Bull Earthquake Eng (2011) 9:1361–1386
DOI 10.1007/s10518-011-9265-3

ORIGINAL RESEARCH PAPER

Seismicity parameters for important urban agglomerations in India

S. T. G. Raghukanth

Received: 19 January 2010 / Accepted: 28 March 2011 / Published online: 22 April 2011

Abstract India's urban population has increased in the recent times. An earthquake near an urban agglomeration has the potential to cause severe damage. In this article, seismicity parameters for region surrounding important urban agglomerations in India are estimated. A comprehensive earthquake catalogue for the region (6°E–42°E latitude and 60°N–100°N longitude) including historic and pre-historic events has been compiled from various sources. To estimate the parameters, past earthquake data in a control region of radius 300 km has been assembled to quantify the seismicity around each urban agglomeration. The collected earthquake data is first evaluated for its completeness. From combined (historical and instrumental) data, the seismicity parameters b-value, seismic activity rate, λ and maximum expected magnitude (m_{max}) have been obtained from the methodology proposed by Kijko and Graham (1998). The obtained activity rates indicate that region surrounding Guwahati urban agglomeration is the most seismically active region followed by Srinagar, Patna, Amritsar and Chandigarh.

Keywords Seismic hazard · Urban agglomerations · Recurrence relations · Earthquake catalogues

1 Introduction

As per census 2001 about 286 million people (27.8% of the total population) in India live in urban agglomerations. The number of cities with a population greater than one million has increased significantly in recent decades. In 1981 there were 12 cities with population more than 1 million in India with 26.8% share of the total urban population. This has increased to 35 in 2001 with 37% share of the total urban population. Currently there are 48 urban agglomerations in India with an estimated population of more than one million

S. T. G. Raghukanth (✉)
Department of Civil Engineering, IIT Madras, Chennai, India
e-mail: raghukanth@iitm.ac.in

(http://www.citypopulation.de/). By 2030, the percentage of total population living in urban agglomerations is expected to increase up to 41% (NHUD 2007). The main reason for this increase is due to large industrial establishments in the past few decades and the consequent migration of rural population to urban areas in search of employment opportunities (Wenzel et al. 2007). Due to this population increase, local governments have undertaken several important infrastructural building programs in the urban areas (http://jnnurm.nic.in/nurmudweb/missioncities.htm). Moreover, the intellectual, corporate and political agencies are often located in urban areas only. As such these urban agglomerations are vital to the economic growth of the country. The high concentration of population and infrastructure in a confined area increases the vulnerability of these agglomerations and leads to particularly large loss potentials. The geographical location and the area covered are the most decisive factors for an urban agglomeration exposure to natural hazards. Most urban areas are situated on the coast or on rivers. Although the infrastructural developments in these agglomerations are mostly confined to safe areas wherever possible, subsequent growth often inevitably spreads to highly vulnerable sites too. At many places the low lying water logged areas are filled up for the construction of buildings due to acute shortage of space.

Among various natural disasters, due to their intensity and the geographical extent of the damage they cause, earthquakes generally pose the highest risk in urban agglomerations. An earthquake near an urban agglomeration has the potential to cause large fatalities and can upset the economic growth of the surrounding region or the country. A total of 750 and 432 people were killed in Ahmedabad and Rajkot urban agglomeration during the 2001 Kutch earthquake (Lahiri et al. 2001). The location of the epicenter at a distance more than 230 kms from these two cities averted a disaster that could have been of an even higher magnitude. The fatalities of all past earthquakes from 1900–2009 have been compiled recently by Bilham (2009). The data shows that a M_w 8 earthquake near an urban agglomeration has the potential to kill more than 0.3 million people where as the maximum fatalities for M_w 7, M_w 6 and M_w 5 events are 40,000, 10,000 and 100, respectively. The fatalities are high in developing nations like India than in the industrial nations for similar sized events. Most of the buildings in these urban agglomerations are unplanned and are expected to be lacking the sufficient earthquake resistance.

In order to reduce vulnerability, site specific microzonation studies are required as a part of the master plan for construction of earthquake resistant structures in the urban agglomerations considering uncertainties in ground motion due to all possible seismic sources. The first step in microzonation is to develop earthquake recurrence relation to quantify the seismic activity in a control region of radius 300 km around the urban agglomeration. The maximum possible earthquake magnitude which is the upper limit of magnitude in the control region also has to be estimated. The seismicity parameters for some regions in India have been derived previously by some investigators (Kaila et al. 1972; Rao and Rao 1984; Shanker and Sharma 1998; Seeber et al. 1999; Jaiswal and Sinha 2007; Raghukanth 2010). Most of these studies concentrated on quantifying the seismic activity of some particular tectonic zones. Although these results gave some information on seismicity parameters however they cannot be directly used to understand site specific seismicity for which a broad region of about 300 kms around the city has to be investigated (USNRC 1997). Moreover the earthquake catalogues used in these studies are not complete and many historical and paleo events have not been taken into account in arriving at the seismicity parameters. Iyengar and Ghosh (2004) and Raghukanth and Iyengar (2006) developed site specific earthquake recurrence relations for Delhi and Mumbai cities by analyzing the earthquake database in a circular region of radius 300 kms around these two cities. However these studies also suffer from the limitation that historical and paleo earthquakes have not been included in the analysis.

In this article an attempt has been made to derive site specific earthquake recurrence relations for the 48 urban agglomerations in India. The methodology proposed by Kijko and Graham (1998) which combines the prehistoric, historic and instrumental seismicity data is used to obtain the seismicity parameters. The obtained results in this study will be of use in deterministic or probabilistic seismic hazard analysis (PSHA) to estimate spatial variation of ground motion in these cities.

2 Indian urban agglomerations

The number of urban agglomerations with million plus population in India from 1950 to 2009 is shown in Fig. 1 (http://esa.un.org/). There were five agglomerations in 1950 namely Delhi, Mumbai, Chennai, Kolkatta and Hyderabad. Currently, the number of urban agglomerations with an estimated population more than a million are 48 (http://www.citypopulation.de/). These are listed in Table 1. The population of Faridabad and Ghaziabad are inlcuded in Delhi. Mumbai urban agglomeration includes Bhiwandi, Kalyan, Thane and Ulhasnagar. It can be observed that population in New Delhi and Mumbai are almost same with a difference of 0.1 million. These two cities occupy 4th and 5th positions in the list of most populous urban agglomerations in the world. The population of Kolkatta and Chennai are about 71 and 36% of Mumbai agglomeration. The location of these 48 agglomerations are shown in Figs. 2 and 3. Most of the urban agglomerations are concentrated near major rivers and sea coasts. During the first half of the last century, majority of the buildings in these urban agglomerations were simple low-rise structures. However, due to rapid economic growth in India, these cities changed dramatically in the past five decades. These forty eight cities have developed into a modern metropolitan area with large concentrations of high-rise buildings, complex infrastructure and industrial facilities. The seismic risk in terms of loss of lives and damage potential to structures has increased tremendously compared with the situation in the past. The building code IS 1893 (2002) brought out by Bureau of India standards divides the vast country into four zones based on the observed damage patterns of past earthquakes. These are Zone II (Low hazard), Zone III (Moderate hazard), Zone IV (Severe hazard),

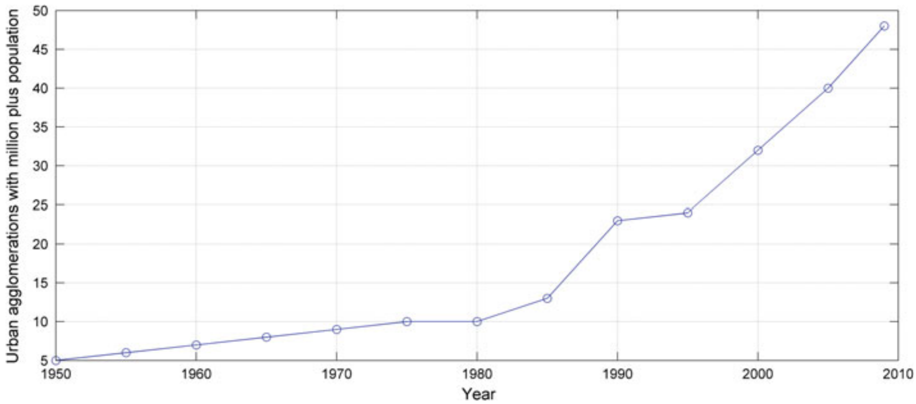

Fig. 1 Urban agglomerations growth in India

Table 1 List of important cities in India having population greater than 1 million

S. No	Agglomeration	Lat.	Long.	Pop. (millions)	Zone (IS)	M_0	Seismicity parameters		M_{Max}
							b	λ	
1	Delhi	28.62	77.22	22.4	IV	4.5	0.85 ± 0.05	1.06 ± 0.17	8.7
2	Mumbai	19.00	72.8	22.3	III	4.3	0.82 ± 0.07	0.32 ± 0.06	6.8
3	Kolkata	22.55	88.37	16	III	4.1	0.71 ± 0.06	0.72 ± 0.11	8.0
4	Chennai	13.05	80.27	8.05	III	4.0	1.04 ± 0.09	0.28 ± 0.07	6.0
5	Bangalore	12.97	77.58	7.6	II	4.0	1.01 ± 0.09	0.63 ± 0.17	6.2
6	Hyderabad	17.37	78.48	7.35	II	5.5	0.09 ± 0.09	0.05 ± 0.01	6.7
7	Ahmedabad	23.03	72.57	5.8	III	4.3	0.77 ± 0.07	0.65 ± 0.20	8.2
8	Pune	18.52	73.85	4.75	III	4.3	0.79 ± 0.07	0.22 ± 0.04	6.7
9	Surat	21.23	72.78	4.075	III	4.3	0.75 ± 0.08	0.17 ± 0.04	7.2
10	Kanpur	26.46	80.33	3.575	III	4.9	0.71 ± 0.08	0.14 ± 0.04	8.7
11	Jaipur	26.92	75.82	3.175	II	4.3	0.96 ± 0.08	0.75 ± 0.27	8.7
12	Lucknow	26.83	80.92	2.875	III	4.3	0.79 ± 0.06	1.08 ± 0.22	8.7
13	Nagpur	21.15	79.08	2.775	II	4.3	0.98 ± 0.09	0.12 ± 0.07	6.7
14	Patna	25.6	85.12	2.450	IV	4.3	0.77 ± 0.06	0.69 ± 0.13	8.7
15	Raipur	21.23	81.63	2.1	II	4.7	0.98 ± 0.1	0.1 ± 0.06	6.7
16	Indore	22.42	75.54	1.93	III	4.3	0.99 ± 0.09	0.32 ± 0.12	6.5
17	Vadodara	22.30	73.20	1.93	III	4.3	0.73 ± 0.07	0.31 ± 0.08	8.0
18	Bhopal	23.25	77.42	1.87	II	4.3	0.90 ± 0.09	0.33 ± 0.13	6.7
19	Coimbatore	11.04	76.96	1.87	III	5.0	1.01 ± 0.09	0.1 ± 0.05	6.2
20	Ludhiana	30.91	75.85	1.78	IV	4.3	0.96 ± 0.04	3.25 ± 0.52	8.2
21	Agra	27.18	78.02	1.76	III	4.3	0.77 ± 0.06	0.54 ± 0.12	8.7
22	Kochi	9.97	76.27	1.69	III	5.0	1.01 ± 0.09	0.74 ± 0.04	6.2
23	Meerut	28.99	77.70	1.65	IV	4.3	0.89 ± 0.05	1.52 ± 0.25	8.7
24	Visakhapatnam	17.07	83.25	1.65	II	4.5	0.99 ± 0.1	0.07 ± 0.04	5.5
25	Asansol	23.68	86.98	1.64	III	4.1	0.98 ± 0.07	0.60 ± 0.10	8.0
26	Bhubaneswar	20.27	85.84	1.62	III	4.5	0.92 ± 0.1	0.27 ± 0.11	5.8
27	Nashik	20	73.78	1.62	III	4.3	0.99 ± 0.08	0.22 ± 0.05	7.3
28	Chandigarh	30.75	76.78	1.57	IV	4.3	0.94 ± 0.04	2.49 ± 0.39	8.2
29	Varanasi	25.32	82.98	1.5	III	4.1	0.63 ± 0.8	0.38 ± 0.09	7.3
30	Kolhapur	16.7	74.23	1.49	III	4.3	0.86 ± 0.07	0.31 ± 0.06	6.7
31	Jamshedpur	22.8	86.18	1.39	II	4.3	1.04 ± 0.08	0.31 ± 0.06	7.4
32	Madurai	9.80	78.10	1.37	II	5.0	1.02 ± 0.09	0.45 ± 0.10	6.2
33	Rajkot	22.30	70.78	1.37	III	4.1	0.77 ± 0.07	0.63 ± 0.19	8.3
34	Jabalpur	23.15	79.93	1.33	III	4.3	0.92 ± 0.09	0.30 ± 0.12	6.8
35	Amritsar	31.64	74.86	1.32	IV	4.3	0.93 ± 0.05	2.94 ± 0.45	8.2
36	Dhanbad	23.80	86.45	1.32	III	4.3	0.99 ± 0.09	0.37 ± 0.08	7.4
37	Allahabad	25.45	81.85	1.26	III	4.7	0.63 ± 0.09	0.15 ± 0.05	6.8
38	Vijayawada	16.51	80.61	1.25	III	4.9	0.09 ± 0.1	0.35 ± 0.05	5.8
39	Aurangabad	19.78	75.29	1.21	II	4.3	0.98 ± 0.09	0.21 ± 0.06	6.7
40	Srinagar	34.08	74.78	1.21	V	4.3	0.94 ± 0.03	4.52 ± 0.08	8.7

Table 1 continued

S. No	Agglomeration	Lat.	Long.	Pop. (millions)	Zone (IS)	M_0	Seismicity parameters		M_{Max}
							b	λ	
41	Solapur	17.68	75.92	1.14	III	4.3	0.78 ± 0.07	0.39 ± 0.09	6.7
42	Ranchi	23.35	85.33	1.13	II	4.3	1.04 ± 0.09	0.26 ± 0.08	6.2
43	Thiruvananthapuram	8.48	76.95	1.11	III	5.0	0.98 ± 0.1	0.09 ± 0.01	6.0
44	Jodhpur	26.28	73.02	1.07	II	4.3	0.96 ± 0.09	0.37 ± 0.11	7.1
45	Guwahati	26.17	91.77	1.06	V	4.3	0.78 ± 0.03	4.05 ± 0.60	8.3
46	Tiruchirappalli	10.81	78.69	1.03	II	5.0	0.99 ± 0.09	0.11 ± 0.05	6.2
47	Gwalior	26.14	78.10	1.02	II	4.3	0.90 ± 0.08	0.41 ± 0.11	8.7
48	Kozhikode	11.25	75.77	1.00	III	5.0	0.99 ± 0.09	0.08 ± 0.02	6.2

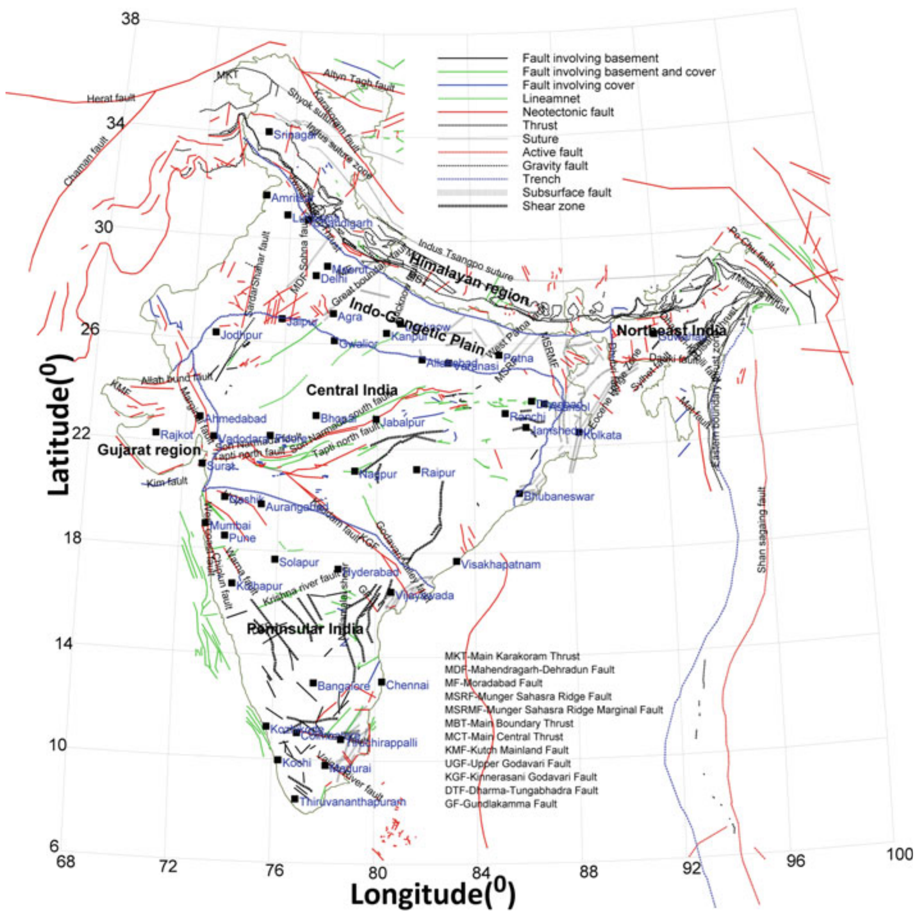

Fig. 2 Seismotectonic map of India (GSI 2000; Valdiya 1976; Balakrishnan et al. 2009)

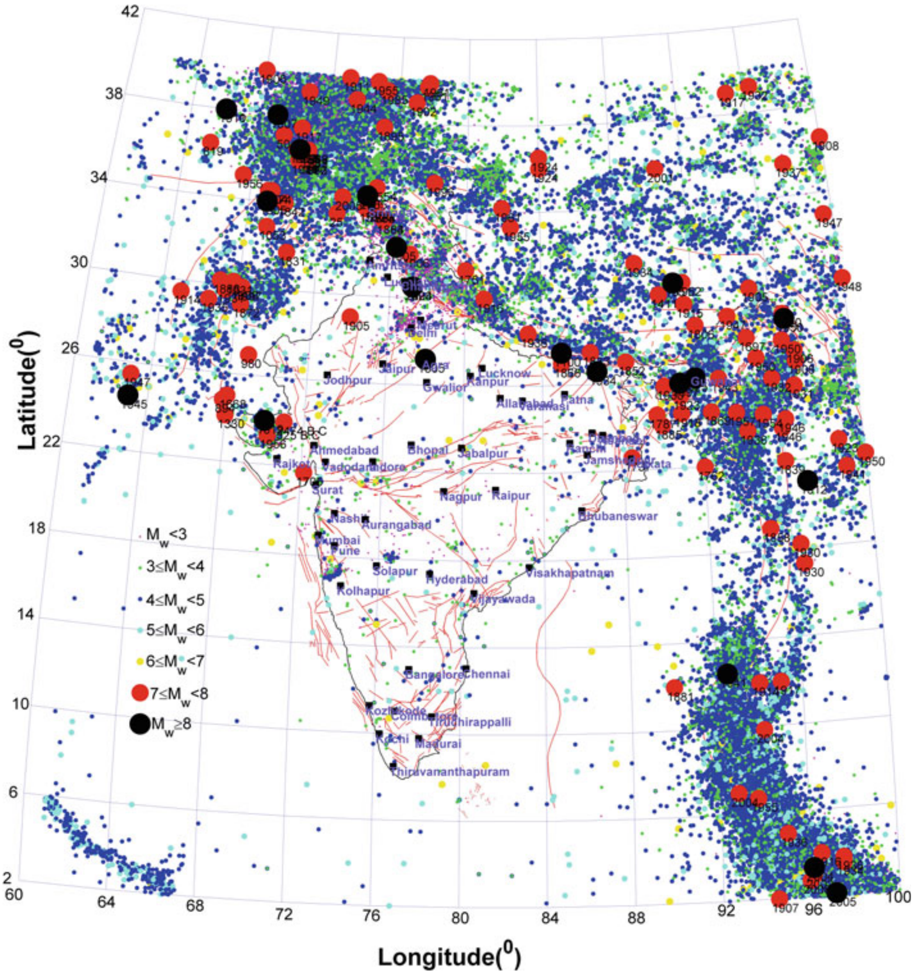

Fig. 3 Sesimicity of India and adjoining region superposed on known faults (58252 events of $M_W \geq 1$ including foreshocks and aftershocks from 2474 BC to 2009 AD)

Zone V (Most severe hazard). The seismic zone to which these urban agglomerations belong to as per IS 1893 (2002) are reported in Table 1. Among the 48 agglomeration in India, Guwahati and Srinagar lie in the zone of most severe seismic hazard.

3 Tectonic setting

The fault map of India prepared from GSI (2000) is shown in Fig. 2. A total of more than four hundred major faults, which influence seismic hazard in India, can be identified from the above map. Faults in neighbouring countries which can influence seismic hazard in India are also shown in this map. Based on this tectonic setup and geology, India can be broadly divided into seven zones namely the Himalayan region, the Gangetic plain, central India, Kutch region, northeast India, the Andaman region and the Peninsular India. These seven regions are shown in Fig. 2.

The collision between the Indian continent and the Eurasian plate gave rise to the Himalyan tectonic unit. The major faults in the Himalayan region are the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT) (Valdiya 1986). Seismologists are of the opinion that one or more great earthquakes are overdue in the Himalayan region (Seeber and Armbruster 1981; Khattri 1987; Bilham et al. 2001). Bilham et al. (2001) divided the entire Himalyas into 10 non-overlapping regions and based on GPS measurements, argued that six regions currently have the potential to generate great earthquakes ($M_w > 8$). Among the 48 urban agglomerations, Srinagar and Chandigarh are located in this tectonic region.

Northeastern region is defined to the east of the Dhubri fault and Guwahati urban agglomeration lies in this block. Northeast India is in the zone of most severe seismic hazard (i.e., zone V; as per IS-1893 2002) in the country and is considered as one of the most intense seismic zones in the world. This region has an extremely complex tectonic and geologic set up. The most striking feature, in this region, is that the Himalaya takes a sharp bend along the Assam syntaxis and continues in a broadly NS arcuate direction to the east of Burma and joins the Andaman arc giving rise to a complex plate boundary. Most of the earthquakes in North East India are caused due to the south–north and the west–east movement of the Indian plate (Chen and Molnar 1990). The two great earthquakes that occurred in this region in the year 1897 (M_w 8.1) and 1950 (M_w 8.6) are considered among the most damaging earthquakes worldwide, in the recent past. The 1897 event that occurred at an epicentral distance of 60 km caused tremendous damage to the Guwahati city. Apart from these two events, several other strong earthquakes have taken place herein, causing immense damage to life and property spreading over a vast stretch.

The Gujarat region lies to the west of the Marginal fault and four urban agglomerations lie in this tectonic domain. This region is regarded as the most active intraplate zone where high magnitude earthquakes occur infrequently. The structural trend of the Kutch rift basin is controlled by a number of E-W faults. The 26th Jan 2001 (M_w 7.7) earthquake which is regarded as the most deadliest intraplate earthquake occurred in this region.

The Gangetic plain lies in between Peninsular India and the Himalayan region. This region is characterized by several hidden faults and ridges in the basement of the Ganga basin (Gansser 1974; Valdiya 1976). These faults have oblique and transverse alignment across the Himalayan tectonic trend. Gansser (1974) pointed out that Gangetic plain is not a sediment filled fore-deep and it represents the depressed part of the Peninsular shield in which several hidden faults exist (Gupta 2006). The Gangetic plain is moderately seismic when compared to the Himalaya (Quittmeyer and Jacob 1979). A total of 11 urban areas are located in this block.

The region to the south of Godavari river and comprising the Dharwar protocontinent is taken as the peninsular India. A total of 16 urban agglomerations are located in this tectonic block. This landmass is far away from the highly active Himalayan collision zone. Although, the magnitudes are low, the Koyna region along the west coast near Mumbai behaves similar to an seismically active region. Apart from this region, sporadic and low-level seismicity is observed along the old shear zones in peninsular India. The damaging events to occur in peninsular India in the instrumental period are the 11th December 1967 Koyna earthquake (M_w 6.5) and the 1993 Latur earthquake (M_w 6.4).

The central India lies in between peninsular India and the Gangetic plain and consists of Singhbum and Aravali protocontinents. In this region 14 urban agglomerations are located. The most striking feature in central India, is the Son-Narmada-Tapti (SONATA) rift zone which is a ENE–WSW trending zone and runs across the Indian shield from west coast to east coast. This rift zone about 1600 km long in central India which separates northern and southern blocks of the Indian shield is a region of moderate seismic activity with infrequent earthquakes. Recently Balakrishnan et al. (2009) based on three dimensional geophysical data located this hidden fault in the Bay of Bengal, as marked in Fig. 2.

Based on the occurrence of earthquakes, it has been felt that the hazard in Gujarat, central India and peninsular India is less severe than in the Himalayan region, but the damages caused due to intraplate events is very high. The events are also felt over a much larger area than Himalayan earthquakes (Singh et al. 2004).

4 Earthquake catalogue

The starting point in seismic hazard analysis is to prepare a reliable earthquake catalogue of past earthquakes in the 300 km control region around the city which is a challenging task. The complete instrumental data will be available generally for relatively short periods of time, i.e for past few decades. This information is generally far too short to understand the frequency of occurrence of large events. For the last few hundred years, macroseismic observations of major seimic events will be available. Although their origin times are uncertain, information on very strong prehistoric seismic events (paleo-earthquakes) which usually occurred over the last thousands of years will be available for some regions. The macroseismic observations and paleo-earthquakes are the only means to extend the instrumental earthquake record into history and prehistory, which is particularly important in estimating seismic hazard.

There have been several efforts in the past to develop earthquake catalogue for some regions in India. Most of the studies concentrated on compilations of previous catalogues only. Such catalogues contain complete information on seismicity available at the time they were developed. On the other hand, some investigators made valuable efforts by searching historical literature and periodicals for new information on seismicity. They even found original sources in ancient manuscripts. Apart from compilation and searching the ancient literature, some investigators carried out palaeoseismic investigations in search of the geological evidence left by historic and prehistoric earthquakes. Some new earthquakes were identified from such studies.

4.1 Instrumental data

The most accurate and complete information on instrumental earthquakes for India is from permanent global seismic network observations. This data from 1922 to early 1960 is available in the International Seismological Summary (ISS) reports and in ISC bulletins. The ISC took over the service from ISS in 1964 and data from 1900 till date is available on the ISC website. The USGS (http://neic.usgs.gov/) website also contains information for location, date, origin time and magnitude. This is considered to be one of the reliable data repositories since 1973. Apart from these global databases, the IMD data base is comprised of historical and instrumentally recorded earthquakes. Only local magnitude M_{L} is assigned to the recorded earthquakes. The USGS database reports 24,319 events of magnitude $M_{\mathrm{w}} \geq 3$ for the study region for the region (2°–40°N; 61°–100°E) starting from 1973 to 2009. The ISC website reports 58,458 events with magnitude $M_{\mathrm{w}} \geq 1$ covering the period 1904 to 2009. The catalogue supplied by IMD lists about 16,396 events for the period 1505–2008.

4.2 Historical data

Oldham was perhaps of the earliest to create an earthquake catalogue for India. A list of significant Indian earthquakes up to 1869 was prepared by Oldham (1883). Chandra (1977) compiled 378 events from 1594 to 1975 and prepared an earthquake catalogue for Peninsular India. The historical events in this catalogue were taken from the publications of Oldham (1883), Turner (1911), Milne (1911), Tandon and Chaudhury (1968), and Guha et al. (1968). Instrumentally located earthquakes listed by IMD and USGS were also included in this catalogue. Quittmeyer and Jacob (1979) prepared a list of Himalayan earthquakes. The catalogue of Bapat et al. (1983) lists about 40earthquakes in India and its neighbouring region prior to 1800 AD. Rao and Rao (1984) reported 295events in Peninsular India from 1340 AD to 1983. Chandra (1992) compiled 711events from the Himalayan region for the period 1505–1986. Guha and Basu (1993) prepared a list of earthquakes of magnitude $\geq$ 3 for Peninsular India. Vitanage (1998) reported 58 historical earthquakes for the period AD 1614-1993 in Sri Lanka. Iyengar et al. (1999) carried out an intensive search of ancient Indian literature for earthquake related information. They identified 38 damaging events in India in the medieval period (1250 BC to 1800AD). Ambraseys and Jackson (2003) identified seven historical events with estimated magnitudes $M_w > 7$ in North India and Tibet. Rao (2005) reviewed several earthquake catalogues prepared for the Indian region and identified fifty important events from 1250 BC to 1963 AD. Iyengar and Ghosh (2005) and Raghukanth and Iyengar (2006) developed earthquake database in a region of 300 km radius around Delhi and Mumbai cities. Jaiswal and Sinha (2007) prepared an earthquake catalogue with 640events for Peninsular India after removing aftershocks. The website (http://isr.gujarat.gov.in/) contains a list of earthquakes from earliest time till 2008 for Gujarat and Northeast India. Pakistan Meteorological Department compiled a list of 58historical events during AD 25–1905 that occurred in Kashmir and in Pakistan. Ambraseys and Bilham (2009) searched historical Persian documents, British and French Consular reports to identify 52earthquakes in Afghanistan for the period AD 734-2004. Recently Raghukanth (2010) compiled all the events up to 2008 that occurred in India and neighbouring region. A total of 23,077 events of magnitude $M_w \geq 3$ for India have been obtained.

4.3 Paleo-earthquake data

Paleo-seismology is a science which interprets geological evidences such as surface faulting, earthquake induced liquefaction and deformation features to identify the location, time and size of the prehistoric events (McCalpin 2009). Such studies are considered reliable to identify only large earthquakes of $M_w \geq 6.5$. Paleo-seismic investigations are widely used in many countries to supplement historical and instrumental data (Giardini et al. 2004; McCalpin 2009). In India, recurrence intervals of large and great earthquakes exceed the duration of instrumental and historical records. Hence prehistoric events identified by paleo-seismic investigations would be valuable in building up a earthquake catalogue.

Sukhija et al. (1999) obtained evidences for three large seismic events ($M_w > 7$) from paleo-liquefaction studies in the epicentral region of the Great Assam earthquake of 1897. Two of these occurred during 1450–1650 AD and 700–1050 AD. The third one is dated around 600 AD. Kumar et al. (2001) carried out paleo-seismic investigations on the Himalayan Frontal Thrust (HFT) and obtained evidences for a great earthquake ($M_w > 8$) in 260 AD and two major events ($M_w > 7$) in 1294 AD and 1423 A.D near Chandigarh. Investigations by Malik and Mathew (2005) support the identificatioin of the above three HFT events.

In NEI evidence for a very large event ($M_w > 8$) *circa* 830 AD near Guwahati City has been obtained by Rajendran et al. (2004). Lave et al. (2005) obtained geological evidences for an earthquake of magnitude ($M_w > 8.5$) on HFT 1100 AD in Far East Nepal. Sukhija et al (2006) have observed paleo-seismic signatures like liquefaction features in the meizoseismal area of the 1993-Latur (Killari) earthquake. Based on radiocarbon dating of organic samples and archaeological artifacts in the region, this paleo-event has been dated to the broad period 190 BC-410 AD. The data also indicated that the magnitude of this event could have been greater than that of the 1993-Latur earthquake. Rajendran et al. (2008) carried out paleoseismic studies in Gujarat. They identified two events of magnitude $M_w > 7$ near the Allah Bund Fault. The first is dateable to 2474 ± 656 BC and the second to 893 AD. They also reported a historical event of magnitude $M_w > 7$ around 325 BC in the Kutch region. It may be remarked here that the first of the above paleo-event matches closely with the 3rd millennium earthquake said to have damaged the flourishing city of Dholavira in Gujarat.

4.4 All India catalogue

A catalogue containing all known events of magnitude $M_w \geq 4$ for the region (2°–40°N; 61°–100°E) has been assembled for further work. The major portion of the data comes from Chandra (1977), Chandra (1992), Bapat et al. (1983), Rao and Rao (1984), Guha and Basu (1993), Rao (2005), Raghukanth (2010), USGS, IMD and ISC websites. The historical events in Iyengar et al. (1999) and paleo-earthquakes identified by the paleoseismologists also has been included in the catalogue. Since the considered region also covers Pakistan and Afghanistan, historical earthquakes listed in Ambraseys and Bilham 2009 and Pakistan Meteorological Department (PMD 2007) has been included in the catalogue. The catalogue starts with the 2474 BC Dholavira earthquake in Gujarat with an approximated M_w of 7.5. A total of 58,252 events of magnitude $M_w \geq 1$ known up to 31st December 2009 are listed in the catalogue. A common problem faced in assembling a catalogue is due to the different magnitude values reported in the literature. Here this is handled by converting all reported values to moment magnitude numbers. For the pre-instrumental period of the catalogue only MMI estimates were available. These have been converted to magnitude numbers using the empirical relation $M_w = (2/3\text{MMI} + 1)$. For many events IMD has reported only the local magnitude M_L. This has been converted to M_w following the approach of Idriss (1985). For events from ISC, USGS catalogues with surface wave magnitude M_S and body wave magnitude m_b the following conversion formulae of Scordilis (2006) derived on the basis of global data are used.

$$\begin{aligned} &M_S - M_W \\ &M_W = 0.67M_S + 2.07,\ \text{for}\ (3.0 \leq M_S \leq 6.1) \\ &M_w = 0.99M_S + 0.08,\ \text{for}\ (6.2 \leq M_S \leq 8.2) \end{aligned} \tag{1}$$

$$\begin{aligned} &mb - M_w \\ &M_w = 0.85mb + 1.03,\ \text{for}\ (3.5 \leq mb \leq 6.2) \end{aligned} \tag{2}$$

The body wave magnitude saturates at the value of 6.2. The focal depth of the events vary from 1 to 320 km. Epicenters of these earthquakes are plotted in Fig. 3. A list of earthquakes with magnitudes $M_w \geq 7$ in the historical and instrumental period along with the references are reported in Table 2.

Table 2 Earthquakes of magnitude $M_w \geq 7$ in India and neighbouring region

Long (°E)	Lat (°N)	Year	Month	Date	M_w	Depth (km)	Reference
24.00	71.00	−2474	–	–	7.5	–	4
24.00	71.00	−325	–	–	7.5	–	4
33.72	72.90	25	–	–	7.5	–	6
37.10	69.50	50	–	–	7	–	6
34.60	74.50	250	–	–	8.5	–	5
30.50	77.20	260	–	–	8	–	8
36.40	65.40	819	6	1	7.3	–	7
26.10	91.80	825	–	–	8	–	4
24.80	67.80	894	–	–	7.7	–	6
26.93	68.90	980	–	–	7.6	–	13
32.85	69.13	1053	–	–	7	–	6
27.50	85.00	1100	–	–	8.5	–	9
30.50	77.20	1294	–	–	7.5	–	8
24.10	68.00	1330	–	–	7.6	–	14
30.00	90.20	1411	9	29	7.7	–	12
30.50	77.20	1423	–	–	7.5	–	8
34.50	69.00	1504	6	1	7.7	–	6
34.00	69.00	1505	7	6	8	–	2
27.20	78.00	1505	7	6	8.5	–	5
34.00	74.50	1552	–	–	7.5	–	2
35.00	75.00	1554	2	–	7.7	–	2
34.60	74.50	1555	2	1	8.5	–	5
34.00	75.00	1662	–	–	7.5	–	2
25.00	68.00	1668	5	6	7	–	2
27.75	94.60	1697	2	13	7.2	–	5
21.75	72.15	1705	2	4	7	–	5
34.00	75.00	1735	–	–	7.5	–	2
22.60	88.40	1737	10	11	7.2	–	11
31.30	80.00	1751	1	1	7	–	12
22.00	92.00	1762	4	2	7.5	–	2
34.00	75.00	1778	–	–	7.7	–	2
34.00	75.00	1784	–	–	7.3	–	2
24.50	89.75	1787	6	1	7.8	–	5
34.00	75.00	1803	–	–	7	–	2
28.50	92.00	1806	6	11	7.7	–	12
24.00	70.00	1819	6	16	8	–	2
31.75	70.35	1831	1	1	7	–	15
36.50	71.00	1832	1	22	7.3	–	15
36.00	71.00	1832	2	21	7	–	2
27.50	86.50	1833	8	26	7.5	–	2
22.00	96.00	1839	3	23	7.8	–	2
34.00	70.00	1842	2	19	7.5	–	2

Table 2 continued

Long (°E)	Lat (°N)	Year	Month	Date	M_W	Depth (km)	Reference
27.00	88.30	1852	5	1	7	–	15
19.00	95.00	1858	8	24	7.5	–	2
33.50	75.50	1863	–	–	7	–	2
27.00	85.00	1866	5	23	7	–	2
24.50	92.50	1869	1	10	7.5	–	2
29.20	68.20	1872	12	15	7	–	2
34.50	69.20	1874	10	18	7.8	–	2
12.00	90.00	1881	12	31	7.8	–	2
33.50	75.50	1884	5	30	7.3	–	2
34.10	74.80	1885	5	30	7	–	2
24.00	90.00	1885	7	14	7	–	2
30.20	67.00	1888	12	28	7	–	7
37.80	75.20	1895	7	5	7	–	2
25.90	91.00	1897	6	12	8.1	–	2
36.00	71.00	1902	4	18	7	–	2
39.00	77.00	1902	8	22	7	–	2
36.00	71.00	1902	9	20	7	–	2
30.00	95.00	1905	2	17	7.1	–	12
32.30	76.25	1905	4	4	8	–	2
29.00	74.00	1905	9	26	7.1	–	2
32.00	77.00	1906	2	28	7	–	2
36.00	71.00	1906	5	20	7	–	2
27.00	97.00	1906	8	31	7	100	2
40.00	68.00	1906	10	24	7	–	2
2.00	94.50	1907	1	4	7.6	50	1
36.50	70.50	1907	4	13	7	260	2
38.00	69.00	1907	10	21	8	–	2
36.50	70.50	1907	12	25	7	240	2
36.50	100.00	1908	2	9	7.3	–	2
36.50	70.50	1908	4	16	7	220	2
36.50	70.50	1908	10	23	7	220	2
36.50	70.50	1908	10	24	7	220	2
26.50	97.00	1908	12	12	7.5	–	2
36.50	70.50	1909	7	7	8	230	2
30.00	68.00	1909	10	20	7.2	–	2
38.00	66.00	1910	7	12	8.7	–	2
38.00	66.00	1911	1	1	7.2	50	2
40.00	73.00	1911	2	18	7.7	–	2
36.00	70.50	1911	7	4	7.6	190	2
21.00	97.00	1912	4	25	8	–	2
21.00	97.00	1912	5	23	8	–	2
29.50	65.00	1914	2	6	7	100	2
12.00	94.00	1914	10	11	7.2	80	2

Table 2 continued

Long (°E)	Lat (°N)	Year	Month	Date	M_W	Depth (km)	Reference
29.50	91.50	1915	2	3	7.1	–	2
4.00	96.50	1916	7	27	7	100	1
30.00	81.00	1916	8	28	7.5	35	1
12.00	95.00	1917	1	20	7	–	2
37.50	70.50	1917	4	21	7	220	2
39.00	95.00	1917	9	4	7	–	2
24.50	91.00	1918	7	8	7.6	–	2
36.50	70.50	1921	11	15	7.7	215	2
36.50	70.50	1922	12	6	7.5	230	2
22.75	98.75	1923	6	22	7.3	–	2
25.30	91.00	1923	9	9	7.1	–	2
36.00	84.00	1924	7	3	7.2	35	1
36.50	84.00	1924	7	11	7.2	35	1
36.00	70.50	1924	10	13	7.3	220	1
36.50	70.50	1929	2	1	7.1	220	2
17.30	96.50	1930	5	5	7.3	–	2
25.80	90.20	1930	7	2	7.1	–	2
18.20	96.40	1930	12	3	7.3	–	2
25.40	96.80	1931	1	27	7.6	–	2
30.20	67.70	1931	8	24	7	–	2
29.80	67.30	1931	8	27	7.4	–	2
25.80	95.70	1932	8	14	7	120	2
39.20	96.40	1932	12	25	7.6	–	2
26.60	86.80	1934	1	15	8.3	–	2
3.50	97.50	1934	5	1	7	145	1
31.50	89.00	1934	12	15	7.1	–	2
29.30	66.50	1935	5	30	7.5	–	2
28.40	83.30	1936	5	27	7	–	2
5.00	95.00	1936	8	23	7.3	40	1
3.75	97.50	1936	9	19	7.2	35	1
35.50	97.70	1937	1	7	7.6	–	2
36.30	71.00	1937	11	14	7.2	240	2
23.50	94.25	1938	8	16	7.2	35	1
12.50	92.50	1941	6	26	8.1	35	1
21.50	99.00	1941	12	26	7	35	1
36.30	71.00	1943	2	28	7	–	2
26.00	93.00	1943	10	23	7.2	35	1
39.00	73.50	1944	9	27	7	40	1
24.50	63.00	1945	11	27	8.2	35	1
23.90	96.20	1946	9	12	7.5	–	2
23.50	96.00	1946	9	12	7.8	35	1
33.00	99.50	1947	3	17	7.7	35	1
28.80	93.70	1947	7	29	7.7	–	2

Table 2 continued

Long (°E)	Lat (°N)	Year	Month	Date	M_W	Depth (km)	Reference
25.50	63.00	1947	8	5	7.3	35	1
30.00	100.00	1948	5	25	7.3	–	2
36.00	70.50	1949	3	4	7.5	230	1
39.20	70.70	1949	7	10	7.6	–	2
22.00	100.00	1950	2	2	7	–	2
28.46	96.66	1950	8	15	8.5	–	2
28.70	96.60	1950	8	16	7	–	2
26.80	95.00	1950	8	26	7	–	2
27.50	96.40	1950	9	13	7	–	2
30.50	91.00	1951	11	18	8	35	1
30.50	91.50	1952	8	17	7.5	–	2
24.20	95.10	1954	3	21	7.3	–	2
33.30	82.40	1955	1	28	7.3	–	2
39.90	74.70	1955	4	15	7.5	–	2
6.70	93.70	1955	5	17	7	–	2
35.10	67.50	1956	6	9	7.5	–	2
23.34	70.20	1956	7	21	7	–	2
24.38	93.76	1957	7	1	7.2	41	2
36.51	70.98	1958	3	28	7.3	188	2
39.91	77.73	1961	4	1	7.4	–	2
39.73	77.62	1961	4	13	7.6	38	2
34.18	81.93	1961	6	4	7	11	2
36.49	70.34	1962	7	6	7.2	204	2
39.49	75.27	1985	8	23	7.3	7	2
35.31	78.20	1996	11	19	7	–	1
29.97	68.20	1997	2	27	7.3	33	2
23.40	70.30	2001	1	26	7.7	25	2
35.79	90.51	2001	11	14	7.1	10	2
2.98	96.11	2002	11	2	7.5	–	1
3.34	96.13	2004	12	26	9.3	16	2
9.84	94.11	2004	12	26	7.8	–	1
6.98	92.81	2004	12	26	7.2	10	2
2.10	97.11	2005	3	28	8.4	–	1
34.49	73.14	2005	10	8	7.6	10	2
2.76	95.96	2008	2	20	7.5	–	1

1, ISC; 2, IMD; 3, USGS; 4, Rajendran et al. (2004, 2008); 5, Iyengar et al. (1999); 6, PMD; 7, Ambraseys and Bilham (2009); 8, Kumar et al. (2001); 9, Lave et al. (2005); 10, Sukhija et al. (2006); 11, Rao and Rao (1984); Rao (2005); 12, Ambraseys and Jackson (2003); 13, Bilham et al. (2007); 14, de Ballore (1896); 15, Oldham (1883); 16, Milne (1911); 17, Ambraseys (2000); 18, Jaiswal and Sinha (2004)

4.5 Declustering

Estimation of the recurrence parameters assumes the sample data series to be temporally statistically independent. Aftershocks and foreshocks are admittedly dependent on the main shock and hence such events get clustered in a general catalogue. The widely used

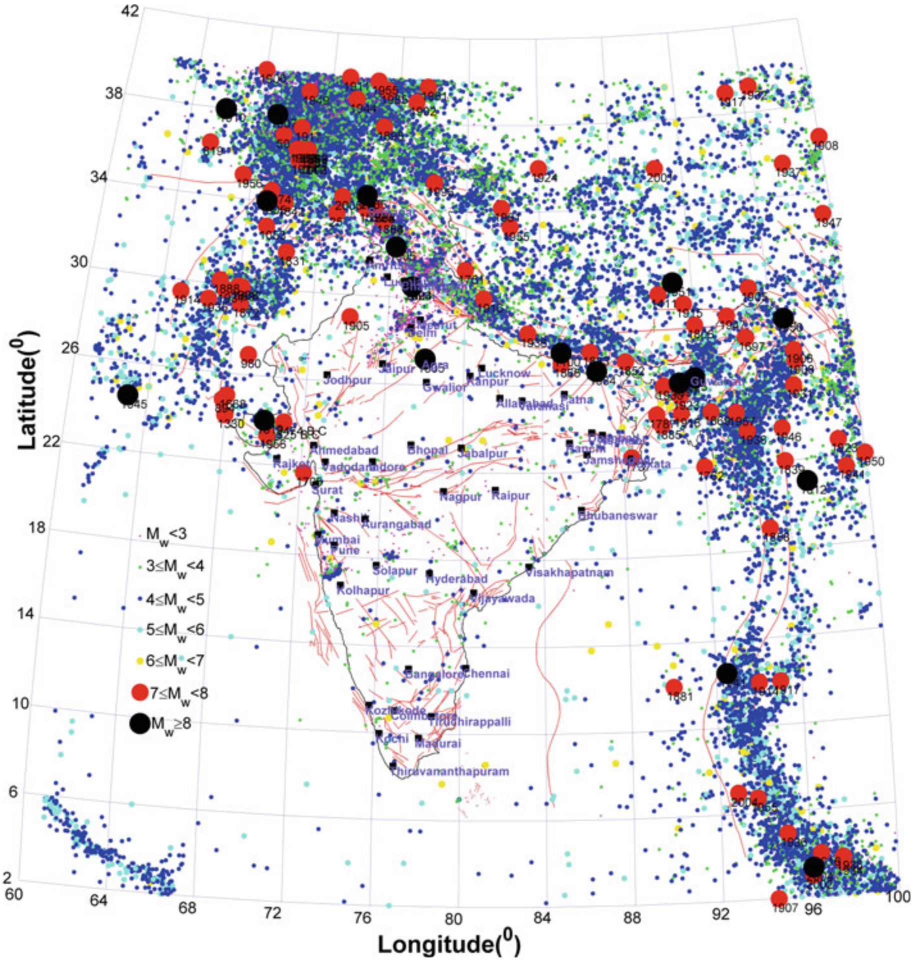

Fig. 4 Seismicity of India (2474 BC to 2008 AD). (Excluding foreshocks and aftershocks)

declustering approach introduced by Gardner and Knopoff (1974) and modified by Uhrhammer (1986) is used here to remove time-dependent events from the earthquake catalogue. The procedure essentially removes a space and time window after each main shock. A total of 28,095 aftershocks and foreshocks have been removed from the above main catalogue. The final catalog after foreshock and aftershock removal is shown in Fig. 4. This database used further is pictorially shown in Fig. 5 as a function of magnitude and time.

In engineering analysis and design, one needs to know the seismic activity due to all causative sources in a region of about 300 km radius around a given site (USNRC 1997). For this reason, past earthquake data in a control region of radius 300 km have been assembled to quantify seismicity around the 48 urban agglomerations.

5 Regional recurrence

The seismic activity of a region is characterized by Gutenberg– Richter recurrence relationship which is presented below

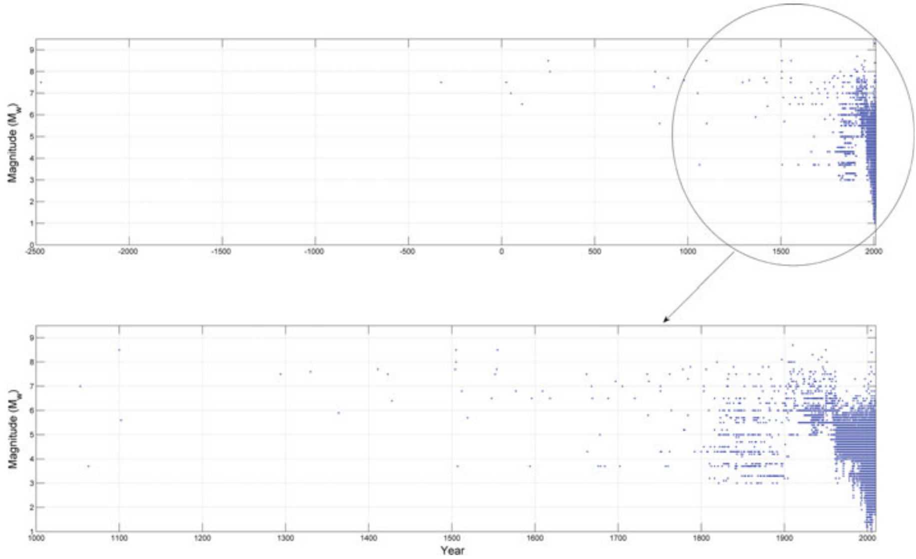

Fig. 5 Time distribution of earthquakes

$$Log_{10}\lambda(m) = a - bm \tag{3}$$

where $\lambda(m)$ is number of earthquakes greater than or equal to magnitude 'm'. The parameters (a, b) values characterize the seismicity of the region. A lower b value means that out of the total earthquakes, a larger fraction occurs at the higher magnitudes, whereas a higher b value implies a small fraction. Although the value of b varies from region to region, it typically lies in the range $0.6 < b < 1.5$. The parameter a characterizes the general level of seismicity in a given area during the study period. The higher the a value, the higher the seismicity. Since in engineering design, the frequency of occurrence of earthquakes dominate the hazard at the construction site, knowledge of (a, b) is of great interest in PSHA. Knopoff and Kagan (1977) showed that an upper bound for magnitude ($M_{\max}$) must be introduced if the Gutenberg–Richter frequency magnitude relation is to be applied in a realistic way.

Given the seismicity database, the parameters (a, b) can be directly obtained through regression analysis of the data by a straight line fit of Eq. 3 between $\log_{10}\lambda(m)$ and m. This is possible, provided complete information for all magnitudes is available. No region in the world will satisfy this demand on the database. The catalogue developed for India is a combination of instrumental, historic and pre-historic data. Apart from this composite database, uncertainties in the reported magnitudes and times for historical and paleo earthquakes also have to be taken into account in arriving at the final results.

To overcome these difficulties, the procedure developed by Kijko and Graham (1998) and Kijko (2004) is applied in the present study to quantify the level of seismic activity at the given 48 sites. This method assumes Poisson distribution for earthquake occurrences with activity rate $\lambda(m)$ and doubly truncated Gutenberg–Richter relationship for magnitudes. The uncertainty in the estimation of magnitudes and time of occurrence of earthquakes is also incorporated in deriving the parameters. The three parameters, namely the mean seismic activity rate, $\lambda(m)$, b-value in Eq. 3 and maximum magnitude ($m_{\max}$) are estimated for the 300 km control region surrounding the 48 sites. An iterative scheme is used to determine simultaneously these three parameters. Determining the seismicity parameters by the maximum likelihood procedure of Kijko and Graham (1998) requires the earthquake catalogue to be partitioned into historic and complete part. The threshold magnitude (m_0) defined as the lowest magnitude above which 100% of the events in a given region are detected also has to be estimated.

In the present study, the earthquake catalogue which is collected from the various sources in 300 km around each grid point is first evaluated for its completeness. Two widely used procedures proposed by Stepp (1972) and Mulargia and Tinti (1985) are applied to determine the interval in a magnitude class over which the class is complete. At each city, the earthquake data is grouped into seven magnitude classes such as $3 \leq M_\mathrm{w} < 4, 4 \leq M_\mathrm{w} < 5, 5 \leq M_\mathrm{w} < 6$, $6 \leq M_\mathrm{w} < 7, 7 \leq M_\mathrm{w} < 8$ and $8 \leq M_\mathrm{w} < 9$. With a time interval of 10 years, the average number of events per year in each magnitude range is determined. If $x_1, x_2, \ldots, x_n$ are the number of events per year in a magnitude range, then the mean rate for this sample is

$$\chi = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{4}$$

where n is the number of unit time intervals. The variance is given by

$$\sigma_\chi^2 = \frac{\chi}{T} \tag{5}$$

where T is the duration of the sample. If χ were to be constant, σ_χ would vary as $1/\sqrt{T}$. As per Stepp (1972) the standard deviation of the mean rate for the six magnitude intervals as a function of sample length are plotted along with nearly tangent lines with slope $1/\sqrt{T}$. The deviation of standard deviation of the estimate of the mean from the tangent line indicates the length up to which a particular magnitude range may be taken as complete. The standard deviation shows stability in shorter windows for smaller earthquakes and in longer time windows for large magnitude earthquakes. A typical completeness test where the standard deviation of the estimate of the mean of the annual number of events as a function of sample length for Delhi urban agglomeration is shown in Fig. 6. The analysis shows that data is complete for the sets $4 \leq M_\mathrm{w} < 5, 5 \leq M_\mathrm{w} < 6, 6 \leq M_\mathrm{w} < 7$ for the past 60 (1949–2009), 90 (1919–2009) and 110 (1899–2009) years, respectively. The time period of catalogue completeness can also be estimated by a simple graphical technique proposed by Mulargia and Tinti (1985). In this procedure known as the visual cumulative method, a plot between the cumulative number of events for a particular magnitude range and time is prepared. For a complete catalog the data will fall on a straight line. The year when the trend of the data stabilizes to approximately a straight line gives the completeness interval. This method is based on the assumption of constant average slope. In Fig. 7 the cumulative number of events versus the time for $M_\mathrm{w} \geq 4.0$ and $M_\mathrm{w} \geq 5$ is shown for Delhi. Using least-square fit with a correlation coefficient ≥ 0.90, we observe that earthquakes falling in the magnitude range, $M_\mathrm{w} \geq 4$, $M_\mathrm{w} \geq 5$ are complete since 1949 and 1914, respectively. These are almost same as that obtained from the Stepp's approach (Fig. 6). The completeness analysis for magnitude intervals with larger values for strong and great earthquakes is difficult to perform because the average return period of such large earthquakes is larger than the time span covered by the catalog.

Based on the completeness test of magnitude class $4 \leq M_\mathrm{w} < 5$, the data set has been divided into *complete part* (1949–2009) and *extreme part* (250–1948). After dividing the seismicity data, the threshold magnitude is found from the complete part of the catalogue (Wiemer and Wyss 2000). The maximum curvature method is used to determine M_0 from the frequency magnitude distribution. The threshold magnitude is taken as the magnitude when the negative slope trend of the data stabilizes to approximate a straight line. The M_0 value for

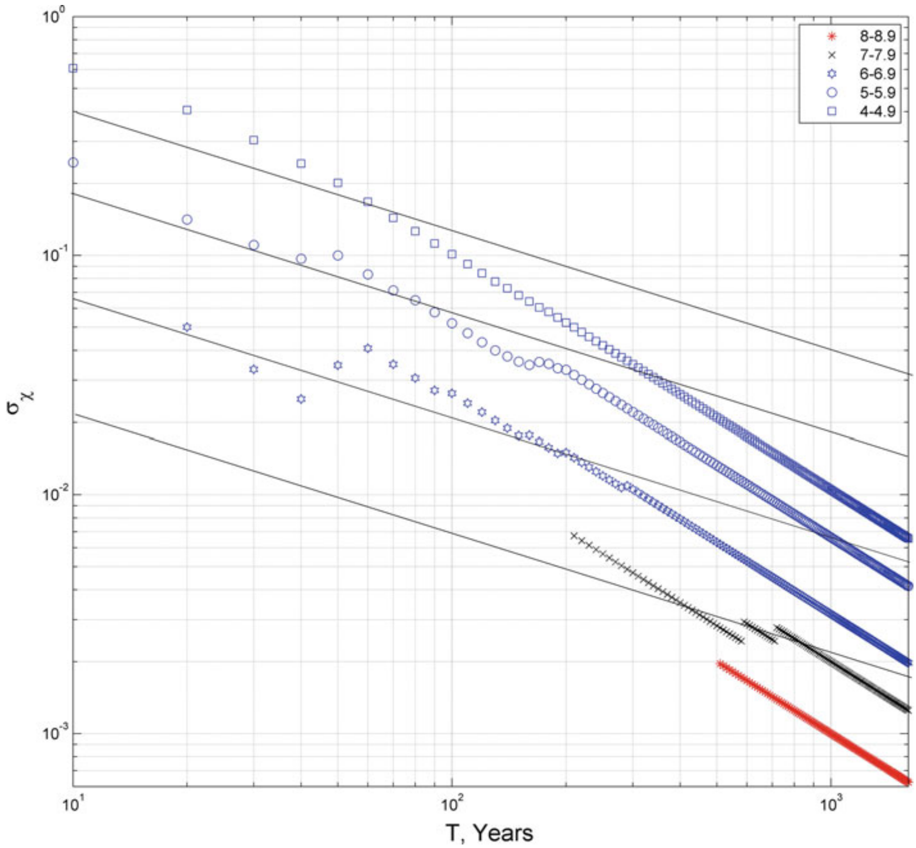

Fig. 6 Completeness test of earthquake data for Delhi urban agglomeration. Variation of σ_χ versus time interval and magnitude. *Line* with slope of $1/\sqrt{T}$

the Delhi region is obtained as M_w 4.5, as shown in Fig. 8. Once the catalog has been divided in time and the threshold magnitude (M_0) is known, the standard computer program written by Kijko and Graham (1998) is used for determining the earthquake recurrence relation. Based on the seismicity database, the uncertainty in the reported magnitudes in extreme part is taken as 0.5, where as for the complete part it is assumed to be 0.3. The *b*-value for Delhi city is obtained as 0.85. The three seismicity parameters for Delhi are reported in Table 1.

6 Seismic hazard parameters

In a similar way, the analysis is repeated for all the forty-seven urban agglomerations in India by utilizing the seismicity data in 300 km region around the city. The estimated threshold magnitudes are reported in Table 1. It can be observed that for Chandigarh and Srinagar, urban areas in Himalayan region m_0 in the control region of radius 300 km is obtained as 4.3. For four urban agglomerations in Gujarat, m_0 is 4.3. In peninsular India urban agglomerations, m_0 lies in between 4.0 and 5.3. The determined threshold magnitude is used further to

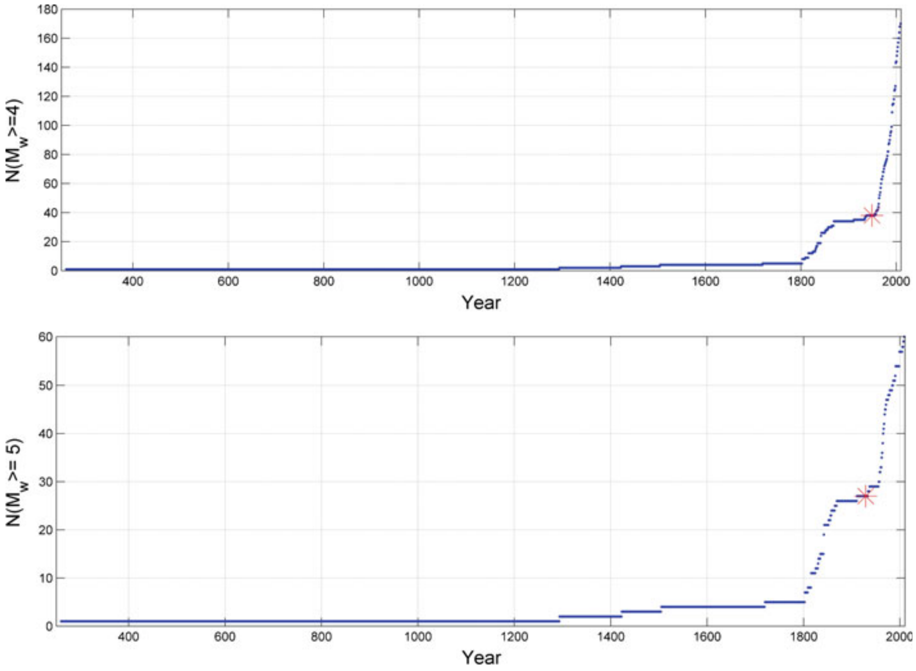

Fig. 7 Graphs between time and cumulative number of earthquakes (N) showing the completeness periods of earthquakes for $M_{\mathrm{W}} \geq 4.0$ since 1950, (B) $M_{\mathrm{W}} \geq 5$ since 1929

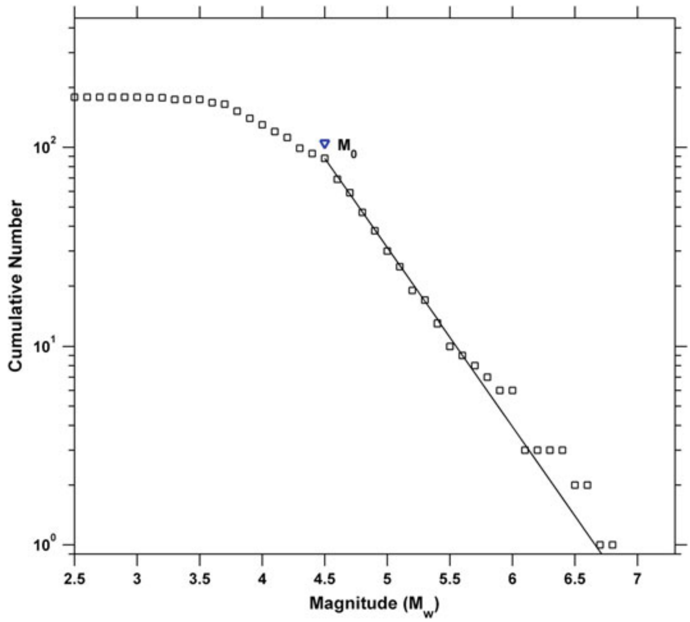

Fig. 8 Estimation of threshold magnitude for Delhi city

estimate the seismicity parameters. The b-value, $\lambda(m_0)$ and M_{max} estimated from the maximum likelihood method of Kijko and Graham (1998) are reported in Table 1. The standard deviation of the obtained b-values and $\lambda(m_0)$ are also reported in Table 1. It can be observed that uncertainty in the estimated b-values for all the 48 agglomerations lies in between 0.03 and 0.1. The increase in the uncertainty for some regions can be attributed to the quality of the earthquake catalogue. Since earthquakes occur frequently in Himalayas and northeast India, the catalogues for 300 km region surrounding urban agglomerations contains complete information about the both small and damaging earthquakes and hence the uncertainty in the estimated parameters is low. In Indo-Gangetic plain, central India and peninsular India, the earthquake catalogues contain very few events and hence the uncertainty in the estimates is high.

The recurrence relation for Chandigarh and Srinagar in Himalayan region is shown in Fig. 9a. The rate of occurrence at all magnitude is high for Srinagar compared to Chandigarh. The return period (T_R) defined as the reciprocal of activity rate for M_w 6 event for Srinagar is 10 years whereas for Chandigarh it is 27 years. The maximum magnitude is also high for Srinagar. Among these two urban agglomerations Srinagar ranks first in terms of seismic activity.

Figure 9b shows the recurrence relations for the 11 urban agglomerations in the Indo-Gangetic region. It can be observed that activity rate for the Amritsar and Ludhiana is high for magnitudes greater than 6 indicating that they are the most active region in Indo-gangetic plain. Although their activity rates are high for magnitudes less than M_w 6, high T_R for major earthquakes ($M_w > 6.5$) makes Amritsar and Ludhiana regions ranked next to Patna. On the other hand, the seismic activity in the 300 km surrounding Allahabad and Varanasi is low when compared to the remaining urban agglomerations in Indo-Gangetic plain. The maximum expected magnitude for these two regions is about M_w 6.8 and M_w 7.3. Kanpur region comes next in the order of increasing seismic activity. The remaining agglomerations lie in between Ludhiana and Kanpur. It is interesting to note that maximum expected magnitude for Delhi is M_w 8.7. The return period for M_w 6 events for these 11 regions lies in between 10 and 70 years.

The obtained recurrence relations for 14 agglomerations in central India are shown in Fig. 9c. The recurrence relation are almost similar for Jaipur and Gwalior regions and their activity rates are higher when compared to other agglomerations in central India. Visakhapatnam region can be considered as the lowest seismically active region in central India. The maximum expected magnitude for this region is less than M_w 6. The return period for M_w 6 events for the 13 regions except Visakhapatnam and Bhubaneswar lies in between 46 and 470 years.

In Fig. 9d, the recurrence relations for Ahmedabad, Vadadora, Rajkot and Surat urban agglomerations are shown. It can be clearly observed that activity rate is high for the region surrounding Rajkot when compared to the remaining three agglomerations and the activity rate is lowest for Surat agglomeration. The return period for M_w 6 events is 30 years for Rajkot and Ahmedabad, 60 years for Vadodara and 123 years for Surat. Based on the seismicity in the 300 km control region surrounding these agglomerations, Rajkot and Ahmedabad can be considered as most active followed by Vadodara and Surat in Gujarat region.

The recurrence relations obtained for the 16 regions in peninsular India are shown in Fig. 9e. It can be observed that except for Nashik region, the maximum expected magnitudes lie in 5.8 to 6.8. Although M_{max} is lower than Nashik, the λ-value's are high for Solapur, Mumbai, Kolhapur, Hyderabad and Pune regions for magnitudes less than M_w 6.5. The lowest

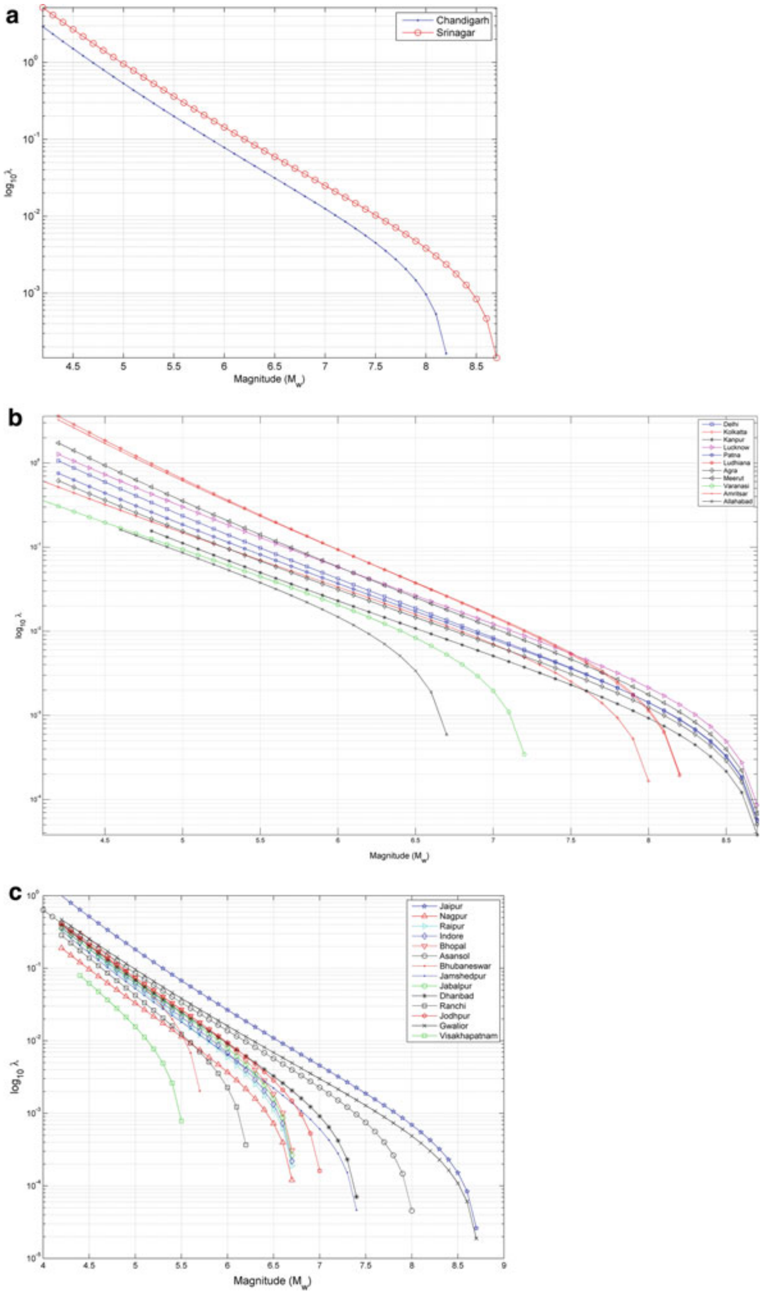

Fig. 9 **a** Regional magnitude–frequency relationship for urban agglomerations in Himalayan region. **b** Regional magnitude–frequency relationship for urban agglomerations in Indo-Gangetic region. **c** Regional magnitude–frequency relationship for urban agglomerations in Central India. **d** Regional magnitude–frequency relationship for urban agglomerations in Gujarat region. **e** Regional magnitude–frequency relationship for urban agglomerations in Peninsular India. **f** Regional magnitude–frequency relationship for Guwahati urban agglomerations in northeast India

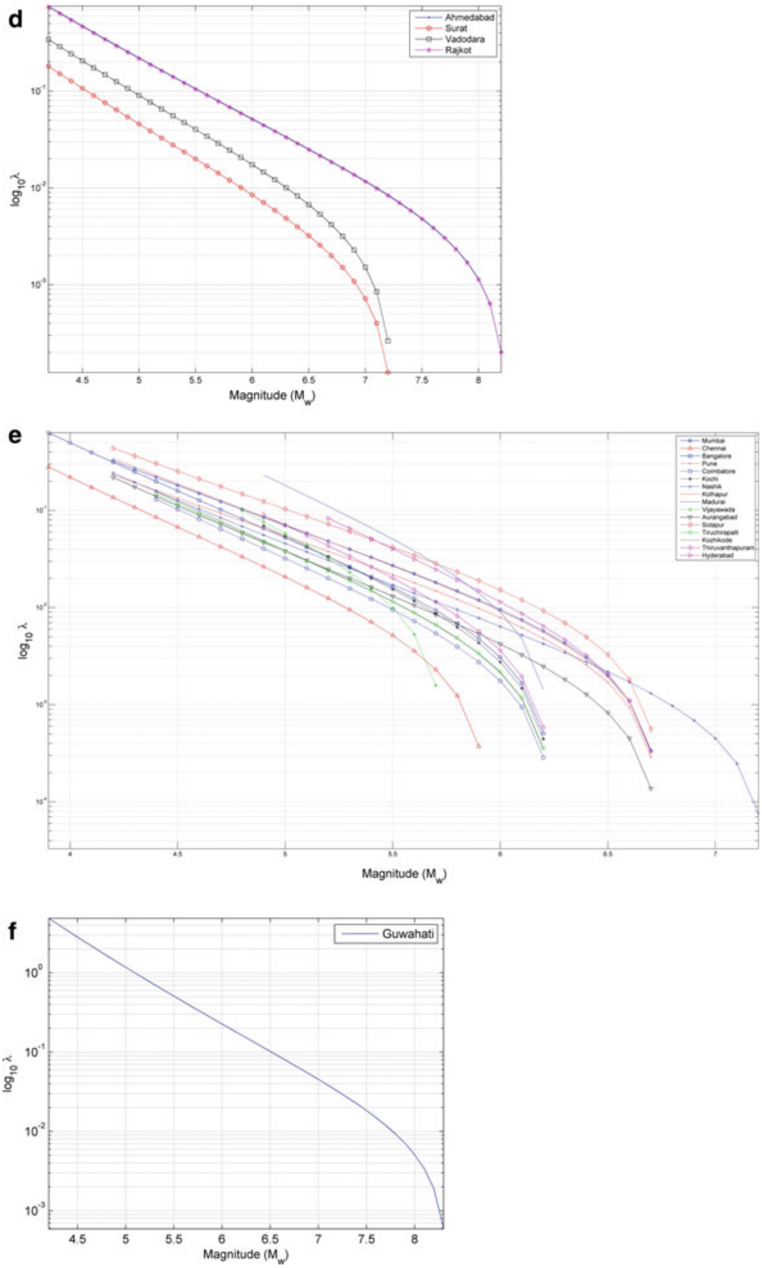

Fig. 9 continued

activity rate for events with magnitudes less than M_w 6 can be observed for Chennai region. The return period for M_w 6 events for the 16 regions lie in between 36 and 306 years.

In Fig. 9f the recurrence relation obtained for Guwahati urban agglomeration located in north-eastern India is shown. The return period for M_w 6 events in Guwhati region is 5 years. The derived recurrence relations for all the 48 urban agglomerations are shown in Fig. 9 as per their tectonic region.

7 Summary and conclusions

This paper is motivated by the desire to derive site specific seismic hazard curves for important urban agglomerations in the Indian subcontinent. A total of 48 urban agglomerations with population more than 1 million has been selected to investigate site specific activity. The most up to date earthquake data has been collected to estimate the hazard parameters for quantifying seismicity. An earthquake catalogue for the region between 2°E–40°E latitude and 61°N–100°N longitude from 2474 BC to 2009 AD has been compiled from various sources in the literature (Figs. 3, 4). The instrumental, historic and paleo earthquakes have been included in the catalog. Seismicity data in 300 km region around each urban agglomeration is assembled to quantify the seismic activity. The earthquake catalogues for each city are first evaluated for their completeness. Based on the completeness test of Stepp (1972) and Mulargia and Tinti (1984), the seismicity data is divided into complete and extreme part. The maximum likelihood procedure of Kijko and Graham (1998) which utilizes the information both in the complete, extreme and prehistoric part of the catalogue is used for estimating the seismicity parameters (λ, b, M_{max}). The parameters are obtained at each city and the final results are reported in Table 1. The uncertainty in the estimated b-values and $\lambda(m_0)$ have also been reported. The developed earthquake recurrence relations are shown in Figs. 9a–e and 10. The obtained activity rates indicate that region surrounding Guwahati urban agglomeration

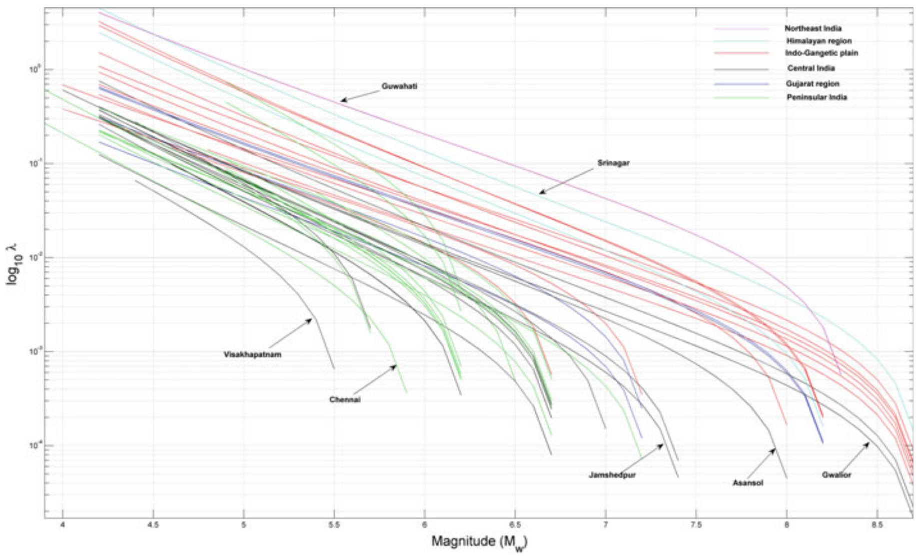

Fig. 10 Regional magnitude–frequency relationship for 48 urban agglomerations in India

is the most seismically active region for events with magnitudes less than M_w 8.1 followed by Srinagar, Ludhiana, Amritsar and Chandigarh. Jaipur and Gwalior lie in Zone II (zone of less seismic hazard) in the building code but the recurrence relations show that maximum magnitude for these two regions can be as high as 8.7. Similarly Kanpur, Lucknow and Agra lie in Zone III (zone of moderate seismic hazard), but the seismic activity in the 300 km surrounding these agglomerations is very high. The results obtained from the present study may be used in engineering constructions and design. These results can be used to preliminarily rank the available construction sites in important projects. In construction projects, when multiple sites are available, engineers might find it difficult to choose an appropriate site. The methodology presented in this study can be used to preliminarily rank the available construction sites by examining the seismic activity in the 300- km region around the site. The estimated recurrence relations (Fig. 10) are for the control region around each grid point and not specific to any particular fault.

It should be mentioned here that in the present analysis past seismicity has been used to estimate the seismicity parameters. The use of geological data such as strain rate or the rate of seismic moment release to constrain the seismicity parameters would increase confidence in using the obtained results (Field et al. 1999). However, with the existing limitations such as non-availability of geological data, the results obtained in the present study, can be considered as the best.

The seismicity parameters cannot be used directly in earthquake resistant design of structures. Since the final surface level vibration causes structural damage, engineers demand design ground motion. The seismic hazard is also defined in terms of ground motion induced at the site due to earthquakes that can occur on the existing faults in 300 km control region. This leads to probabilistic seismic hazard analysis (PSHA) in addressing the seismic hazard of important cities (Cornell 1968). The three basic inputs required in PSHA are the earthquake recurrence relationships, knowledge of the faults and ground motion models. The seismicity parameters (Table 1) obtained in this study provides an important input to PSHA. Fault level recurrence relations can be easily estimated from regional seismicity parameters in a heuristic fashion by invoking the principle of conservation of seismic activity (Raghukanth and Iyengar 2006). The estimated recurrence relations combined with fault map (Fig. 2) and region specific attenuation relations can be used to prepare hazard curves for peak ground acceleration and response spectra by PSHA at these 48 urban agglomerations.

T earthquake catalogue developed in this study for India can be obtained from the author upon request.

Acknowledgments Thanks are due to Prof. R. N. Iyengar for providing information regarding historical and paleo earthquakes. I thank the reviewers for their comments which helped me to improve the quality of the manuscript.

References

Ambraseys N, Bilham R (2009) The tectonic setting of Bamiyan and seismicity in and near Afghanistan for the past twelve centuries. In: Claudio Margottini (ed) UNESCO Special Publication: The Destruction of the Giant Buddha Statues in Bamiyan, Central Afghanistan, UNESCO's emergency activities for the recovering and rehabilitation of cliff and niches. ISBN 978-448-0375-5

Ambraseys N, Jackson D (2003) A note on early earthquakes in northern India and southern Tibet. Curr Sci 84(4):570–582

Balakrishnan TS, Unnikrishnan P, Murthy AVS (2009) The tectonic map of India and contiguous areas. J Geol Soc India 74:158–170

Bapat A, Kulkarni RC, Guha SK (1983) Catalogue of earthquakes in India and neighbourhood from historical period up to 1799. Indian Soc Earthq Technol, 211 pp

Bilham R (2009) The seismic future of cities. Bull Earthq Eng 7:839–887

Bilham R, Gaur VK, Molnar P (2001) Himalayan seismic hazard. Science 293:1442–1444

Chandra U (1992) Seismotectonics of Himalaya. Curr Sci 62(1–2):40–71

Chandra U (1977) Earthquakes of Peninsular India—a seismotectonic study. Bull Seism Soc Am 67(5): 1387–1413

Chandra U (1978) Seismicity, earthquake mechanisms and tectonics along the Himalayan mountain range and vicinity. Phys Earth Planet Interiors 16(2):109–131

Cornell CA (1968) Engineering seismic risk analysis. Bull Seism Soc Am 58:1583–1601

de Montessus de Ballore MF (1896) Seismic phenomena in the British Empire. Q J Geol Soc Lond 52:651–668

Field DH, Jackson DD, Dolan JF (1999) A mutually consistent seismic-hazard source model for Southern California. Bull Seismol Soc Am 89:559–578

Gansser A (1974) Data for orgenic studies: Himalaya. In: Spencer AM (ed) Mesozoic-Cenzoic Origenic belts. Geological Society, London, pp 267–278

Giardini G, Wiemer S, Fäh D, Deichmann N (2004) Seismic hazard assessment of Switzerland, Publication series of the Swiss seismological service. ETH Zürich, 91 pp

Gardner JK, Knopoff L (1974) Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bull Seism Soc Am 64:1363–1367

GSI (2000) Seismo tectonic Atlas of India and its Environs. Geological Survey of India, India

Guha SK, Basu (1993) Catalogue of earthquakes (>3.0) in Peninsular India. AERB Technical Document No. TD/CSE-1, pp 1–70

Guha SK, Gosavi PD, Varma MM, Agarwal SP, Padale, JG, Marwadi SC (1968) Recent seismic disturbances in the Shivaj isagar Lake area of the Koyna hydroelectric project, Maharashtra, India. Comprehensive report up to June 1969, Central Water and Power Research Station, Poona-24, India

Gupta ID (2006) Delineation of probable seismic sources in India and neighbourhood by a comprehensive analysis of seismotectonic characteristics of the region. Soil Dyn Earthq Eng 26:766–790

Idriss IM (1985) Evaluating seismic risk in engineering practice. In: Proceedings of the 11th international conference on soil mechanics and foundation engineering, San Francisco, vol 1, pp 255–320

IS 1893 (2002) Indian standard, criteria for earthquake resistance design of structures, Fifth revision, Part-I. (Part I) Bureau of Indian Standard, New Delhi

Iyengar RN, Ghosh S (2004) Microzonation of earthquake hazard in greater Delhi area. Curr Sci 87:1193–1202

Iyengar RN, Sharma D, Siddiqui JM (1999) Earthquake History of India in medieval times. Indian J History Sci 34(3)

Jaiswal K, Sinha R (2007) Probabilistic seismic-hazard estimation for Peninsular India. Bull Seism Soc Am 91(1B):318–330

Kaila KL, Gaur VK, Harinarayana (1972) Quantitative seismicity maps of India. Bull Seism Soc Am 62: 1119–1131

Khattri KN (1987) Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalaya plate boundary. Tectonophysics 138:79–92

Kijko A, Graham G (1998) Parametric-historic procedure for probabilistic seismic hazard analysis: Part I. Estimation of maximum regional magnitude $M_{\max}$. Pure Appl Geophys 152:413–442

Kijko A (2004) Estimation of the maximum earthquake magnitude $M_{\max}$. Pure Appl Geophys 161:1–27

Knopoff L, Kagan Y (1977) Analysis of the theory of extremes as applied to earthquake problems. J Geophys Res 82:5647–5657

Kumar S, Wesnousky SG, Rockwell TK, Ragona D, Thakur VC, Seitz GG (2001) Earthquake recurrence and rupture dynamics of Himalayan Frontal Thrust, India. Science 294(5550):2328–2331

Lahiri AK, Sen TK, Rao KR, Jena PR (2001) Economic consequences of Gujarat earthquake. Econ Polit Weekly 36(16):1319–1332

Lave J, Yule D, Sapkota S, Basant K, Madden C, Attal M, Pandey R (2005) Evidence for a Great Medieval Earthquake (∼1100 A.D.) in the Central Himalayas, Nepal. Science 307:1302–1305

Malik JN, Mathew G (2005) Evidence of Paleoearthquakes from trench investigations across Pinjore Garden fault in Pinjore Dun, NW Himalaya. J Earth Syst Sci 114(4):387–400

McCalpin J (2009) Paleoseismology, Volume 95 of International geophysics series, 2nd edn. Academic press, 613 pp

Milne J (1911) A catalogue of destructive earthquakes–A.D. 7 to A.D. 1899, Brit. Assoc Advan Sci Rep, Portsmouth meeting, 1911, Appendix No. 1, pp 649–740

Mulargia F, Tinti S (1985) Seismic sample areas defined from incomplete catalogues: An application to the Italian territory. Phys Earth Planet Interiors 40:273–300

NHUD (2007) National urban housing and habitat policy. Government of India Ministry of Housing & Urban Poverty Alleviation, New Delhi
Oldham T (1883) A catalogue of Indian earthquakes from the earliest times to the end of 1869 A.D. Mem Geol Surv India. XIX, Part. 3
PMD (2007) Seismic hazard analysis and zonation for Pakistan, Azad Jammu and Kashmir. Pakistan Meteorological department, Pakistan
Quittmeyer RC, Jacob KH (1979) Historical and modern seismicity of Pakistan, Afghanistan, North Western India and South eastern Iran. Bull Seism Soc Am 69:773–823
Raghukanth STG (2010) Seismicity parameters for India. Seismol Res Lett 81(2):207–217
Raghukanth STG, Iyengar RN (2006) Seismic hazard estimation of Mumbai city. Curr Sci 92(11):1486–1494
Raghukanth STG, Iyengar RN (2007) Estimation of seismic spectral acceleration in peninsular India. J Earth Syst Sci 116(3):199–214
Rajendran CP, Rajendran K, Duarah BP, Baruah S, Earnest S (2004) Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong northeast India, earthquake: implications for regional tectonism. Tectonics. doi:10.1029/2003TC001605
Rajendran K, Rajendran CP, Earnest A, Ravi Prasad GV, Dutta K (2008) Assessing the previous activity at the source zone of the 2001 Bhuj earthquake. J Geophys Res, doi:10.1029/2004JB003309
Rao BR (2005) Monograph on history of Indian earthquakes from earliest to 2005. http://seisinfo-india.org/seismocity.html
Rao BR, Rao PS (1984) Historical seismicity of Peninsular India. Bull Seism Soc Am 74(6):2519–2533
Reasenberg P (1985) Second-order moment of central California seismicity, 1969-1982. J Geophys Res 90:5479–5495
Seeber L, Armbruster J (1981) Great detachment earthquakes along the Himalayan arc and longterm forecasts. In: Simpson D, Richards M (eds) Earthquake prediction. Am. Geophys, vol 4, Ewing Series. Union, Washington, DC, pp 259–277
Seeber L, Armbruster JG, Jacob KH (1999) Probabilistic Assessment of Seismic Hazard for Maharashtra, Government of Maharashtra, Unpublished Report
Shanker D, Sharma ML (1998) Estimation of seismic hazard parameters for the Himalayas and its vicinity from complete data files. Pure Appl Geophys 152:267–279
Singh SK, Garcıa D, Pacheco JF, Valenzuela R, Bansal BK, Dattatrayam RS (2004) Q of the Indian shield. Bull Seism Soc Am 94(4):1564–1570
Stepp JC (1972) Analysis of completeness of the earthquake sample in the Puget sound area and its effect on statistical estimates of earthquake hazard. In: International conference on microzonation, vol II, pp 897–909
Sukhija BS, Rao MN, Reddy DV, Nagabhushanam P, Hussain S, Chadha RK, Gupta HK (1999) Paleoliquefaction evidence and periodicity of large prehistoric earthquakes in Shillong Plateau, India. Earth Planet Sci Lett 167:269–282
Tandon AN, Chaudhury HM (1968) Koyna earthquake of December, 1967, India Meteorol. Dept., Scientific Report No. 59
Turner HH (1911) Seismological investigations, XII. Seismic activity, 1899–1903 inclusive, Brit Assoc Advan Sci., 16th Rept., pp 57–65
Uhrhammer R (1986) Characteristics of northern and southern California seismicity. Earthq Notes 57:21
USNRC (1997) Regulatory guide 1.165: Identification and characterization of seismic sources and determination of safe shutdown earthquake ground motion. Report No. DG-1032(RG 1.165), USA
Valdiya KS (1976) Himalayan transverse faults and folds and their parallelism with subsurface structures of north Indian Plains. Tectonophysics 32:353–386
Wenzel F, Bendimerad F, Sinha R (2007) Megacities-megarisks. Nat Hazards 42(3):481–491
Wiemer S, Wyss M (2000) Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the Western United States, and Japan. Bull Seism Soc Am 90:859–869