The *M* 4.9 Delhi earthquake of 5 March 2012

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The occurrence of an *M* 4.9 event on 5 March 2012 at Delhi–Haryana border is a reminder about the active nature of different tectonic sources in and around Delhi. The earthquake was well recorded by local and regional networks of seismic stations and has generated good instrumentally recorded data. The epicentre of the earthquake falls near the surface expression of the Mahendragarh–Dehradun Fault (MDF), located to the northwest of Delhi. Peak ground acceleration recorded in the Delhi region varied from a minimum of 2.50 cm/s^2 to a maximum of 39.4 cm/s^2 on the transverse component at the Ridge Observatory and Jaffarpur stations respectively, located about 60 and 34 km away from the epicentre. The maximum velocity computed from acceleration time histories was 1.11 cm/s. According to the preliminary reports, a maximum intensity of VI, on the modified Mercalli intensity scale, was observed near the epicentral zone. Ground motion site amplification was not uniform; it varied between 3 and 6 at different sites. The recent earthquake is not just reminder that Delhi is vulnerable to local earthquakes; it also demonstrates site-dependent amplification, calling for further studies.

Keywords: Earthquake, peak ground acceleration, seismic stations, tectonic sources.

BEING the capital city, happenings around Delhi attract much attention. Its proximity to the Himalaya, an active plate boundary, makes it more vulnerable to earthquakes. Local tectonic features, known to have caused earthquakes in the past, exist in the vicinity of Delhi. The seismic zoning map of India (Bureau of Indian Standards, IS: 1893 Part-I)[1] places Delhi in seismic zone IV, which is broadly associated with seismic intensity VIII on the modified Mercalli intensity (MMI) scale. The *M* 4.9 earthquake on 5 March 2012 at the Delhi–Haryana border is a reminder of the potentially active tectonic sources in the vicinity of Delhi. It was just about six months ago, on 9 September 2011 that Delhi experienced another earthquake of magnitude 4.3, which was sourced near Sonipat.

Delhi has a well-known history of felt earthquakes, both from regional and local sources[2]. The M_w 4.1 (25 November 2007), M_w 2.6 (18 March 2004) and M_w 3.8 (28 April 2001) earthquakes are some of the recent events felt here. While occurrence of these events cautions us about the possible hazard scenario in Delhi due to local and regional tectonic sources on one hand, they also provide useful data to validate our models on ground motion and site dependence of amplification[3,4]. The data generated by the 5 March 2012 earthquake also serves this purpose.

An earthquake that caused no damage to the built environment, the 5 March event was felt widely in Haryana, Delhi and neighbouring states. Intensity on the MMI scale equivalent of VI was experienced in the epicentral region close to the Delhi–Haryana border (Figure 1). This communication discusses the source parameters of this earthquake in the background of the tectonic framework and presents data useful for future studies, especially for site amplification.

Lying on an extension of the peninsular shield, the region comprising Delhi forms part of a complex tectonic regime. Geological and geophysical studies have indicated the presence of several faults and lineaments in this region – the Sohna Fault, Delhi Fold Belt, Rajasthan Great Boundary Fault, Moradabad Fault and the Delhi–Hardwar Ridge being prominent among them. Besides these small-scale structures, the major Himalayan boundary faults – Main Boundary Thrust (MBT) and Main Central Thrust (MCT) – form the structural barriers to the north. It is generally believed that earthquakes originating on these thrust major faults pose a threat to Delhi. Apart from these, two of the important tectonic features that need to be considered in the context of seismicity around Delhi are the Mahendragarh–Dehradun Fault (MDF) and Aravalli–Delhi fold axes. Following a NE–SW trend and

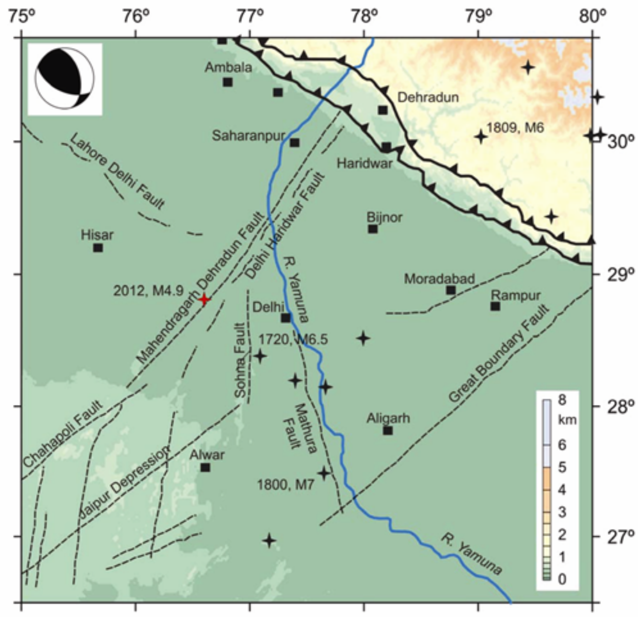

Figure 1. Map showing the position of Delhi with prominent structural features of the region. The locations of some notable earthquakes in the region, including the 5 March 2012 earthquake (red star) are shown.

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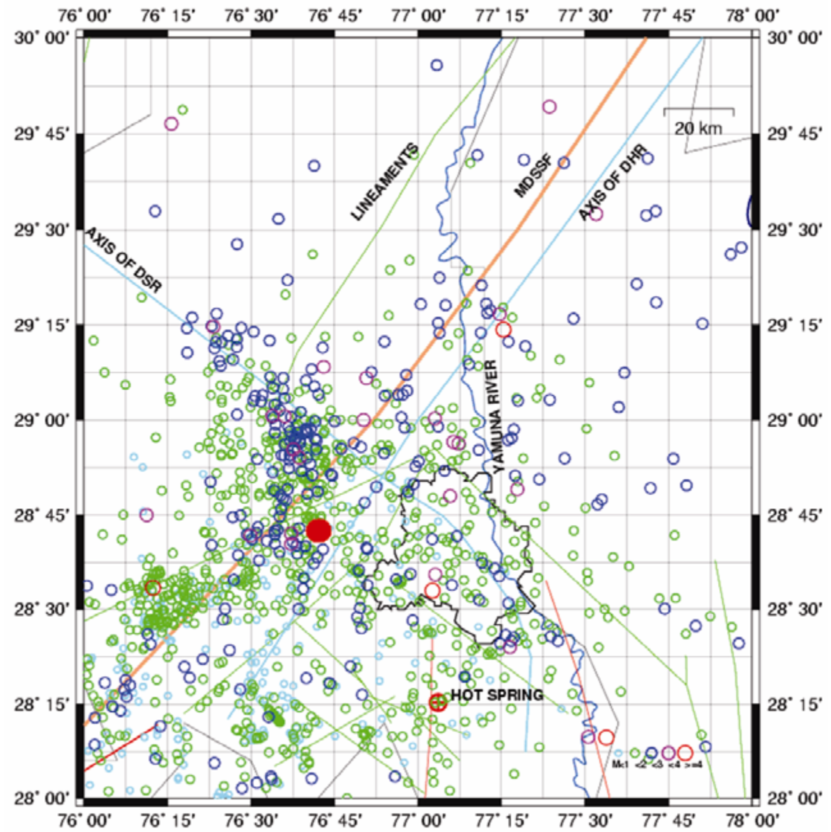

Figure 2. Seismicity in and around Delhi within a window of 76–78°E long. and 28–30°N lat. for a period 2001–11 (source IMD; for locations of the seismic stations, see www.imd.gov.in).

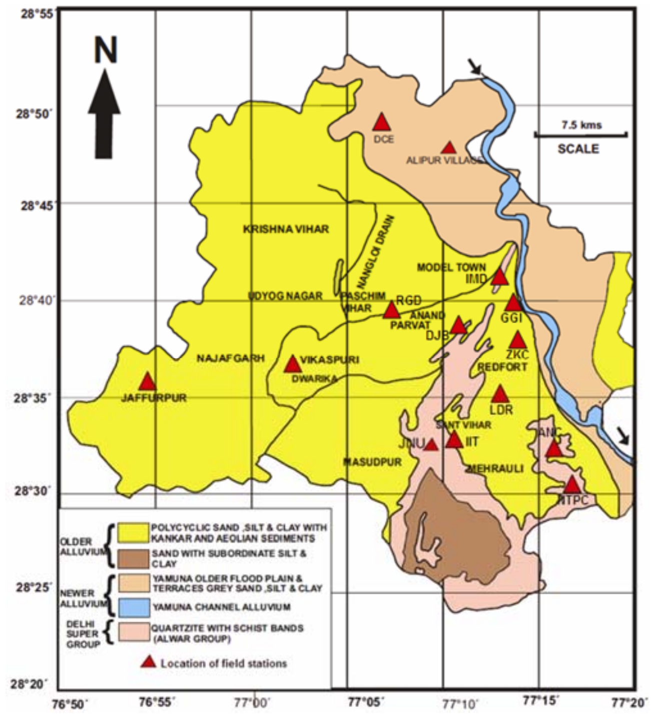

Figure 3. Geological map of Delhi showing the sites of accelerographs and seismographs, which recorded the earthquake event; for details on the strong motion network and data, see www.pesmos.in

located between 76°E and 79°E long., the Delhi–Haridwar ridge is an active structure believed to have generated moderate seismicity in the past. The structure appears to be an extension of the Aravalli mountain belt beneath the alluvial plains of the Ganga on the subducting Indian plate[5]. The N–S-oriented Sohna Fault that runs from Sohna to the west of Delhi and the NE–SW-oriented Moradabad faults are other structures of importance. Following a roughly conjugate direction, the Mathura Fault follows a NNW–SSE direction from Mathura in the south to Panipat in the north. The Rajasthan Great Boundary Fault (RGBF) zone is another well-defined fault, which runs for about 400 km NNE–SSW to NE–SW as a major dislocation zone in Rajasthan (Figure 1). Seismicity in this region is quite scattered and a spatial correlation with specific structures is difficult. An updated spatial pattern of earthquakes in the region around Delhi is shown in Figure 2.

The important rock formation exposed in Delhi is mainly the quartzite of the Alwar series of the Delhi Super group, unconformably overlain by unconsolidated Quaternary to Recent sediments. Major geological formations of Delhi are shown in Figure 3. The older alluvium comprises of silt and clay with minor lenticular fine sand and kankar beds. The newer alluvium consists mainly of

Table 1. Source parameters of the earthquake on 5 March 2012

Date/ Origin time	Latitude (°N)	Longitude (°E)	Magnitude	Depth (km)	S1	Dip1	Rake	S2	Dip2	Rake	Mo (dyne-cm)
5/03/2012 7 : 41 : 04.7 (UTC) 13 : 11 (IST)	28.7	76.7	4.9 (M_L) 5.0 (M_w)	9	347.93	47.85	131.34	115.26	56.18	53.88	1.180E24
(Revised) 5/03/2012 7 : 41 : 04.7 (UTC) 13 : 11 : 04.7 (IST)	28.748	76.603	4.9 (M_L) 5.0 (M_w)	14							

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 sides of the ridge, is variable and understanding such variations is important in quantifying site amplification.

Although no large earthquakes are known to have occurred in the Delhi region, smaller events are quite frequent (Figure 2). India Meteorological Department (IMD) has been operating and maintaining different local and regional networks consisting of a 16-station digital telemetry system around Delhi, which had recorded 5 March 2012 earthquake. It has been well recorded by other stations of the national network as well as the strong motion network. The location of the seismic stations, those triggered in Delhi during the event are shown in Figure 3. Located about 34 km from the epicentre, the Bahadurgarh and Jaffarpur stations, nearest to the source recorded the earthquake. The former is equipped with an accelerograph, and the latter has a short-period seismograph. Source parameters of the earthquake recorded at these stations are given in Table 1. Table 2 provides details of the strong motion array with recorded PGA and computed velocity of three components (L, T and V) at various stations.

Soon after the occurrence of the earthquake, IMD brought out a preliminary report with hypocentral parameters that were later updated (Table 1, row 1).

The above parameters were computed using auto-location software making use of all the datasets (about 60 station records) from local and regional seismic networks, including Delhi Telemetry System, RTSMN System and National Seismic Network, maintained by IMD. CMT solution was obtained from Response Hydra software used by IMD on an operational basis, that utilizes the entire waveform from the beginning of the P-wave arrival until just before the arrival of the first surface waves for distant stations. The CMT solution generated by the software considering the stations in the distance range 20–180° is shown as an inset in Figure 1.

The focal mechanism shows predominantly strike–slip motion with a component of reverse faulting. Given the fact that the software used regional and distant stations, the method is not reliable and the solution may not be unique. To have better control on the hypocentral parameters, we used data from the local stations and the revised parameters are based on data from 29 stations (14 strong-motion accelerographs, 11 broadband seismographs and four short-period seismographs), located within an epicentral distance of ~ 300 km. The revised parameters are given in Table 1 (second row).

Thus we can make the following conclusions from the present study.

- The epicentre of the earthquake falls near the surface expression of MDF located to the northwest of Delhi.
- The recorded Peak Ground Acceleration (PGA) in Delhi region ranges from a minimum of 2.5 to a maximum of 39.4 cm/s^2 on the transverse component as observed at the Ridge Observatory and Jaffarpur stations respectively. The Ridge Observatory is located on hard rock (quartzite with schist bands) 60 km away from the source, whereas the Jaffarpur station is located 34 km away from the epicentre on alluvial sediments (sand, silt and clay with kankar). The maximum velocity computed from acceleration time-histories is 1.11 cm/s.
- Observations suggest that stations located on soft sediments/soil recorded high PGA values, whereas for stations sitting on hard rock, the PGA values were low.
- An amplification of ground motion of the order 3–6 has been observed at sites located on soft soils. Amplification of the order of 5 was observed at IIT Delhi, when compared to the Ridge Observatory. Similarly, amplification of the order of 3 was observed at Zakir Husain College site in comparison to the Karol Bagh site, although both are equidistant from the epicentre. Contrary to the above observations, it was also noted that two sites, viz. Gurgaon and Kaithal, which are about 53 and 118 km away from the epicentre recorded almost the same acceleration ~ 6–8 cm/s^2 on all the three components. These observations clearly highlight the site dependence of amplification and call for proper soil characterization.
- The CMT solution shows a predominance of strike–slip motion with a component of reverse faulting. For the 28 April 2001 (M_w 3.4) and 18 March 2004

Table 2. Recorded peak ground acceleration (A_{max}) and computed velocity (V_{max}) at various sites

Station	Epicentral distance (km)	Station coordinates: Latitude (°N)	Station coordinates: Longitude (°E)	Local geology	Acceleration (A_{max}; cm/s^2) L	Acceleration T	Acceleration V	Velocity (V_{max}; cm/s) L	Velocity T	Velocity V
Acharya Narendra Dev College, Govindpuri	68.7	28.539	77.264	Soft soil	9.14	9.03	–5.76	0.232	0.246	0.109
DCE Bawana Road	50.2	28.795	77.118	Soft soil	7.62	10.32	–5.6	–0.254	0.421	–0.162
Delhi Jal Board, Karol Bagh	58.2	28.652	77.188	Hard rock	–3.68	–2.67	1.75	0.063	–0.060	–0.055
Delhi University	59.9	28.691	77.212	Hard soil	10.32	8.42	6.93	–0.207	0.255	–0.108
Guru Gobind Singh IP University Kashmere Gate	62.3	28.665	77.233	Soft soil	9.55	8.99	–2.58	0.193	–0.170	0.051
Gurgaon	53.3	28.449	77.029	Soft soil	6.71	–8.3	6.02	–0.212	–0.331	–0.151
Kaithal	118.0	29.801	76.418	Soft soil	–6.72	–8.3	6.96	0.239	0.249	–0.172
Noida	89.8	28.507	77.479	Soft soil	–7.84	–8.26	–5.34	0.288	0.260	0.131
Shivaji College, Raja Garden		28.655	77.123	Soft soil	8.18	–8.03	8.89	0.251	0.181	–0.158
Roorkee	177.0	29.866	77.901	Soft soil	1.81	–1.65	0.89	–0.061	0.065	–0.028
Sonipat	48.0	29.001	77.002	Soft soil	22.16	26.56	22.59	–0.872	–0.850	–0.541
Alipur, Delhi	54.6	28.795	77.14	Soft soil	–14.84	11.07	–9.11	–0.505	–0.264	–0.252
IIT Delhi	61.7	28.546	77.191	Soft soil	13.83	–11.04	–11.18	0.382	0.430	0.284
Ridge Observatory IMD	60.4	28.68	77.215	Hard rock	–2.58	2.5	–2.04	–0.081	0.067	–0.077
Government Engineering College, Jaffarpur	34.4	28.594	76.914	Soft soil	–35.6	39.36	–35.87	1.110	–0.882	0.691
Zakir Hussain College	56.3	28.64	77.23	Soft soil	–11.08	10.05	7.23	0.226	0.189	0.102
JNU	59.2	28.54	77.166	Hard rock	8.85	–7.1	8.07	–0.167	–0.212	0.158
NSIT, Dwarka	45.6	28.608	77.041	Soft soil	–8.92	9.3	7.89	0.196	–0.255	–0.147
NPTI, Badarpur	73.6	28.508	77.304	Soft soil	15.52	–10.53	8.15	0.317	0.251	–0.229

(M_w 2.6) Delhi earthquakes, Bansal *et al.*[3] generated focal mechanism solutions based on the first motion and waveform modelling. Based on these solutions the authors suggested that these earthquakes involved normal faulting with a large strike–slip component. The focal mechanism of the Delhi earthquake of 25 November 2007 (M_w 4.1) computed by Singh *et al.*[4], shows strike–slip faulting with some normal component similar to the above-mentioned two small events in the area. On the contrary, Shukla *et al.*[6] reported thrust faulting with minor strike–slip component for small and regional earthquakes in and around Delhi. Since the focal mechanism reported by them is not well constrained, a comparison may not be appropriate.

- The strong ground-motion histories recorded by the local array of accelerographs will be of immense help in developing hazard scenarios due to future earthquakes in the region. This is an important step in the preparation of specific modules for mitigating the risk due to such events.
- Although there is general awareness of the seismic hazard that Delhi is exposed to, the current scientific knowledge and data need to be improved.

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Impact of population density on the surface temperature and micro-climate of Delhi

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Increasing urban surface temperature due to change of natural surfaces is one of the growing environmental problems in urban areas, especially in cities like Delhi. The present work is an attempt to assess the urban surface temperature in Delhi using remote sensing and GIS techniques. ASTER datasets of thermal bands were used to assess the land surface temperature (LST) using temperature emissivity separation technique. Ward-wise population density was calculated from the Census of India 2001 data to correlate the population density with LST. The study shows that surface temperature changes with the increase in the impervious surface area, which is related to the increase in the population density.

Keywords: Micro-climate thermal bands, population density, surface temperature, thermal bands.

IN today's world of globalization and industrialization, urban environmental studies have become an important area of research. Land surface temperature (LST) is a critical parameter in urban climatology[1]. Remote sensing satellite data have been utilized to assess urban land surface thermal characteristics through mapping and assessing surface temperature from thermal infrared images[2]. In the urbanization process (demographic pressure), removal of natural land-cover types and their replacement with common urban materials such as concrete, asphalt, stone, brick and metal has significant effect on the environment, including reduction in evapotranspiration, promotion of more rapid surface run-off, increased storage and transfer of heat that can be sensed, and deterioration of air and water quality. The result of this change can have significant effects on local weather and climate[3]. Substantial amount of the variance of temperature rise in cities is explained as a function of population growth[4]. The holistic impacts of land surface cover, water and vegetation discussed above have climatological and meteorological implications on the urban atmosphere at various scales and all of these factors are linked with population growth. There is little doubt that population growth impacts local climate[5–12]. Micro-climate change intensity [as change in urban heat island (UHI) intensity] tends to increase with increasing city size and/or population[13–20], and as cities

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