to Prof. Dariush Motazedian for providing EXSIM Code. GMT software from Wessel and Smith (1998) was used in plotting part of the figures and is gratefully acknowledged. The comments from two anonymous reviewers helped in improving the manuscript.

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