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Seismic Microzonation of Indian Megacities: A Case Study of NCR Delhi

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Abstract India's high earthquake risk and vulnerability is evident from the fact that about 59 % of India's land area could face moderate to severe earthquakes. North India and particularly the Himalayan belt have experienced many strong to moderate earthquakes since eighteenth century. Some of the major earthquakes in past are having the magnitude more than 7.0 M_W. The present study focuses the progressive modifications on the National seismic zonation map of India officially by National agencies, other individual studies and by International Program and summarizes the seismic microzonation work performed for some of the strategic important mega cities in India. This study also analyzes the systematic development of zonation maps and various methods adopted. It has been found that the different techniques have been adopted for microzonation studies of major mega cities. The detailed methodology for Microzonation of National Capital Region of Delhi (NCR of Delhi) has been presented as a case study which emphases on the improvement of these techniques for better use in the future.

Keywords Seismic microzonation · Seismic hazard · Earthquake catalogue · Site response · Liquefaction

Introduction

Over the last few years, earthquake risk mitigation has gained worldwide attention and its need has been repeatedly demonstrated by disastrous earthquakes, which claimed thousands of lives and caused huge economic losses to industry and infrastructure. The earthquake is perhaps one of the most destructive natural disasters in the world which no one can claim to predict with accuracy. Many earthquakes in the past have left many lessons to be learned which are very essential to plan infrastructure and even to mitigate such calamities in future. Microzonation has generally been recognized as the most accepted tool in seismic hazard assessment and risk evaluation and it is defined as the zonation with respect to ground motion characteristics taking into account source and site conditions. In other words it is an effort to evaluate and to map the potential hazards found in an area, urban area in particular, that could be induced by strong ground shaking during an earthquake [1]. These hazards include ground motion amplification, liquefaction and landsliding etc. Safety against the earthquake hazard has two aspects: firstly, structural safety against potentially destructive dynamic force and secondly the safety of a site itself related with geotechnical phenomena [2]. Rapid urbanization is a factor that calls for construction of mega structures, and main reason for human loss and property damage, when due importance is not given for adequate preparation for possible hazard. Many large cities around the world have put effort into developing microzonation maps for better understanding of earthquake hazard within the cities.

Numerous studies are being carried out all over the world to quantify the seismic risk posed due the seismic activities in the particular region. A historical review of

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past events helps in the preparation of a seismic hazard profile of an area. Ample work exists in relation to historical perspective of seismic activity [3–5] and seismic vulnerability [6, 7] at the global scale. Significant contribution in this respect at country or regional level includes reconstruction of historical seismicity on the Pacific coast of USA [8], Philippines [9], Caribbean region [10], Canada [11], Middle East [12], North Africa, Middle East and Spain [13], Persia [14], America [15], Europe [16], Iran [17], Bursa [18], Bucharest [19], Alexandria [20], Beijing [21], Napoli [22], Santiago de Cuba [23], Sofia [24], Zagrab [25, 26], Australia [27], China [28], Germany [29], Russia [30], Las Vegas [31] and Bam City [32]. A huge volume of research exists on historical seismicity and seismic hazard in the Indian subcontinent and adjoining parts. Some of the studies include earthquakes in India [33–36] the Himalayan seismicity [37–39], Indian seismicity during medieval times [40], North Indian earthquakes [41], India and the Himalayas [42], Delhi and North India [43, 44] Gujarat [45–47]. These studies have enabled the establishment of the link between seismic occurrence, behaviour, cause and associated hazard.

The present paper describes the seismic hazard in the NCR of Delhi, India. For the very purpose of achieving the goal of the study and the high seismic risk posed by the region, NCR of Delhi is selected as a study area. The study area i.e. NCR of Delhi has a population more than 28 million according to 2011 census report, located on the banks of river Yamuna. Being the capital of India, the city is considered as highly important viewing to social and economical issues, comes under seismic zone IV according to seismic zonation map of India [48, 49], and thereby specifying basic peak ground acceleration (PGA) of 0.24 g. The region is located near the highly active Himalayan seismic belt, in addition to that there are many near field seismic sources which would generate significant hazard in the region.

Brief Review of Seismic Zonation Studies in India

Seismic Zonation Efforts in India by the Bureau of Indian Standards

In India, the Geological Survey of India (GSI) first came up with the national seismic hazard map of India in 1935 after the 1934 Bihar–Nepal earthquake [50]. In 1962, the Bureau of Indian Standards (BIS) which was formed to standardize, certify and manage quality of various products, have published the seismic macro zoning map of India [48] based on earthquake epicentres and the isoseismal map published by the GSI in 1935. According to this, India was divided into seven zones ranging from 0 (no damage) to VI (extensive damage). The zoning was reviewed in 1966 [49] and additional information like the geology and tectonic features were taken into account for modifying zones with more weightage being assigned to the tectonic features. The 1962 and 1966 [48, 49] BIS zonation maps had seven zones and each zone was assigned the maximum Modified Mercalli Intensity (MMI) based on the historically observed or expected intensities for those zones.

The earthquake macro zonation map underwent major revision in 1970 after the 1967 Koyna earthquake. The magnitude of this earthquake was M_S 6.5 and occurred at the Deccan Plateau which was previously assigned the zone 0 in the earlier maps. This raised the need to utilize both geological and geophysical data to review zoning. The major change was the removal of the zone 0 as it was not appropriate to consider a region with zero probability of earthquake shock. Another addition was the merging of zones V and VI [51]. The zonation was therefore reduced to five zones as compared to the earlier classification of seven zones. Each zone was assigned a probable intensity in MMI scale varying from V to IX for the zone I–V and placed Koyna around zone IV in the upgraded map. In 1984, the zonation map was modified [52], where the regions of different seismogenic potential were identified on the basis of past earthquakes and the regional tectonic features. The occurrence of the Latur earthquake (1993, Mb 6.3) caused an intensity of IX damages in MSK scale but prior to the earthquake, Latur was placed in seismic zone I. This was followed by destructive earthquakes of 1997 Jabalpur (Mb 6.0) and 2001 Bhuj earthquake (M_w 7.7) that raised questions on the validity of the seismic zonation map of Peninsular India (PI). This further led to the revision of the seismic zonation map and in 2002, only four zones were identified: II, III, IV and V [53].

The modifications in the zonation map of India with the occurrence of significant earthquakes suggest the assessment of hazard on a regional scale is not consistent with the local variation. The zonation map represents only the status of the present knowledge about the seismicity and the various methodologies available and has to be retrospect at regular intervals to update the information [50].

Review of Seismic Hazard and Microzonation Studies in India

Seismic zonation of India was also carried out by individuals even prior to the first zonation map by BIS in 1962. Different authors used different criteria to obtain the zonation map. The early maps were qualitative and based on the severity of damages [54, 55] while the subsequent map were quantitative and based on MMI scale [56–58] and later on the zones classified based on the probabilistic hazard analysis [59–61]. The recent seismic zonation for

India was obtained by Bhatia et al. [62] under the banner of the Global Seismic Hazard Assessment Program (GSHAP) and Parvez et al. [63]. The zoning procedure of Khattri et al. [61] and Bhatia et al. [62] to estimate the PGA is similar and it is based on the attenuation relationship of [64, 65] respectively. Parvez et al. [63] deterministically computed the ground motion using regional structural models, seismogenic zones, focal mechanisms and earthquake catalogues to prepare hazard map of India. It has been observed that though the national zonation maps serve for a first hand guideline for the seismic hazard in the country but the observed PGA value varies significantly because of local geological conditions [66].

This arises the need for detail assessment of the seismic hazards at local level by taking into consideration all the available geological, geophysical, geotechnical and seismological data. Preliminary seismic hazard assessment has also been carried out for important cities like Delhi [67], Mumbai [68], Bangalore [69, 70], Chandigarh [71], Chennai [72], Kolkata [73, 74] and Peninsular India [75, 76]. Seismic Microzonation for important Indian cities that is vulnerable to the earthquake hazards has been carried out by various authors like Delhi [43, 44, 77–83], Dehradun [84], Gujarat [85], Guwahati [86], Haldia [87], Jabalpur [88, 89], Sikkim [86, 90], Talchir [91] and Ahmedabad [46, 47] Surat and surrounding region [45, 92].

Many researchers like [38, 43, 67, 81, 82, 93–98] have taken the initiative to carryout seismic hazard analysis of Delhi. Singh et al. [98] estimated the ground motion of Delhi using the empirical Green's function and the stochastic method by assuming a point source and finite source. Ground motion estimated using only the far field sources from the Himalayan (e.g., 1999 Chamoli earthquake) region but the past earthquake shows that the Delhi has been affected by the near field sources also [99]. Iyengar and Ghosh [67] and Rathod [43] carried out seismic hazard analysis by adopting both deterministic and probabilistic methodology considering the seismotectonic parameters around 300 km radius from the city and presented rock level PGA maps for the return period of 2,500 years. Satyam [83], Rao and Satyam [82, 100] and Rathod et al. [101] presented the microzonation maps for the Delhi considering Geotechnical, Geological, Geophysical and Seimological data as an input. Finite fault simulation technique [102] has been used to generate PGA map at bedrock considering the both far field and near field sources. Rathod [43] carried out extensive field investigations by conducting MASW (Multi channel Analysis of Surface Waves) and Seismic Refraction tests at 210 locations. The Seismic response of soil was also estimated using the microtremor assessments at 185 sites. In addition to that liquefaction hazard maps are also presented by adopting SPT and V_S based methods. Mohanty et al. [77] have also come up with a first order seismic microzonation map of Delhi on a Geographic Information System (GIS) platform where Delhi was divided into four zones of hazards based on five thematic maps viz., PGA, soil type, geology, ground water fluctuation, and bedrock depth. Rathod et al. [103] proposed an attenuation relationship for Delhi and Northern India using extended finite fault simulation technique based on dynamic corner frequency approach to generate synthetic ground motions.

The microzonation map for Guwahati was prepared by Nath et al. [86] and classified into five broad zones of hazard based on eight themes; geology and geomorphology, basement depth, land use, land slide, safety factor, shear wave velocity, predominant frequency, and surface consistent PGA. Similarly a first order seismic microzonation map has been prepared by Mohanty and Walling [87] based on the integration of thematic maps of PGA, predominant frequency and elevation map. The ground motion in terms of PGA was estimated using attenuation relationship of Toro et al. [104]. Mohanty et al. [91] prepared a seismic zonation map of Talchir basin by taking the Response Spectra Ratio (RSR) values. Walling et al. [105] characterized the Talchir basin by applying the Nakamura's [106] HVSR technique on the microtremor data and observed predominant frequency at the range from 0.3 to 2.4 Hz.

Raghukanth and Iyengar [68] estimated the seismic hazard of Mumbai city using state of art probabilistic analysis considering the uncertainties in the seismotectonic details of the region and developed design spectra for different type of soils. Mhaske and Choudhury [107] presented geospatial contour mapping of shear wave velocity for Mumbai city. Suganthi and Boominathan [108] studied the site response behavior of Chennai soils by carrying out site response study using SHAKE91 and collected geotechnical data. A detailed work of seismic microzonation considering geotechnical, geophysical and seismological details has been presented by Sitharam and Anbazhagan [109]. Menon et al. [110] carried out seismic hazard analysis of Tamil Nadu by adopting probabilistic hazard analysis method and hazard maps are compared to the zoning prescribed by the seismic codes of India.

Mandal et al. [111] and Parvez and Madhukar [112], Trivedi et al. [113] were working towards the microzonation of Bhuj, Kutch and Ahmedabad respectively based on the Microtremor survey. Trivedi et al. [47, 113] carried out seismic microzonation of the Ahmedabad city based on the geotechnical, geophysical and seismological data. However, they have used far field ground motion only to generate response spectra and results are based on the single ground motion.

Rao et al. [92] and Thakker [45] carried out seismic microzonation of Surat city and surrounding region through extensive site specific investigations. Both DSHA and PSHA were conducted. Site specific earthquake characteristics were obtained based on site response analysis by DEEPSOIL and proposed microzonation [114, 115].

As discussed earlier, the seismic zonation studies were started in India way back in 1935 with first seismic hazard map of India published by GSI. Even after many years, despite the endeavors from various sources to provide a solution for the problem of earthquake hazards in India, there were many limitations, which need to be properly addressed. Based on the critical review of literature, the following points can be noted:

- The zonation map as it gives the picture at a regional scale mostly on the bedrock level without addressing the local site conditions.
- For regional seismic hazard studies preparation of a detailed seismotectonic map considering up to date seismicity and seismotectonic details is very much essential within a circular area of radius around 350 km around the study area as per USNRC [116, 117] before starting any microzonation work.
- Earthquake catalogue is one of the essential ingredients of the seismic hazard analysis. And no catalogue at homogenized magnitude followed by proper declustering is available for the study region. Very few catalogues are available for NCR of Delhi, earthquake data are sparse and in different magnitude scale, some of them are in MMI and it also contains aftershocks and foreshocks data. Hardly any efforts are made for the preparation of earthquake catalogue at homogenized magnitude with proper processing of the data for the region.
- Majority of the microzonation maps published so far in India are based on the deterministic seismic hazard analysis (DSHA). However special attention may be given to the probabilistic seismic hazard estimation, where the uncertainty is quantified and hazards are presented with required probability exceeded in particular years.
- Proper selection of ground motion prediction equations (GMPEs) is critical for seismic hazard analysis. Several attempts have been made to carryout seismic hazard analysis in India but while selecting GMPEs, the majority of works overlooked differences in the tectonic environments between the region for which they were developed and the targeted regions. Due to lack of strong motion recordings, very few strong motion accelerograph (SMA) data is available in the region and that too with no access to them. Based on limited and borrowed dataset, only two seismic attenuation relationships are available for the Himalayan region. The availability of very few relatively poorly constrained GMPE's for the region invokes the need to develop new GMPE.
- In most of the attempts, the ground motions were estimated using only the far field sources however, the past experience shows that the near field sources may also affect the region.
- Estimation of ground response is the integral part of any microzonation attempt. The significant natural variability in earthquake ground motions and dynamic properties of soils requires the use of number of ground motions and range of soil properties in the analyses. Most of the ground response analyses in India have used only single input ground motion to predict the response of ground.
- Extensive geotechnical information is essential for liquefaction assessment of an area. NCR of Delhi has varied geological and physiographic units such as rock outcrop, older alluvium (Pleistocene), newer alluvium (Holocene) and recent Yamuna flood plains. The response of earthquake to each of these units will be different.
- Geophysical (e.g., seismic refraction, surface wave methods, down hole etc.) tests are very essential to estimate shear wave velocity models for the region which can be further useful in site characterization, site response and liquefaction potential. However, in majority of attempts shear wave velocities have been estimated from the empirical equations related to standard penetration tests without assessing the suitability of such equations for the targeted region.
- The modifications in the zonation map of India with the occurrence of significant earthquakes suggest that the assessment of hazard on a regional scale is not consistent with the local variation. The national seismic zoning maps are generally prepared in small scales neglecting numerous source and site factors however seismic microzonation requires larger scale taking into considerations both earthquake source and regional geological and geotechnical site conditions in order to be used for urban and land use planning. Thus detailed seismological, geological and geotechnical studies are necessary to quantify and map the seismic hazard.

Case Study of National Capital Region of Delhi

Delhi, the national capital of India have assigned seismic zone IV as per Indian standard code of practice [53] and is seismically active since the historical times [118]. Delhi has been experiencing moderate to high seismicity from far field Himalayan earthquakes and near field seismic sources in past and recent times. The earthquakes of 1720, 1803, 1842, 1934, 1956, 1960, 1991, 1999, 2005, 2007, 2010 and 2011 are there to name a few. Apart from far field seismicity, Delhi has also been affected from time to time by the near field earthquakes of M_w <5.0. As the study region is surrounded by highly active seismic features, even for the moderate earthquake it is vulnerable, because of the presence of varied structures founded on soft soils of varying thicknesses. The water table is also very shallow as both the regions are in the high flood zone of river Yamuna. The possibility of liquefaction to occur in the region is also high especially where the soils are loose saturated sandy silt or silty sand.

Since microzonation is an important guiding tool in land use planning and safe construction practices to avoid the losses from the future earthquakes, the methodology for the microzonation have been discussed in the present article for an Indian mega city namely NCR of Delhi.

NCR of Delhi is one of the first experimented regions of the country. It is a unique example for inter-state regional development planning for a region with National Capital as its core. The NCR as notified covers an area of about 33,578 sq. kms falling in the territorial jurisdictions of four State Governments namely, National Capital Territory (NCT) of Delhi, Haryana, Uttar Pradesh and Rajasthan, however the area of the study region is around 2,800 sq. kms. As reported by the NCR Planning Board [119], it is one of the largest NCRs of the world and constitutes about 1.6 % of the country's land area. According to the recent Census of India [120], the total population of NCR of Delhi is more than 28 million. The historic Delhi is bound in the North, South and West by state of Haryana, in the East by state of Uttar Pradesh and in farthest south by Rajasthan.

Recent Seismic Activity in the Region

The region is situated in highly earthquake prone belt [53] near the very active Himalayan belt. The tremors of most recent far field Pakistan earthquake ($M_w = 7.4$) on 18th January 2011 lasted for more than 20 s in Delhi. The recent earthquakes of moment magnitude 3.2 (26/01/2011) and 4.3 (07/09/2011) occurred in the Delhi region, whose epicenters were located at a distance of 36 kms from city, were strongly felt with a loud noise. The tremors of Sikkim earthquake (18/09/2011) of $M_w = 6.9$ were also felt in Delhi. The heavily populated city, which is the national capital with number of manmade structures and world heritage monuments, could be prone to damage due to an earthquake of considerable magnitude (>6) from near field sources. The region has been affected not only from the far field Himalayan seismic activity but also from near field events as well. Table 1 shows the very recent and historical earthquakes in the region. Delhi is having a typical geological set up, which can sustain large amplified shaking. This imposes a very high risk of an earthquake disaster in Delhi, resulting into high casualties and great damage to properties. To determine the potential hazard due to an earthquake, appropriate site characterization, determination of the dynamic soil behaviour and understanding of the seismotectonics of the region are very essential in order to suitably design a structure.

General Geology and Seismotectonic Setting

NCR of Delhi is bounded by the Indo-Gangetic alluvial plains in the North as well as East, by the Thar Desert in the West and by Aravali hill ranges in the South. The terrain of Delhi is flat in general except for a low NNE-SSW trending ridge which is considered an extension of the Aravali hill ranges of Rajasthan and with river Yamuna flowing towards south direction in the eastern side of Delhi. The area can be divided into three major geomorphological units i.e., Delhi ridge, older alluvium (Pleistocene) and newer alluvium (Holocene). The exposed rock outcrops in Delhi are mainly quartzites of the Alwar series. The characteristic details of Delhi sand/silt and quartzite along with bedrock depth and ground water table are collected from the available literature. Extensive borehole data is collected from various public and private organizations and soil sections spanning the complete NCR are prepared.

Mostly, the seismicity around Delhi appears to be associated with a major geological structure, which is known as the Delhi–Hardwar Ridge [97]. It coincides with the extension of the Aravali Mountain belt beneath the alluvial plains of the Ganges basin to the Northeast of Delhi towards the Himalayan Mountains. It is observed that the Delhi region has a long seismic history of being shaken by earthquakes of local origin as well as those of Himalayan origin. The tectonic map of the region has been prepared (Fig. 1) based on the features as given in the GSI [121], Sharma et al. [97] and Iyengar and Ghosh [67]. The study region is characterized by several dominant features such as Himalayan Main Boundary Thrust (MBT) and Main Central Thrust (MCT), Delhi–Hardwar ridge, Delhi–Lahore ridge, Aravali–Delhi fold, Sohna fault, Mathura fault, Moradabad fault and Rajasthan Great Boundary Fault in addition to several other minor lineaments. It is difficult to associate the seismicity of Delhi with any particular tectonic unit. It is observed that a number of lineaments appear to be seismically active simultaneously but to different extents. Therefore, in order to carry out the seismic hazard analysis, the seismic potential of all the tectonic features (Fig. 1) must be taken into consideration.

Table 1 Major recent and historical seismic events in the region

Date (dd/mm/yy)	Magnitude (M_w)	Latitude	Longitude	Region
18/09/2011	6.9	27.72	88.06	Sikkim
07/09/2011	4.3	28.99	77.22	Delhi Sonepat border
04/04/2011	5.7	29.60	80.80	India Nepal border
23/03/2011	5.2	36.30	76.60	India China border
21/03/2011	5.7	36.50	70.90	Hindukush region
14/03/2011	3.3	30.50	79.10	Chamoli
26/01/2011	3.2	29.00	77.20	Sonepat Baghpat border
19/01/2011	7.4	28.90	64.00	Pakistan
26/11/2010	4.3	28.60	77.20	Delhi Haryana border
15/06/2008	4.3	29.45	81.10	Pithoragarh
25/11/2007	4.6	28.67	77.20	Delhi-UP border
22/07/2007	4.7	30.91	78.30	Khursali
18/03/2004	2.6	28.62	77.23	Delhi
28/04/2001	3.4	28.63	77.15	Delhi
28/03/1999	6.5	30.51	79.40	Chamoli
19/10/1991	6.8	30.78	78.77	Uttarkashi
15/08/1966	5.6	28.67	78.93	Delhi
27/08/1960	6.0	28.20	77.40	Delhi
10/10/1956	6.7	28.20	77.70	Delhi
04/04/1905	7.8	31.90	77.30	Kangra
05/03/1842	5.5	30.00	78.00	Delhi
16/01/1842	5.5	27.00	78.00	Delhi
–/–/1809	6.0	30.00	79.00	Delhi
01/09/1803	6.8	27.00	77.00	Delhi
15/07/1720	6.5	28.40	77.10	Delhi

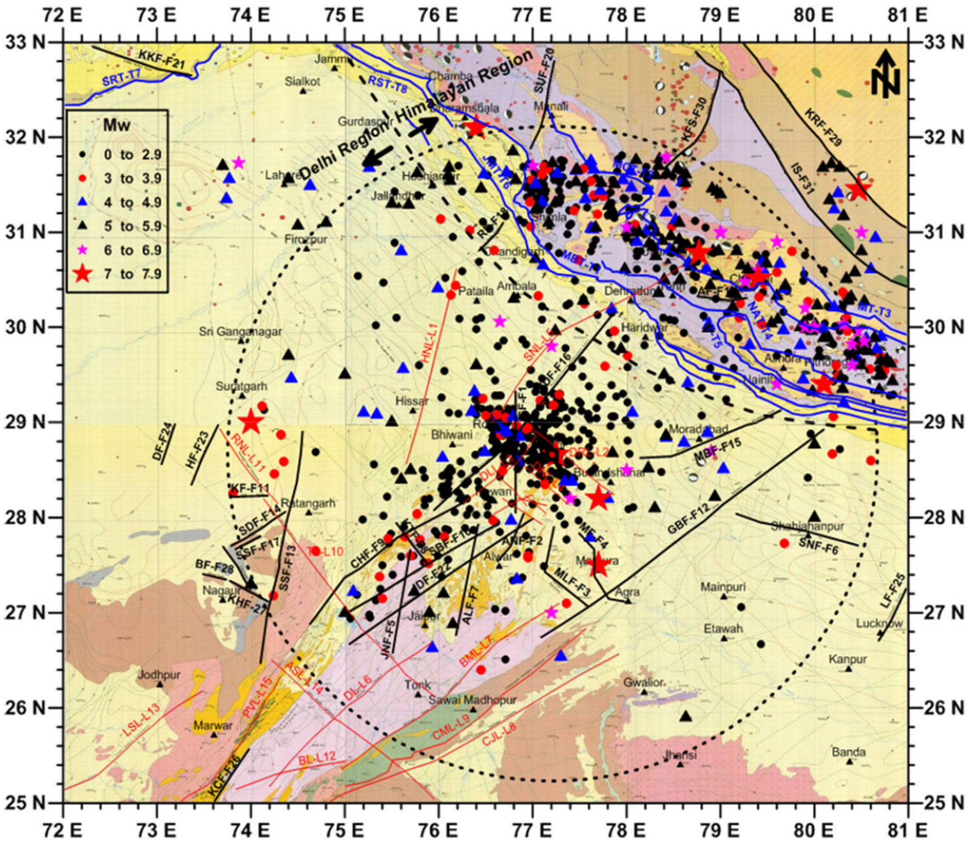
Preparation of Earthquake Catalogue and Recurrence Relationships

The earthquake catalogue for the area surrounding 350 km radius around the city was prepared for the region by collecting Pre-historical, historical and instrumental earthquake data from different sources [i.e., GSI, Indian Meteorological Department (IMD), International Seismological Centre (ISC), National Geophysical Research Institute (NGRI), United States Geological Survey (USGS) and catalogues published in literature].

A common problem faced in assembling a catalogue is due to the different magnitude scales reported in the literature. Here this is handled by converting all reported values to moment magnitude (M_W). There are some common and dependent events in the collected data which makes the declustering as an essential process for catalogue compilation. In present study, two main declustering approaches have been explored. The first approach was introduced by Gardener and Knopoff [122] and has been used in numerous hazard related studies (e.g. [123]). It simply defines a space and time window after each event. First of all, the original parameters given by Gardner and Knopoff [122] for Southern California are explored. In addition, window parameters optimized for Central Europe by Grünthal [29], and alternatives given by Uhrhammer [124] for California have been applied. The second approach evaluated is by Reasenberg algorithm [125] modified by Helmstetter et al. [126], who defined interaction windows in space-time in a more sophisticated way that attempts to introduce some of the physical background behind triggering. The results of these two declustering approaches vary considerably. However, sensitivity tests show that the difference in terms of resulting hazard is minor [127]. Modified version of the Reasenberg approach is selected as a preferred method for the present study, because of its consideration of physical background behind triggering. The Seismotectonic map of the region along with the epicentres of declustered earthquake events is shown in Fig. 1.

After developing catalogue, completeness of magnitudes in time has to be established before proceeding further. In the present study, three widely used methods namely, statistical techniques referred as Kijko and Sellevoll [128, 129], Kijko [130] and Stepp [131] and graphical techniques such as cumulative visual interpretation (CUVI) method

Fig. 1 Seismotectonic map of NCR of Delhi [43]



[132] are used to calculate the completeness periods for different magnitude classes of the catalogue. The completeness periods from these techniques have been used to compute the G-R (Gutenberg–Richter) magnitude-frequency relationship. The regional recurrence relationships obtained using CUVI and Stepp [131] methods are presented in Fig. 2. The number of earthquakes greater than or equal to magnitude *m* per year (λ_m) can be estimated from these recurrence relationships.

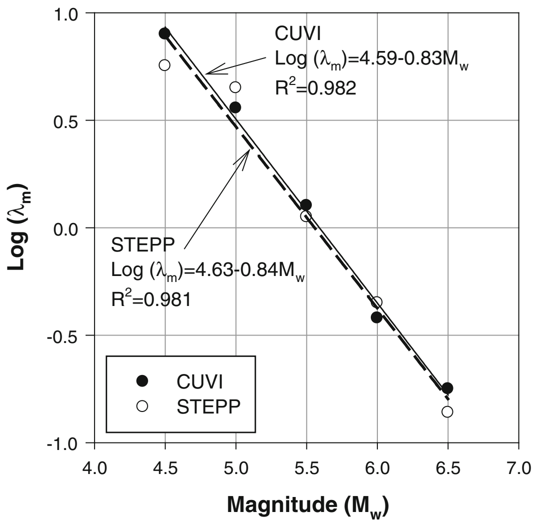


Fig. 2 Regional recurrence relationships using CUVI and Stepp [131] method for study region considering earthquake events from Delhi and Himalayan region

Generation of Synthetic Ground Motions

As discussed earlier, in the recent past many moderate to higher magnitude events occurred in and around Delhi, which is alarming about the possibility of such earthquakes in future. From the engineering point of view most commonly used data are strong motion accelerograms (SMA) recorded at various locations. In the absence of a robust database of strong-motion records, seismological modelling is a rational alternative until sufficient instrumental records become available for the region.

The strong motion for Uttarkashi (1991, $M_W = 6.8$) and Chamoli (1999, $M_W = 6.5$) earthquake have been simulated on hard rock levels using recently developed stochastic finite fault modelling based on dynamic corner frequency [133]. Parametric studies have been carried out and simulations were taken up at 27 locations where strong motion recordings are available [43]. The comparison between recorded and simulated PGA values is presented in Fig. 3. As the recorded and simulated PGA values are in

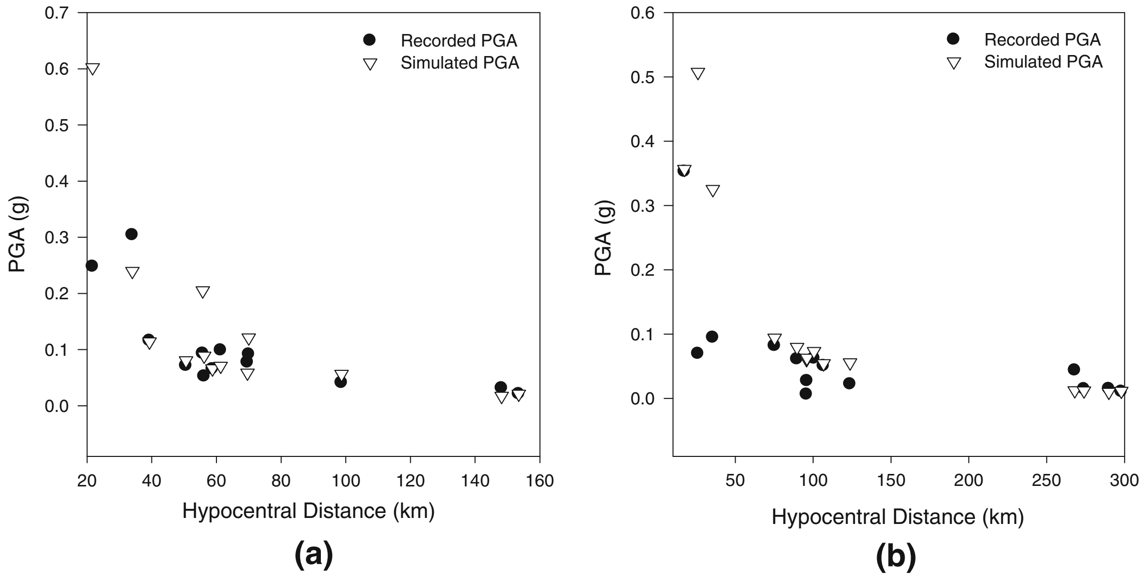


Fig. 3 Recorded and simulated PGA values for **a** Uttarkashi (1991, $M_W = 6.8$) and **b** Chamoli (1999, $M_W = 6.5$) earthquake

good agreement with each other, the simulation has been extended for generating the database to be used for developing the attenuation relationship. The simulated acceleration histories can also be very useful for performing the ground response analysis (GRA) where recorded motions are not available.

Development of Predictive Relationship of Strong Motion

Since earthquakes are quite common in the Himalayas and in North East India (NEI), in 1985 three strong motion arrays comprising of 135 stations were established in these regions [134]. The Kangra array is in the Himachal Pradesh region, the Shillong array is in NEI, and the Uttarakhand array is in northwest Himalayas. Apart from these three arrays, the Delhi Strong Motion Array was established by Central Building Research Institute (CBRI), Roorkee in 1995 [135]. A 16-element digital telemetered seismic network (DTSN) was established by Indian Meteorological Department (IMD), New Delhi in 2000–2001 [136].

Seismic attenuation relation is a prerequisite for PSHA, which requires the strong motion data for different magnitude and distance ranges. But none of the data is accessible except for the 1991 Uttarkashi and 1999 Chamoli earthquakes. So, the problem of non-availability of strong motion data is overcome with the help of stochastic finite fault approach of Boore [133] which is an improved version of the methodology proposed by Motazedian and Atkinson [137]. Acceleration time series for earthquakes with magnitudes from M_W 3.0 to 8.0 and fault distances from 10 to 500 km are simulated. An attempt has been made to simulate the directivity effect also.

Regression analysis is performed on 1,650 simulated acceleration time series to propose ground-motion relations as a function of magnitude and distance. The least squares basis for the non-linear regression model has been applied for periods from 0 to 4 s. The ground motion relation is for rock site condition and the functional form of the same is:

$$\log_{10}(PGA) = c_1 + c_2(M_w - 6) + c_3(M_w - 6)^2 + c_4(R) + c_5 \log_{10}(R) + \log_{10}(\varepsilon) \tag{1}$$

where PGA is the geometric mean of the horizontal PGA values in units of g; M_w is the moment magnitude; $R = \sqrt{(D^2 + H^2)}$, R is the hypocentral distance in km, $D =$ Depth, $H =$ Nearest fault distance; ε is a random error. The regression coefficients and error are estimated as: $c_1 = 0.66845$, $c_2 = 0.49908$, $c_3 = -0.04665$, $c_4 = -0.00257$, $c_5 = -0.85968$ and standard deviation of random error $\sigma(log_{10}\ \varepsilon) = 0.1118$.

The estimated PGA values from the proposed relationship are compared with recorded instrumental values of the Uttarkashi (1991, $M_W = 6.8$) and Chamoli (1999, $M_W = 6.5$) earthquake are shown in Fig. 4. The proposed attenuation relationship is in good agreement with the actual recorded data. The comparison among the existing and proposed attenuation for magnitude 7.0 is shown in Fig. 5. Most of the authors (Fig. 5) stated the lower prediction of ground motion at small distances and higher magnitudes due to non-availability of data. Such trend is not observed here due to the use of seismological modelling.

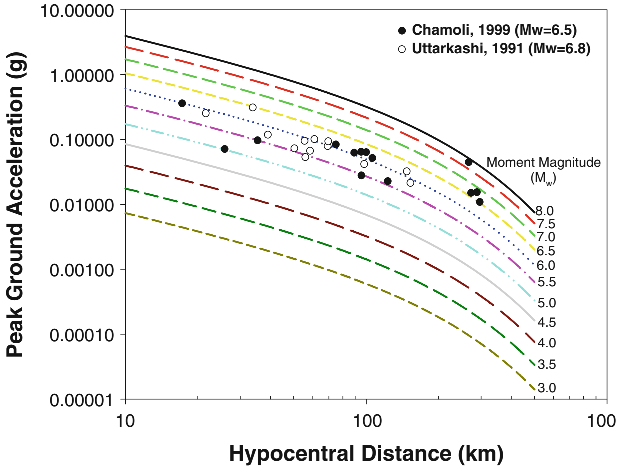


Fig. 4 Actual and predicted spectral acceleration with respect to distance and magnitude

Geophysical Site Characterization

Two types of geophysical tests i.e. Seismic Refraction and Multichannel Analysis of Surface Wave (MASW) tests have been employed for getting 1D and 2D *P*-wave and *S*-wave velocity models at 210 locations in NCR of Delhi. A GPS instrument was used to measure the latitude and longitude of the test locations. The 48 channel digital Engineering Seismograph (McSeis SX 48) with a frequency band of 4.5–4,600 Hz is used. Two varieties of geophones i.e. 28 Hz (refraction) and 4.5 Hz (MASW) were used to acquire seismic data. An array of 24 geophones with a spacing of 3 m was used for both Seismic Refraction and MASW testing. Seismic energy is generated using propelled energy generator (PEG) of 40 kg hammer for Refraction and a wooden hammer of 11 kg for MASW. The acquired data is then processed through a set of software suite SeisImager.

The 2D contour profiles at various depth intervals are prepared for both V_P and V_S. V_P values at 30 m depth are ranging from 1,500 to 2,000 m/s in Southern part and 400–600 m/s in Trans Yamuna region. The V_S values are more than 500 m/s in the Southern part and ranging from 180 to 250 m/s in Trans Yamuna region. A classification based on V_{S30} is proposed and compared with NEHRP (National Earthquake Hazard Research Program) site classes. The whole study area classified into five zones ZA, ZB, ZC, ZD and ZE as shown in Fig. 6. These zones are matching well with the geological units and soil characteristics of the region. In addition, the sub soil classifications have also been carried out based on V_{S30} using NEHRP and IBC (International Building Code) classifications. According to these classifications, the entire region of Delhi falls into two site class C ($360 < V_S < 760$ m/s) and D ($180 < V_S < 360$ m/s).

Borehole data is synthesized and soil profiles for NCR of Delhi are prepared. A statistical analysis has been performed to propose the empirical relation among V_S, SPT N, V_P and depth. An error analysis has also been performed to check the accuracy of the predictions.

Seismic Hazard Analysis

Seismic hazard analysis is the quantitative estimation of ground-shaking hazards at a particular site based on the identification of all possible sources of seismic activity, estimation of their associated seismicity and prediction of the probable consequent ground motions. Seismic hazard may be analyzed deterministically, as when a particular earthquake scenario is assumed, or probabilistically, in which uncertainties in earthquake size, location and time of occurrence are explicitly considered. The procedures for DSHA and probabilistic seismic hazard analysis (PSHA)

Fig. 5 Comparison between present and existing attenuation relations

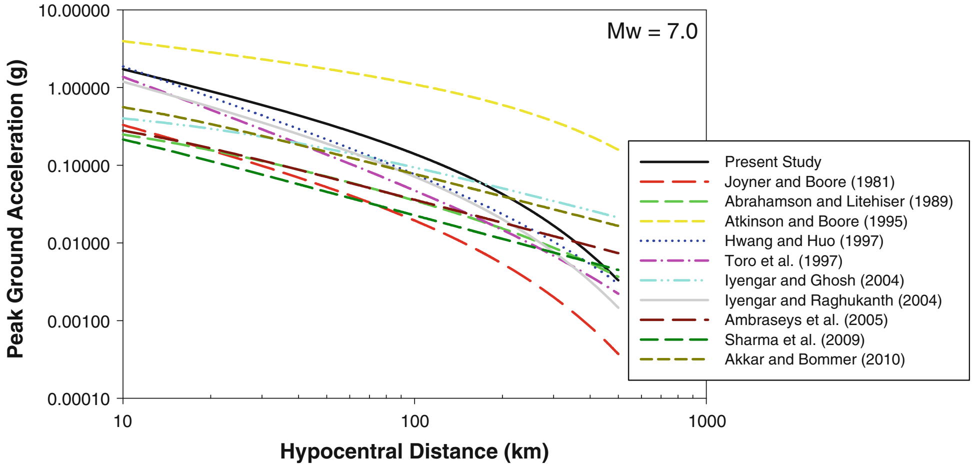
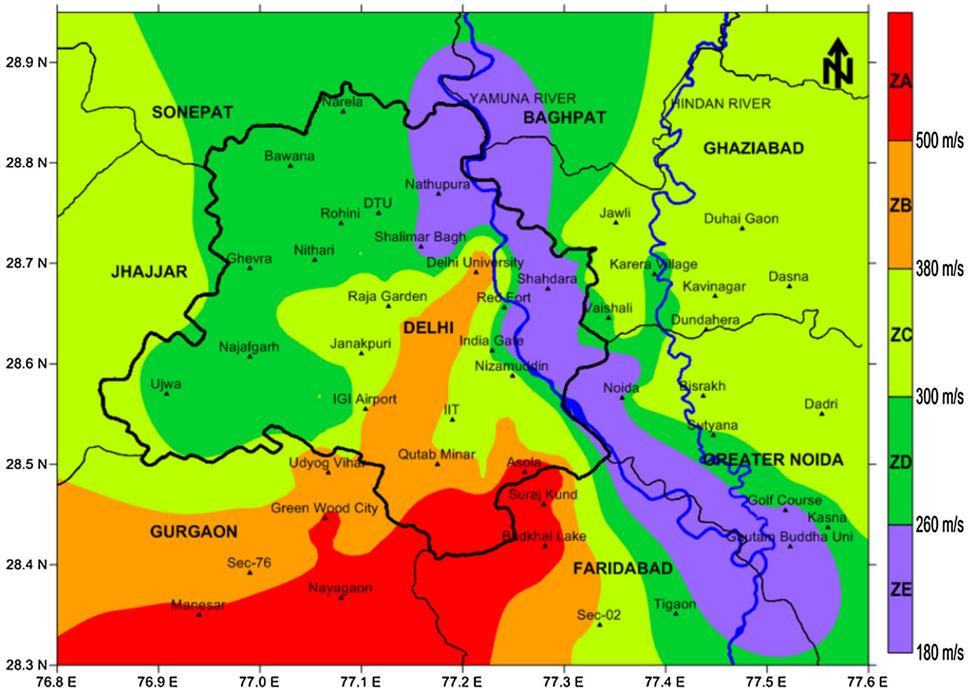


Fig. 6 Proposed site classification map for NCR of Delhi based on average shear wave velocity up to 30 m depth (V_{S30})



are well explained by Kramer [2] which was originally described by Reiter [138]. PSHA method was initially developed by Cornell [139] and there after many researchers have adopted this methodology for evaluating hazard.

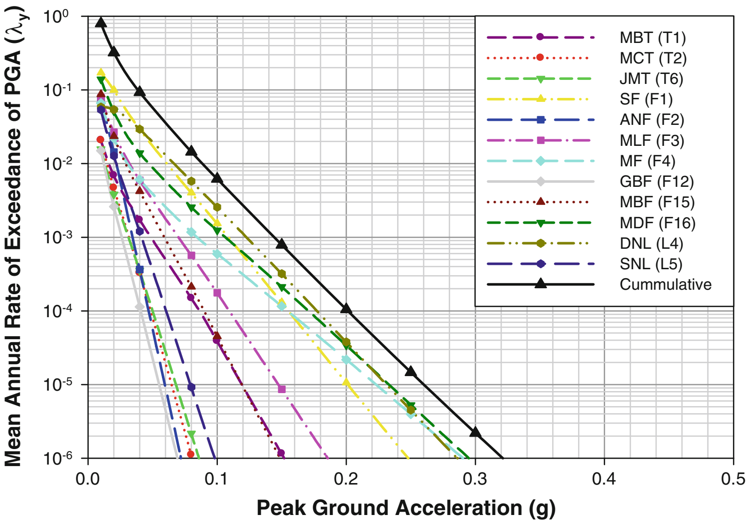
The DSHA has been carried out for all 36 seismogenic sources delineated in the study region. The PGA map at bed rock level is then prepared. Fault level recurrence is necessary to differentiate activity rate among the seismic sources. So, fault deaggregation has been carried out for sources which are capable of generating PGA >0.03 g. The hazard in terms of PGA is estimated for the study region and a typical hazard curve obtained at IIT Delhi location is shown in Fig. 7. The mean annual rate of exceedance of PGA for each vulnerable source is calculated and the cumulative effect is taken into account for further study. The PSHA has been attempted for 10 and 2 % probability of exceedance in 50 and 100 years respectively. One of the PGA map at bedrock level for 2 % probability of exceedance in 50 years is shown in Fig. 8 for study area. The bedrock PGA values vary from 0.145 to 0.228 g.

Ground Response Analysis

GRA is required to determine the response of ground to the motion of the bedrock and also determining the effect of local soil conditions on amplification of seismic waves and hence estimating the free field response spectra for future design purposes. The one dimensional equivalent linear GRA is carried out using DEEPSOIL [140] programme for the study region.

The current procedure of GRA is modified and proposed by Rathod [43] and the same modified procedure has been adopted for NCR of Delhi region. Uncertainties in geological conditions and spatial variability characteristics of soil are captured through statistical analysis. The uncertainties in various parameters like earthquake ground motion, PGA, shear wave velocity, layer thickness, shear modulus ratio and damping ratio with strain are modelled in the analysis using Monte Carlo simulation technique. No estimate was available for variation of shear modulus reduction ratio (G/G_{max}) curve and damping ratio (D) curve for the soils present in study area. So, the standard deviations proposed by Darendeli [141] for G/Gmax curve and damping ratio curve are adopted in the present analysis, which are further truncated at higher and lower strains.

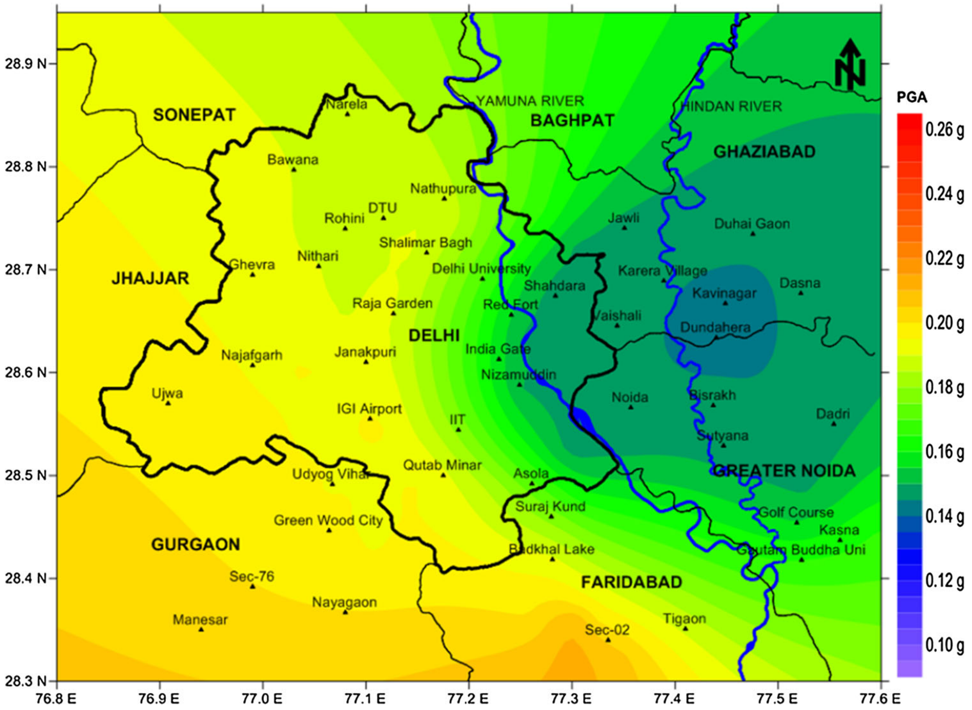
A total of 10 recorded earthquake ground motion histories are selected for analysis. The variations in the properties are used as an input to the Microsoft EXCEL and 100, 200, 500 and 1,000 samples for each case are prepared for further analysis. Microsoft EXCEL, MATLAB and DEEPSOIL are simultaneously used for this purpose. A parametric study is attempted in an elaborate manner to come up with sensitive parameters for GRA. The influence of input ground motion selection, variation in shear wave velocity (i.e. $\sigma_{\ln V_S}$), number of samples used, variation in shear modulus reduction and damping curves (i.e. variation in nonlinear properties) and effect of individual layer thickness are investigated through parametric study



MBT: Main Boundary Thrust, MCT: Main Central Thrust, JMT: Jwala Mukhi Thrust, SF: Sohna Fault, ANF: Fault Near Alwar, MLF: Fault Left of Mathura, MF: Mathura Fault, GBF: Great Boundary Fault, MBF: Moradabad Fault, MDF: Mahendragarh-Dehradun Fault, DNL: Lineament Near Delhi, SNL: Lineament Near Saharanpur

Fig. 7 Typical seismic hazard curve for IIT Delhi location

Fig. 8 Bedrock level PGA (g) map for 2 % probability of exceedance in 50 years



using stochastic seismic site response analysis [43]. Based on the analysis, the shear wave velocity and layer thickness are found to be the most sensitive parameters among others.

The whole study area is divided into five site classes (A, B, C, D and E) based on the cluster analysis. The site class A is considered as rock/hard soil while site E is considered as loose soil. The GRA is then performed for each site class at 200 samples by varying the V_S profiles at standard deviation of 0.05, 0.10, 0.20, 0.30 and 0.40. Typical results for site class A at 200 samples and $\sigma_{\ln V_S} = 0.05$ for spectral acceleration at ground surface and acceleration transfer function are shown in Fig. 9a, b respectively. The comparison among all site classes for spectral acceleration at ground surface and amplification factor is shown in Fig. 10a, b. It can be observed here that the amplification factors are higher for loose soil at a particular period only and not for zero period however, the PGA values are still lower than for rock/hard soil. This means the PGA at

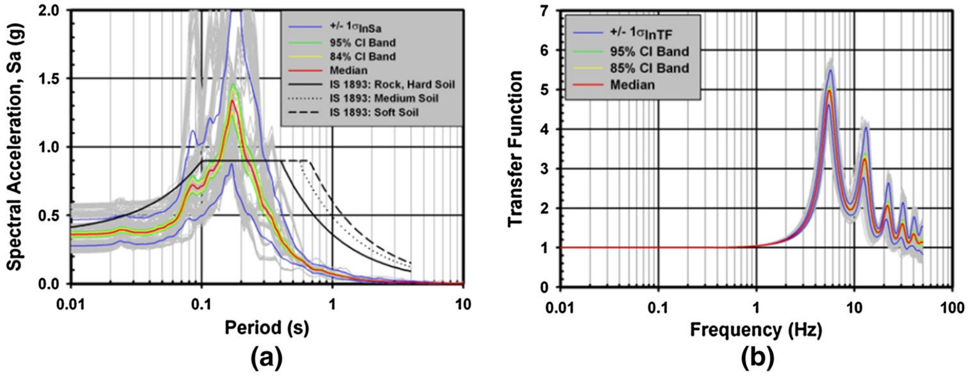


Fig. 9 **a** Spectral acceleration at ground surface. **b** Acceleration transfer function

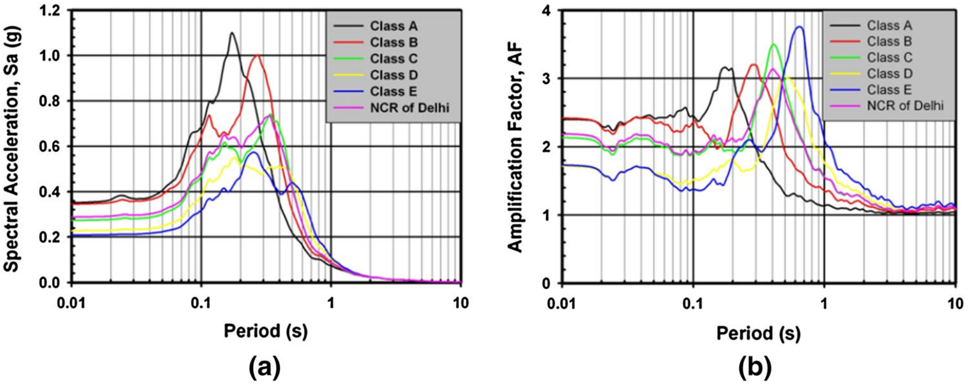


Fig. 10 **a** Spectral acceleration at ground surface. **b** Amplification factor

surface is found to be higher for rock/hard soil than loose soil. The PGA values observed are 0.349, 0.343, 0.273, 0.226 and 0.208 g for site class A, B, C, D and E respectively.

Assessment of Liquefaction Potential

The geotechnical characterization reveals that sandy silt and silts of Holocene and Pleistocene ages are the major soil types present in most part of the NCR of Delhi. The uncemented, saturated sand/silts are considered to be highly susceptible to liquefaction. Andrus et al. [142] reported that the Pleistocene soils are also prone to liquefaction and an aging factor was proposed by them. The liquefaction potential of study region is evaluated for a worst scenario of ground water table at surface separately using the SPT *N* value based method by Idriss and Boulanger [143] and shear wave velocity (V_S) based method by Andrus and Stokoe [144] and Andrus et al. [142]. A combined liquefaction hazard map for the study area is also prepared and shown in Fig. 11 by using the results of both V_S based and SPT based approaches. The individual hazard coming from each method is superimposed in this map. There are some places which show susceptibility towards liquefaction by SPT based method and not susceptible to liquefaction by V_S based methods. All such cases are combined together in this map.

Based on the analysis for liquefaction potential using SPT based method [143], it is observed that the liquefaction potential is certain in Greater Noida, Gautam Buddha University, Kasna, Sutyana, western part of Ghaziabad, the trans-Yamuna region such as Yamuna Vihar, Geeta Colony, Vishwas Nagar, Silampur, Mayur Vihar, Preet Vihar, Vinod Nagar and in some places of Noida like Udyog Vihar, Sec-15, 30, 51, 62 that are comparatively nearer to the river also has severe liquefaction potential. In western side of Delhi like Punjabi Bagh, Paschim Vihar and in some places of Dwaraka the possibility of liquefaction is moderate. In northern part, Nathupura, Bawana, Narela, Sahibabad, Vijjay Vihar, Anand Vihar, Rithala, Haidarpur the higher liquefaction potential is observed. In southern part of study area including Gurgaon, Manesar, Udyog Vihar, Surajkund, Faridabad the liquefaction potential is low and in some areas like Qutab Minar, Jawaharlal Nehru University, Dhaula Kuan, IGI Airport, Vasanth Kunj, Push Vihar, Greater Kailash it is remote due to rock at the surface or at shallow depths and presence of gravelly sands with high SPT *N* value. Based on the analysis for liquefaction potential using shear wave velocity based methods [142, 144] methods, it is observed that liquefaction is certain in places like Greater Noida, Sec-30, 55, 61 of

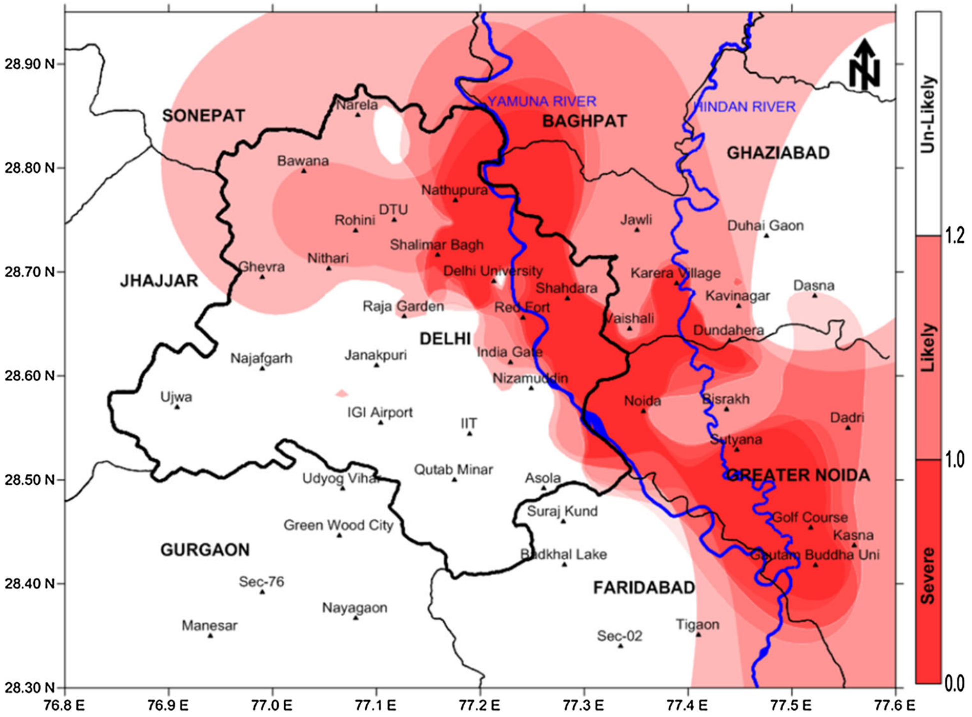


Fig. 11 Combined liquefaction hazard map of NCR of Delhi using SPT and V_S based methods

Noida, Kasna, Sutyana, Mukherjee Nagar, Pusta Road, Yamuna Vihar, Nand Nagri, Geeta Colony, Vishwas Nagar, Gandhi Darshan, Preet Vihar, Mayur Vihar, Pragati Maidan, Varun Enclave, Nathupura, Shalimar Bagh which are falling in the north and eastern side of Delhi. Liquefaction is not occurring in the western side of Delhi because of dense silty sands and also not occurring in the south and central portion, which has high shear wave velocities. In places falling in the south and central part of the area including Gurgaon and Faridabad has very high factor of safety. It is observed that liquefaction is not occurring in NCR of Delhi at depths with V_S values greater than or equal to 190 m/s. This liquefaction hazard map will help in selecting a suitable ground improvement technique and a foundation system by the engineers for future infrastucture developments in the study area.

Conclusions

A review of the research work available is attempted in the present paper to discuss the limitation and recent advancement in seismic microzonation. Some of the issues are taken up and an attempt has been made to provide the solution through the case study of NCR of Delhi.

The detailed seismological, geological and geotechnical studies have been carried out for the seismic hazard assessment of the NCR of Delhi. All the tectonic units in the study region are delineated, and a newly modified and updated fault map is prepared. Apart from the Himalayan sources, several near field minor lineaments are found to contribute towards the seismicity of Delhi. The tremors of near field—low magnitudes events of 2011 strongly felt in the area with a loud noise which confirms the seismic activity of closer minor lineaments and faults. All such seismotectonic features are delineated which may be useful for future studies. A detailed procedure for catalogue compilation is explained and various declustering algorithms are discussed and used. The results of various declustering algorithms vary significantly and hence it is suggested to decide carefully about the declustering algorithm to be used. The completeness of magnitude in time and regional recurrence relationships are established. The estimated recurrence relationships based on three different approaches are found to be in good agreement with each other. In the dearth of availability of strong motion data, seismological modelling is found to be a promising option. The results of seismological modelling are validated against two recorded earthquakes in the region. Based on the database of synthetic ground motion, an attenuation relationship is proposed. The DSHA and PSHA are carried out and a PGA map at bedrock level is proposed. The geophysical site characterization has been carried out by conducting seismic refraction and MASW methods and a site classification map for NCR of Delhi is proposed. To account for the uncertainties in input parameters for GRA, a modified procedure for GRA has been proposed and used for present study. Based on the results of the GRA, spectral acceleration curves for various site classes are proposed and compared with [53]. It can be noted that the surface

PGA values estimated for site class E are observed to be less than for site class A, however, the amplification factor at specific period only is found to be higher for site class E than site class A. Liquefaction potential of the study area is evaluated and trans Yamuna region is found to be susceptible for it.

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