Estimation of Ground Motion in Delhi using 7th September 2011 Earthquake

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SUMMARY:
Although Delhi, the national capital of India is close to rupture areas of large and great Himalayan earthquakes, a quantitative study of the amplification of seismic waves in the region is still lacking. Delhi has substantially varying soil cover. Thus, study of site characteristics becomes very important in Delhi and it is essential that this study should be done for large number of sites within the city. In recent time two earthquakes occurred in Delhi on 25th November 2007(Mw=4.2) and 7th September 2011(Mw=4.2). These earthquakes were widely felt at different locations in Delhi as well as National Capital Regions (NCR) and were recorded at many strong motion stations installed in Delhi. Records of September 2011 earthquake are used to estimate the site effects at seven of these sites using standard spectral ratio (SSR) technique. Site effects in Delhi using SSR technique were already available at 55 sites from previous studies. Out of these 55 sites, 7th September 2011 earthquake was recorded at five sites which further improved our estimation of effects at these five sites. Then, through the computed transfer functions, 5% damping horizontal acceleration response spectra are estimated at 57 different sites in Delhi using random vibration theory (RVT) approach. Finally the spectral acceleration maps at four different natural periods are produced for this earthquake. The spectral acceleration map is strongly influenced by shallow geological and soil conditions as indicated in the contour maps.

Key words: Delhi, NCR, IMD, 7th September, SSR

1. INTRODUCTION

The recent spurt in earthquake activity in South East Asia has enhanced the consciousness about the increasing vulnerability that large population in region close to Himalayas is confronted with and is causing significant social and economic impacts. The observation of strong motion and the investigation of the destruction from these earthquakes provide the disciplines of seismology and earthquake engineering with informative and valuable data, experiences and lessons, and raise a number of important scientific challenges. Himalaya is among the most seismically active regions in the world, and has experienced several earthquake disasters during historical times. In the last fifty years, population of India has doubled and resulted in very rapid growth of settlements, especially in urban areas. Presently about 50 million people in India, living in Himalayan region and adjoining plains, are at risk from earthquakes. During the last 200 years, the Indian peninsula has experienced several great earthquakes, namely,. Kutch, Gujrat(1819), M=8.0; Assam earthquake(1897), M=8.7; Kangra earthquake(1905), M=8.0; Bihar-Nepal earthquake(1934), M=8.3; Assam earthquake(1950), M=8.5. Most of the parts of Himalayas comprising North India and North-eastern India are mapped as either seismic zone IV or V in the seismic zonation map of India (on a scale of II to V). Two of the recent significant earthquakes in North India are the Uttarkashi earthquake of 1991 (M_w 6.8) and Chamoli earthquake of 1999 (M_w 6.5).

Despite being one of the most seismically active regions of the world, the strong motion (SM) data set in India is, in general, very sparse. For this reason, the seismic hazard in India, till now, has been estimated using either the intensity data or attenuation relations, derived for other regions (e. g. Khattri et al., 1984; Krishna, 1992). Therefore, in the absence of adequate SM data, the ground motion can be synthesized from postulated earthquakes. Since this is the key input in earthquake resistant design, modeling of available strong motion data is a natural starting point.

It has long been established that different soil types respond differently when subjected to ground motion from earthquakes. Usually, the younger, softer soils amplify ground motion relative to older, more compact soils or bedrock (Aki, 1988). Assessing local site effects reliably is one of the crucial aspects of seismic hazard estimation. The site effect alters ground motions and changes the damage potential of a large earthquake. Many methods are available for accessing the site effects. These methods can be categorized into two major groups: the analytical (theoretical) and the empirical. Both methods have their respective advantages and limitations. The empirical methods are found to be more effective as they are based on actual recorded ground motions. The empirical methods use two techniques: reference site and non-reference site techniques. One of the reference site techniques is standard spectral ratio (SSR) technique which is defined as the spectral ratio of a sedimentary site with respect to a bedrock reference site (e.g., Borcherdt, 1970). The assumption is that the two sites have similar source and path effects and the reference site has the flat spectrum response. This technique has been used previously in many geological environments (e.g. Bansal et al., 2009, Borcherdt et al.,1989, Singh et al., 1988, Singh et. al., 2002, Singh et al., 2007, Mittal, 2011).

Delhi, the National Capital of India, faces a high seismic hazard, not only due to the seismically active Himalayas and complex local tectonics, but also due to local site effects. The city of more than 10 million inhabitants, lies approximately 200 km from Main Boundary Thrust (MBT) and 300 km from Main Central Thrust (MCT), the two most active thrust planes of the Himalayas. Delhi falls in the Seismic Zone IV that has high seismicity. Many studies dealing with site effect, microzonation, estimation of ground motion, and seismic hazard are performed in Delhi(e.g., Khattri, 1999; Iyengar, 2000; Singh et al., 2002; Mukhopadhay et al., 2002; Nath et al., 2003; Sharma et al., 2003; Parvez et al., 2004; Iyengar and Ghosh, 2004; Parvez et al., 2006; Mohanty et al., 2007; Bansal et al., 2009; Mundepi et al., 2010; Singh et al., 2010). Unfortunately, earthquake recordings in Delhi, except at Ridge Observatory (NDI), are still very limited. As a consequence, the results of some of these studies are poorly constrained by earthquake recordings

Given this scenario, the best strategy to map ground motion in the city from postulated earthquakes is to estimate it first at a hard reference site and, then, through known transfer functions of different sites with respect the reference site, to compute it at these sites through the application of random vibration theory. Since NDI is situated on hard rock where digital recordings of local and regional earthquakes are available, this site may be conveniently taken as the reference site. Singh et al. (2002) and Bansal et al.(2009) used this approach to synthesize ground motions at NDI in Delhi from postulated large/great earthquakes in the central seismic gap of the Himalayan arc and local earthquake respectively. The motions at the reference site of NDI were synthesized using an EGF summation technique introduced by Ordaz et al. (1995). They used transfer functions of six sites w.r.t NDI (determined from strong motion records) to estimate ground motion at these sites. Mittal (2011) used similar approach to estimate ground motion at 55 sites in Delhi.

In recent time two earthquakes occurred in Delhi on 25th November 2007(Mw=4.2) and 7th September 2011(Mw=4.2). These earthquakes were widely felt at different locations in Delhi as well as National Capital Regions (NCR) and were well recorded in the epicentral region. Here, we take advantage of transfer functions from 7th September 2011 earthquake and earlier studies (Mittal, 2011) to estimate response spectra of postulated local M_w=5.5 in Delhi. For input ground motions at the reference site of NDI, we generated time histories following the methods used by Singh et al. (2002) and Bansal et al. (2009) for local event of 25th November 2011 earthquake. Because of substantially increased number of transfer functions now available, this work provides much more extensive coverage than earlier studies and enables us to plot iso-spectral acceleration lines.

2. LOCAL GEOLOGY

The rock formations exposed in the Delhi area are mainly quartzite of the Alwar series of the Delhi Super group (± 1500 million years in age), unconformably overlain by unconsolidated Quaternary to Recent sediments (less than 1.65 Ma) (Fig. 1). The terrain is generally flat except for a low NNE-

SSW trending Delhi Ridge in the southern and central part of the area which consists of Quartzite while the Quaternary sediments, comprising the older and newer alluvium, cover the rest of the area. The older alluvium comprises silt, clay with minor lenticular fine sand and kankar beds. The newer alluvium mainly consists of sand, silt and clay occurring in the older and active flood plains of the Yamuna River. Thickness of the alluvium, both on the eastern and western side of the ridge, is variable but west of the ridge, it is generally thicker (290 m).

3. DATA AND IIT ROORKEE NETWORK

In 2007, a 20 station Delhi Digital Strong-Motion Network(DDSMN) became operational in Delhi. This network is operated by Indian Institute of Technology (IIT), Roorkee (Kumar et al., 2012). Fig. 1 shows the location of the stations and the surface geology of Delhi. This instrumentation has recorded many earthquakes (regional as well as local) since its installation (Table 1). Two well recorded earthquakes by this network are 25th November 2007(Mw=4.2) and 7th September 2011(Mw=4.2). 25th November 2007 earthquake was recorded at 5 stations of this network. This earthquake also got recorded at 6 other stations of strong motion instrumentation network (SMIN) by IITR under which 300 accelerographs have been installed in different part of country. 7th September 2011earthquake was well recorded by DDMSN at 8 stations in Delhi, while it was recorded at 2 other stations of SMIN. Our analysis of this dataset is a step towards addressing a missing section in our knowledge of local earthquakes in Delhi and the associated seismic hazard.

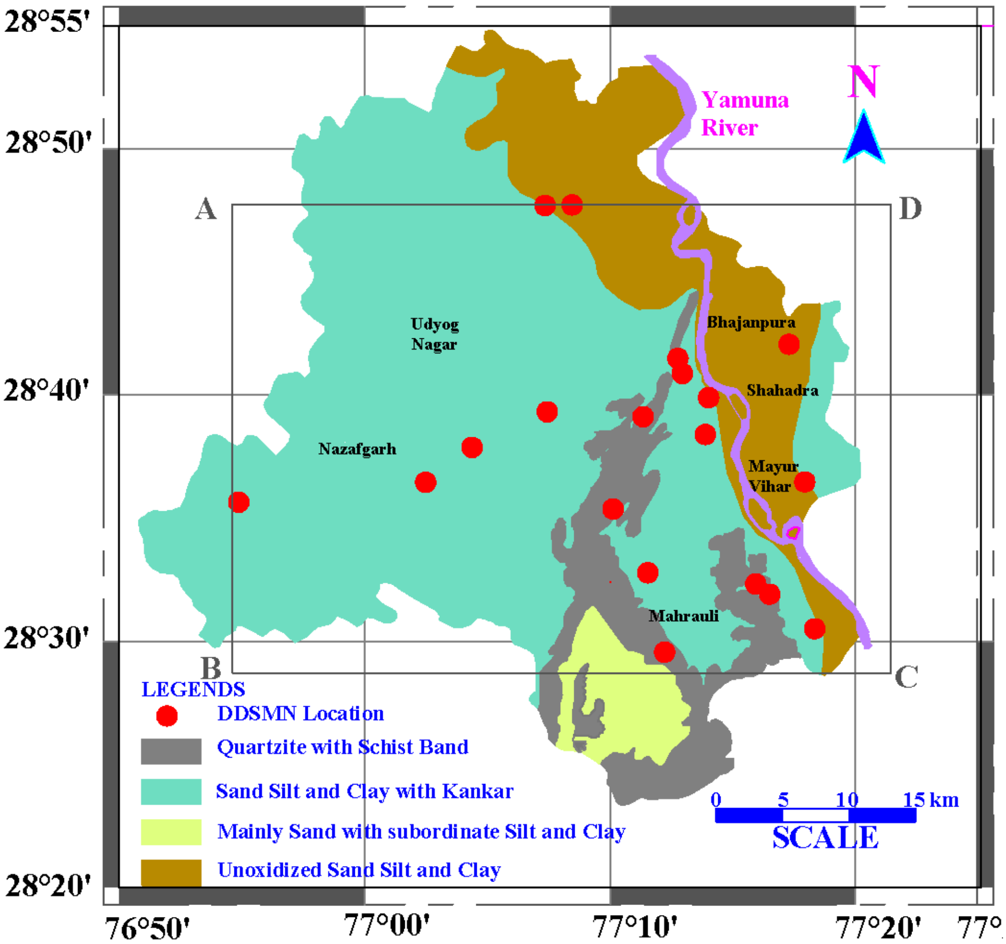


Figure 1. Location of the DDSMN stations and the surface geology of Delhi. ABCD shows the study area.

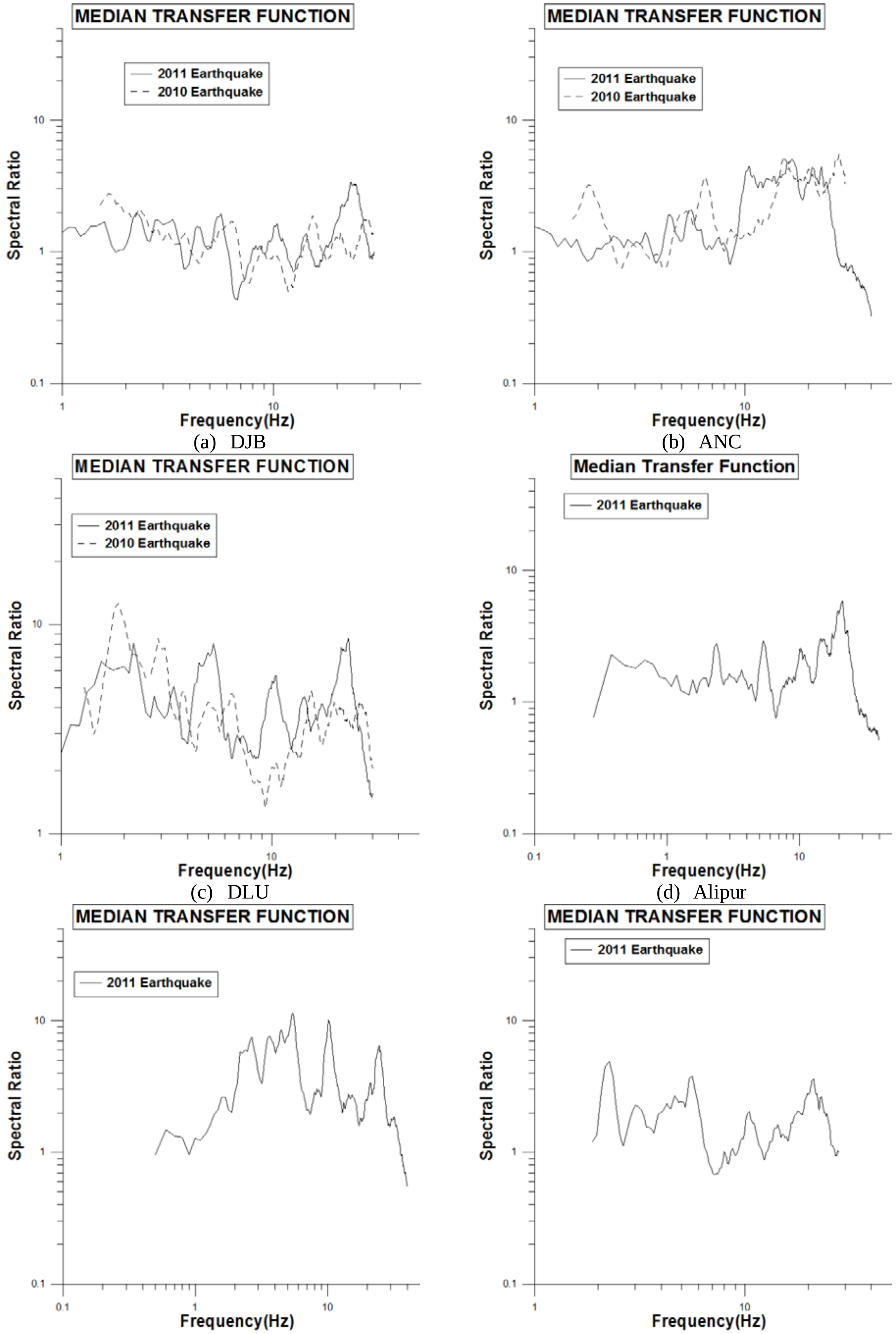
Table 1. Significant earthquakes in and around Delhi recorded by IITR network. All distances are taken from IMD ridge.

Date	Lat (^{0} N)	Long(^{0} E)	Magnitude	Region	Distance from Delhi, km
25/11/2007	28.57	77.1	4.2	Delhi Metropolitan	15
24/02/2010	28.60	76.90	2.5	Rohtak, Haryana	32
18/01/2011	28.90	64.00	7.4	Southwestern Pakistan	1287
26/01/2011	29.00	77.20	3.2	Haryana-Delhi Border	35
18/02/2011	28.60	77.30	2.3	Delhi	13
04/04/2011	29.60	80.80	5.7	Nepal India Border Region	362
07/09/2011	28.60	77.00	4.2	Haryana-Delhi Border	23
05/03/2012	28.70	76.70	4.9	Haryana-Delhi Border	50
12/03/2012	28.90	77.30	3.5	Baghpat, Uttar Pradesh	25

4. SITE EFFECT IN DELHI DURING 7TH SEPTEMBER 2011 EARTHQUAKE

Many studies have been performed on site amplifications in the Delhi region. These studies are based on (a) Analysis of microtremors (e.g. Mukhopadhyay et al.,2002 ; Mundepi et al., 2010), (b) Earthquake recordings (Singh et al., 2002; Nath et al., 2003; Bansal et al., 2009; Mittal, 2011), (c) Results of bore hole penetration tests (Iyengar and Ghosh, 2004), and (d) Numerical modeling of wave propagation (e.g., Parvez et al.,2004;2006). Singh et al. (2002) used the recording of Chamoli earthquake(Mw=6.5) of 1999 to estimate transfer functions at three locations in Delhi. Bansal et al.(2009) estimated the site effects at a few sites in Delhi from the earthquakes of 2001 and 2004. However Mittal (2011) estimated transfer functions at 55 sites in Delhi using recordings of 13 earthquakes. One of the earthquake used by Mittal (2011) for estimation of site effects was of 24 March, 2010, recorded at 12 locations in Delhi by DDSMN. In present work, transfer functions are estimated at 7 sites using recordings of September 2011 earthquake. However transfer functions at four sites out of these seven are already available from March 2010 earthquake by Mittal(2011), but more number of transfer functions at same site will provide the opportunity to validate the results. Standerd spectral ratio(SSR) with respect to the hard NDI site are shown in Figs. 2(a-f). We note that the wave paths and the radiation patterns from these local events to the stations differ. Thus, the differences in the spectra of a given event at different sites are not only due to local site effects. However it seems reasonable to assume that the superficial geology is the major factor causing the difference.

Fig. 2(a-b) shows SSRs at DJB and ANC where both of the local ones were recorded. The SSRs during the two earthquakes are quite similar. However, the SSR at DLU (Fig. 2c) for the two earthquake is not so much similar. The difference in the focal mechanism and the depth may be responsible for the observed difference in the SSRs at DLU for the two shallow earthquakes. However, the SSRs computed from the recordings of far sources may provide a reasonably reliable estimation of SSRs from close and intermediate distance sources. Figs. 2(d-f) shows SSRs at Alipur, Jakir Hussain and NSIT for September 2011 earthquake.



(a) DJB (b) ANC (c) DLU (d) Alipur (e) Jakir Hussain (f) NSIT

Figure 2. Transfer Function at different sites in Delhi from 2011 earthquake

5. GROUND MOTION IN DELHI FROM 5.5 MAGNITUDE

In the present work empirical Green's functions (EGFs) method proposed by Ordaz et al. (1995) is applied to synthesize the expected ground motions from local earthquake namely Delhi Metropolitan (Delhi - Haryana Border, Region) earthquake of Nov. 25, 2007. One significant advantage of the EGF method is that the wave propagation and the site effects are included in the recordings. The method proposed by Ordaz et al. (1995) to synthesize ground motion for a target event, using a recording of a small event as EGF, is based on adding N scaled EGF records, each differed in time with a random delay. The probability distribution of the delays is such that, on the average, the simulations follow an ω^2-source spectral scaling at all frequencies. It is a point-source approximation and does not include directivity effects. We modelled the recording at NDI of the local earthquake from Nov. 25, 2007 (28.57N, 77.10E; depth=30.0 km; Mw 4.2) as the EGF and used $\Delta\sigma$ = 130 bars for both the EGF and the target events. Fig. 3 illustrates a synthesized N-S accelerogram of the postulated earthquake.

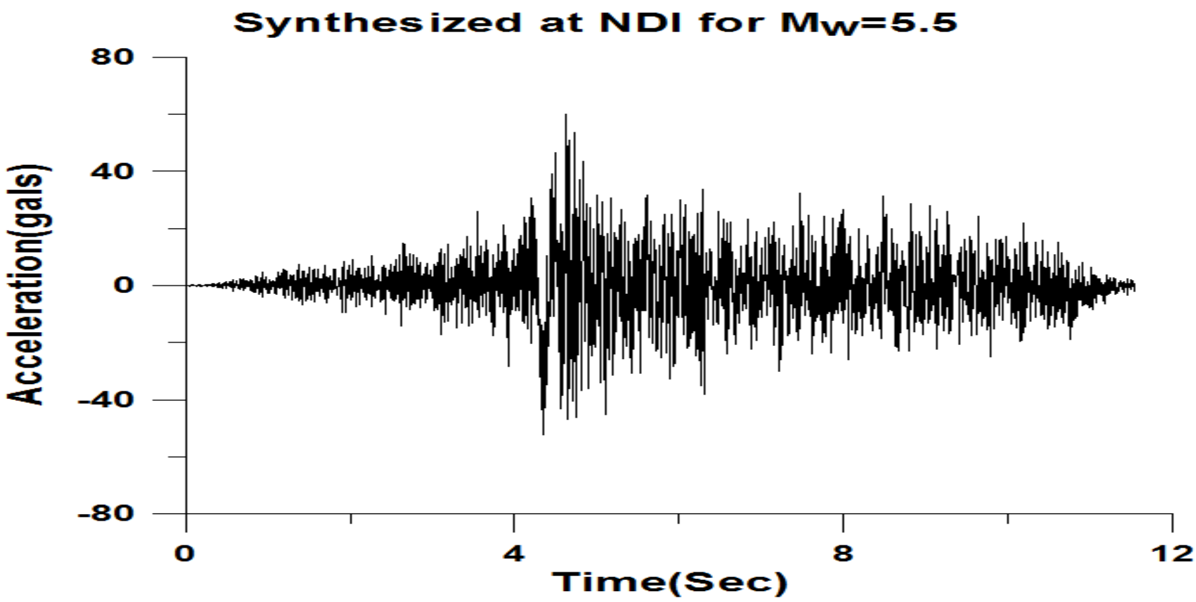


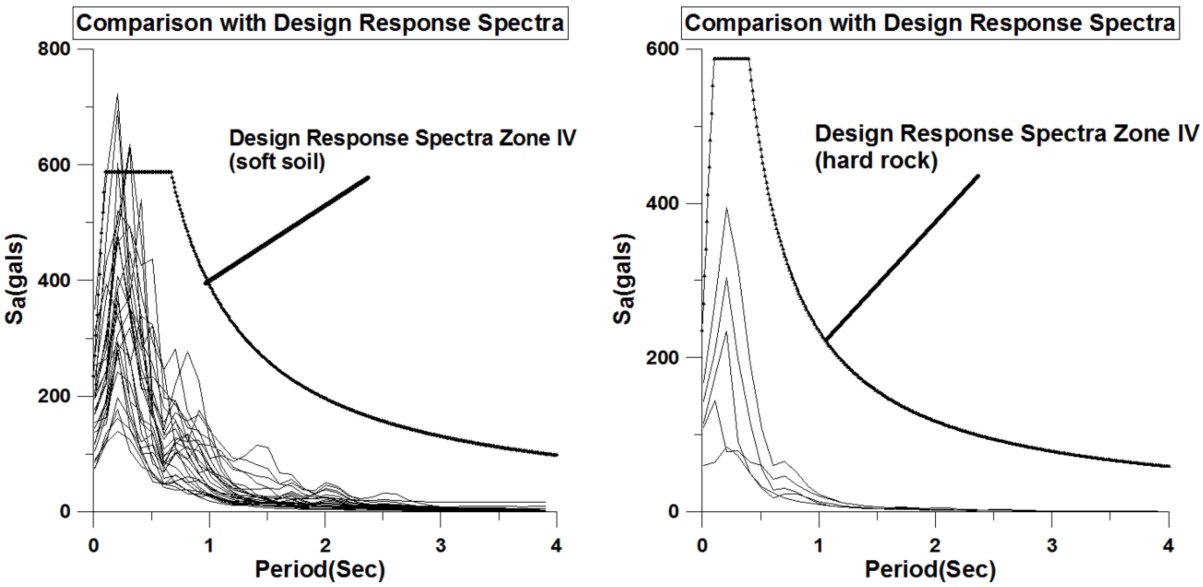
Figure 3. synthesized acceleration time history for M_w = 5.5 local earthquake

6. RESPONSE SPECTRA IN DELHI

Once the synthesized acceleration time histories is available at the reference site (NDI), the ground motions at 58 sites in Delhi are estimated by using the transfer functions of those sites based on Mittal(2011) and present study. We use Random vibration theory to estimate ground motions in Delhi during future postulated earthquakes in the region. RVT-based site response is an extension of stochastic ground motion simulation procedures developed by seismologists to predict peak ground motion parameters as a function of earthquake magnitude and site-to-source distance and has been successfully applied in predicting various earthquake ground-motion parameters (Hanks and McGuire, 1981; Boore, 1983; Toro and McGuire, 1987; Ordaz et al., 1988; Singh et al., 1989).

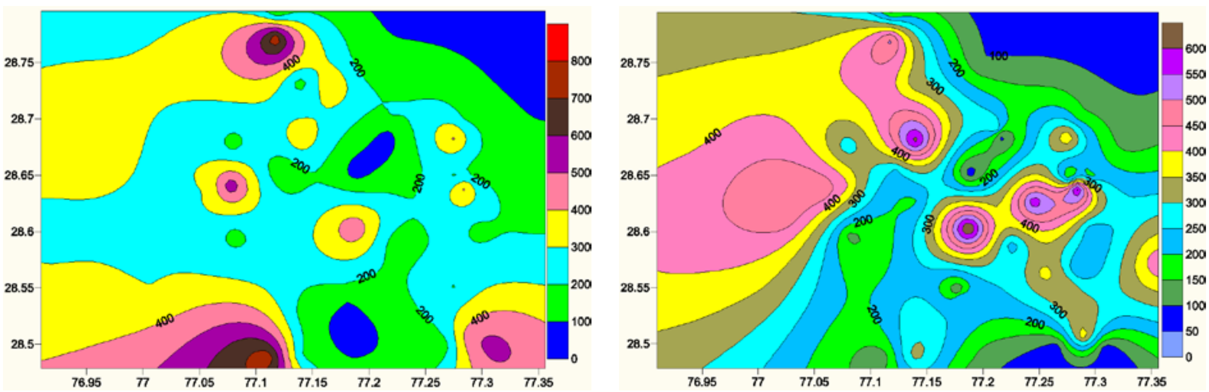
The sources in Delhi region are assumed to follow ω^2-source scaling in the far field and the point-source approximation is valid. We estimate the horizontal response spectra, S_a, with 5% damping at different sites in Delhi during various postulated earthquakes. Estimated Sa at all sites known to have soft soil are grouped together and compared with IS 1893-2002 spectra for soft soil with zero period acceleration of 0.24g (Type III) (Fig. 4a). Similarly estimated Sa at all sites known to have stiff soil are grouped together and compared with IS 1893-2002 spectra of Type I Fig. 4(b). IS 1893-2002 is the Indian standard code for earthquake resistant design of structures and this code provides response spectra with unity ZPA for three types of soil.

Fig. 4a shows that the zone IV response spectrum for the Mw =5.5 earthquake near Delhi is almost in agreement (except at some frequencies). For all the rock sites, the zone IV response spectrum is conservative as evident from Fig. 4(b). These results are combined to form a iso-spectral acceleration (Sa) maps of Delhi corresponding to 0.1 sec, 0.3 sec, 0.5 sec and 1 sec periods (5% damping) as shown in Fig. 5. Spectral acceleration map is strongly influenced by the shallow geological and soil conditions as indicated in the contour maps. Three pockets of high acceleration values are seen due to both regional and local earthquakes. These pockets coincide with the boundaries of different geological formations and hence are indicative that the high spectral acceleration may be associated with the junction of soil/geological formations rather than the formation itself.



Soft Soil Hard Soil

Figure 4. Comparison of response spectra at soft soil sites and hard rock sites from M_w =5.5



0.1 Sec 0.3 Sec

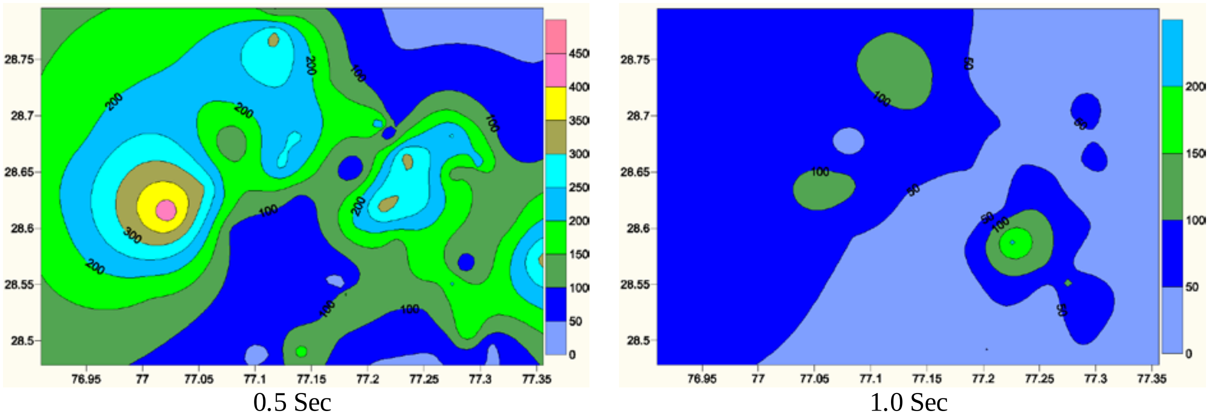


Figure 5. Iso-acceleration maps at different periods during local Mw=5.5 magnitude earthquake. All studies are confined to rectangle ABCD in Fig. 1.

CONCLUSIONS

Delhi in India is one such mega city where hazard studies are of prime importance due to its high population and vicinity to earthquake prone Himalayas. Seismic instrumentation in Delhi has been relatively sparse. As a consequence, the knowledge of local and regional seismicity and seismotectonics remains poor. Delhi is subject to strong shaking from large/great plate-boundary, thrust earthquakes located at distances exceeding ~250 km, and from moderate, local and regional earthquakes. In this work an attempt has been made to understand and quantify seismic hazard of different parts of Delhi from local earthquake.

A procedure is applied for seismic hazard estimation making use of synthesized strong ground motion at reference site for 5.5 magnitude originating near Delhi, transfer functions (with respect to the reference site) and finally RVT to estimate response spectrum. This work revealed relatively higher vulnerable zones in Delhi in small pockets due to local site conditions and prevailing topography. These pockets seem to coincide with the junctions of (a) Aravalli quartzite and recent Yamuna alluvium (towards the East), (b) Aravalli quartzite and older quaternary alluvium (towards the South), and (c) older quaternary alluvium and recent Yamuna alluvium (towards the North). The results show significant change in ground motion from one place to another, which is caused due to the variation in soil type or thickness or topographical variations in the basement. We estimated ground motion at different sites using actual earthquake recordings and is assumed to be more reliable.This study will be useful for city planners as a first order seismic risk evaluation.

The conclusions above are based on limited data and, hence, are necessarily preliminary. Since some of these transfer functions are of the first order and determined from local earthquakes, we suggest that they be validated in future using more earthquake data. Detailed studies need to be undertaken for soil investigation at all the sites. This will help in determining the local site effects more accurately for assessment of amplification of ground motion. As shown by Iyengar (2000), Delhi has highly undulating basement and soil thickness vary drastically even at nearby sites. Therefore transfer functions as close as possible should be obtained to produce higher order shake map.

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