Seismic hazard assessment for Delhi region

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Seismic hazard assessment is the process of evaluating the design parameters of earthquake ground motion at any site. The design parameters most widely used are intensity and peak ground acceleration (PGA). Sometimes peak velocities, peak displacements and response spectrum are also used. Seismic hazard assessment can be carried out either in the deterministic framework or probabilistic framework. It is more appropriate to estimate seismic hazard at a given place in probabilistic terms. This can be done in two ways: (i) estimating the probability with which a prescribed level of strong ground motion, say, 0.1 g (in terms of PGA), is exceeded over a period of, say, 50 years; (ii) estimating the PGA which is exceeded with a prescribed probability, say, 10%, in a period of , say, 50 years.

The main objective of the present communication is to estimate earthquake hazard in Delhi region in two ways, i.e. (i) estimating the probability with which a prescribed level of strong ground motion (in terms of PGA), is exceeded over a certain period (in years), which is taken as 50 years; and (ii) estimating the PGA which is exceeded with a prescribed probability over a prescribed period, which is taken as 10% probability of exceedance within 50 years. The results are presented in the form of contour maps spreading over Delhi region depicting exceedance probabilities and PGAs. These hazard maps are of paramount importance for seismic zonation for building codes, designing earthquake-resistant new structures, estimating vulnerability of existing structures and their retrofitting, and finally for future habitat planning.

Keywords: Attenuation, exceedance probability, seismotectonics, seismic hazard assessment, seismic microzonation.

BASED on epicentral distribution of past earthquakes ($M > 5$) and the isoseismals of such events, the seismic zoning map of India has been prepared to design the engineering structures in such a way that they withstand the large earthquakes safely. The map is published by Bureau of India Standards (BIS – 1893 (part I) – 2002) and is being used to specify the levels of force or ground motion for earthquake-resistant design. According to the map, about 57% of the Indian subcontinent is vulnerable to earthquake intensities of VII (MSK) or more, including the capital, New Delhi. The seismic zoning map of India divides the country into four seismic zones, namely Zone II (MSK intensity VI), Zone III (MSK intensity VII), Zone IV (MSK VIII) and Zone V (MSK intensity IX or more). The assigned peak ground acceleration (PGA) in units of g are Zone V = 0.36 g; Zone IV = 0.24 g; Zone III = 0.16 g and Zone II = 0.10 g.

The basic concepts with which these seismic zoning maps are prepared are that regions which had experienced earthquakes in the past, may get similarly affected in future, during the expected lifespan of man-made constructions. Thus, the maps do not consider the frequency of occurrence of earthquakes and therefore do not divide the country into areas of equal seismic hazard and risk. These maps provide a general estimate of the lateral forces for which structures are to be designed and cannot be straight away used for microzonation studies. Rather they provide rough guidelines on expected intensities and one has to generate site-specific seismic hazard incorporating site effects and seismicity. This calls for detailed seismic hazard assessment for the Indian cities and preparation of hazard maps, which can be straightway used for disaster mitigation and management. Studies on seismic hazard and risk assessment have been taken up in India recently and several organizations have been working in this direction, with the aim to produce microzonation and risk maps which would provide basic information for disaster mitigation and management planning. Delhi, being the capital of India and falling under the high seismic zone, requires immediate attention from seismic hazard assessment point of view. According to Iyengar[1], the seismic status of Delhi is as follows: (i) Delhi, capital of India, well known to be seismically active; (ii) MSK seismic intensity VIII; (iii) according to Indian Code IS: 1893–2002, Zone-IV (PGA: 0.24 g); (vi) Might face an earthquake of magnitude 6.0 in a period of 50 years and there is 80% probability of magnitude 7.0 event in the region and (v) In a 50-year window (1983–2033), Delhi would experience PGA = 0.2 g with 10% probability of exceedance.

The present communication attempts to estimate seismic hazard for Delhi region using probabilistic framework after collating all the information available on geo-scientific parameters.

Seismic hazard assessment is the process of evaluating the design parameters of earthquake ground motion at any site. The design parameters most widely used are intensity and PGA. Sometimes peak velocities, peak displacements and response spectrum are also used. Seismic hazard assessment can be carried out either in the deterministic framework or probabilistic framework, however, it involves broadly the following steps: (i) Identification of potential earthquake zones using past earthquake and seismicity data. (ii) Determination of earthquake parameters related with each zone. (iii) Evaluation of seismic hazard in terms of intensities, PGAs, etc. (iv) Seismic hazard at site using attenuation relations and site effects.

It is more appropriate to estimate the seismic hazard at a given place in probabilistic terms. It can be done in two ways: (i) estimating the probability with which a prescribed

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level of strong ground motion, say, 0.1 g (in terms of PGA), is exceeded over a period of, say, 50 years; (ii) estimating the PGA which is exceeded with a prescribed probability, say, 10%, in a period of , say, 50 years.

Seismic hazard is the probability of occurrence of earthquake at a particular site. In order to quantify this, it is engineering practice to define it as the predicted level of ground acceleration which would be exceeded with 10% probability at any site due to occurrence of an earthquake anywhere in the region, in the next 50 years. Therefore, the main objective of the present communication is to estimate earthquake hazard in Delhi region in two ways, i.e. (i) estimating the probability with which a prescribed level of strong ground motion (in terms of PGA), is exceeded over a certain period (in years), which is taken as 50 years and (ii) estimating the PGA which is exceeded with a prescribed probability over a prescribed period, which is taken as 10% probability of exceedance within 50 years. The results are presented in the form of contour maps spreading over Delhi region depicting exceedance probabilities and PGAs. These hazard maps are of paramount importance for seismic zonation for building codes, designing earthquake-resistant new structures, estimating vulnerability of existing structures and their retrofitting and finally, for future habitat planning.

Delhi being the national capital has had the privilege of planned development, but the unusual growth of this burgeoning megacity has set-off all the plans. The urban population has escalated from 8.472 million in 1991 to 12.82 million in the 2001 census, which is a substantial growth of 51%. This growth has put tremendous pressure not only on national resources, but has also increased risks of natural disaster. The city is dotted with all kinds of buildings and infrastructural facilities comprising good construction to poorly designed and constructed ones.

Delhi and its environs have experienced earthquakes since the ancient times and the eyewitnesses account of the event of 15 July 1720 lucidly describes the damages caused to the fortress and destruction of numerous houses and loss of many human lives. These descriptions indicated damages, which can be related to the MMI intensity of VIII–IX. The 1 September 1803 Mathura earthquake caused massive damage and loss of life in the Central Himalaya as well as some locations in the Gangetic Plains, including Delhi. Details can be found in Rajendran and Rajendran[2]. The same event is reported to have damaged the upper portions of the Qutub Minar[3]. In the recent past an earthquake of $M = 6.0$ occurred on 27 August 1960 in Delhi, causing considerable damage in the region. There have been a number of events recorded since then. Apart from this, Delhi has been affected time and again by major earthquakes from the Himalayas, such as the 1905 Kangra earthquake, 1991 Uttarkashi earthquake and 1999 Chamoli earthquake. The 2001 Bhuj earthquake was also felt in Delhi and the recent Pakistan earthquake of 8 October 2005 shook a few buildings in Delhi. The PGA recorded was about 1.5% g. These near-field and far-field seismic activities are suggestive of the potential seismic hazard of the Delhi region. Therefore, there is need to develop seismic hazard maps for the region.

The entire Delhi region is situated between lat. 28°24′01″–28°53′00″N and long. 76°50′24″–77°20′37″E and covers approximately 1485 sq. km. The geological map of Delhi is available and published by the Geological Society of India (GSI).

For seismio-tectonic characterization, it is common practice in engineering to take an area of 250–300 km around the site under consideration. Therefore, to consider seismic activities around Delhi, the area between lat. 26–31°N and long. 75–80°E has been taken. The area in and around Delhi is highly criss-crossed by faults because of the complexity from conjoining of various sets of tectonic grains. Geological mapping and remote-sensing studies indicate the presence of many fault patterns. The important tectonic features are Mahendragarh–Dehradun fault and Aravalli–Delhi fold axes. The seismicity around Delhi is attributed mostly to Delhi–Haridwar ridge, which falls between 28–30°N to 76–79°E with a NE–SW trend. The trijunction of Delhi–Hardwar ridge, Delhi–Lahore ridge and Aravalli–Delhi fold axes is also seismically active area. The other dominant tectonic feature of the region is Sohna fault located southwest of Delhi; Moradabad fault trending NE–SW and other fault patterns trending roughly NW–SE direction. The Delhi–Hardwar ridge coincides with the extension of the Aravalli mountain belt beneath the alluvial plains of the Ganga basin to the northeast of Delhi towards the Himalayan mountains. Apart from these regional features, Delhi is being shaken by the movements of dominant faults of the Himalayan region. The region has several dominant features such as Himalayan Main Boundry Thrust (MBT) and Main Central Thrust (MCT), the Delhi–Hardwar ridge, the Delhi–Lahore ridge, the Aravalli–Delhi fold axes, and the Sohna fault, Mathura fault, the Rajasthan Great Boundary fault and the Moradabad fault in addition to several other minor lineaments.

The Delhi region is considered earthquake-prone and has been hit by several earthquakes since historical times. The first known earthquake[3] dates back to AD 893. The first ever recorded earthquake in Delhi occurred on 6 July 1505. However, the first documented earthquake of magnitude 6.5 with intensity X in MMI occurred in Delhi on 15 July 1720. A number of persons were reported to be killed, buildings collapsed and cracked, roads fissured and ramparts of mosque at Fatehpuri were damaged. The aftershocks persisted for 40 days and occasional aftershocks were felt for 4–5 months. The other violent earthquake was reported to have occurred near Mathura on 1 September 1803, when the cupola of Qutub Minar was believed to have fallen down. A detailed description of this earthquake can be found in Rajendran and Rajendran[2]. A moderate earthquake occurred again in 1842 in Mathura, which caused minor damage in Delhi. Kangra earthquake of 4 April 1905 was also felt in Delhi and produced MMI intensity of VII in the region. On 10 October 1956, a major earthquake of magnitude 6.7 occurred near Bulandshahar, Uttar Pradesh (lat. 28.15°N, long. 77.67°E). The earthquake was reported to be felt in a larger area and 23 persons were killed in Bulandshahar district. An earthquake of magnitude 6.0 occurred just south of Faridabad on the 27 August 1960 killing two persons, injuring about 100 people and damaging many buildings (minor cracks) in the epicentral tract. There was another earthquake on 15 August 1966 near Moradabad, which revealed that the Moradabad fault (which is not far off from Delhi) is seismically active.

Besides these earthquakes which originated in and around Delhi, distant earthquakes were also felt and have caused damage in Delhi. The Uttarkashi earthquake of 20 October 1991, magnitude 6.6 in the Himalayan region was severely felt in Delhi and the neighbourhood. Further, the Chamoli earthquake (M = 6.8, 29 March 1999) of the Himalayan region was severely felt in Delhi and caused some minor damage to poorly constructed buildings in some parts of the city. As the physiographic set-up of Delhi includes continued extension of peninsular-shield, major earthquakes of the peninsular shield region are also felt in this region. The Bhuj earthquake of the 26 January 2001, magnitude 6.9 was felt in Delhi and its environs. The list of major earthquakes affecting Delhi region depicts the prolonged seismic history of the region with frequent occurrence of earthquakes of magnitude 6.0 or above. Distribution of the epicentres of earthquakes appears to follow a NW–SW trend correlated with the direction of major tectonic features of the region. It is difficult to associate the seismicity of Delhi with any particular tectonic unit and also the number of lineaments appears to be seismically active simultaneously but to a different extent. Therefore, in order to carry out seismic hazard assessment of Delhi, it is imperative to take into account the seismic potential of all tectonic features. Details on historical seismicity of Delhi are available in a recently published report by Department of Science and Technology[4].

There have been number of approaches available in literature and considerable work has been carried out for Delhi region for realistic assessment of seismic hazards[4–8]. Both probabilistic and deterministic frameworks have been used. The present communication uses the probabilistic methodology.

For the purpose of earthquake-resistant design of structures and reliable estimate of likely forces, one needs a quantitative estimate of seismicity at a specified site. There have been several suggested approaches for such an estimate. Quantitative seismicity maps have also been prepared for a region on the basis of these approaches. One such approach is to prepare energy release maps. The region in question is divided into a number of grid points and the total energy released due to all past earthquakes in each grid point is computed. Such energy release maps have been found to show good correlation with tectonics of the region under consideration.

For obtaining an estimate of seismicity at a particular site, a quantity known as seismic risk (R) has also been introduced in literature. It can be defined and determined in a number of ways. In the present work, it is defined as the probability that ground motion at a given intensity at a given site will exceed a certain value during a time period of, say, D years. The most useful and widely used measure of intensity of strong shaking at a site is the PGA reached during an earthquake. This quantity can be computed at a given site from a knowledge of epicentral locations of all past earthquakes and their magnitude using a suitable formula. Based on the above background, the methodology for seismic hazard assessment encompasses the following steps:

(i) First, the region around Delhi, from 26 to 32°N lat. and 76° to 81°E long. is divided into 1/2° × 1/2° grid.

(ii) At each grid point, PGA (in fraction of g) is computed from a knowledge of magnitude and epicentre location of all past earthquakes. This is done using any one of the several attenuation relationships available for the region under consideration. In India, attenuation relations are scarce and therefore for the present work, the following international[9,10] and national[5,11] relations have been used:

$$\log(a) = -0.62 + 0.177M - 0.982\log(r + e^{0.284M}) + 0.132F - 0.0008Er, \quad (1)$$

where a is PGA in g; r is the distance in km to the closest approach of the zone of energy release as defined by Campbell (1981); M is the magnitude; F is 1 for reverse/reverse oblique fault and 0 otherwise and E is 1 for interplate and 0 for intraplate events.

$$\log(a) = -0.789 + 0.2128M - \log(\mathrm{sqrt}(7.2^2 + R^2)) - 0.00255r \quad (2)$$

where R is the focal distance in km and other parameters are the same as above.

$$\log(a) = -1.072 + 0.3903M - 1.21\log(X + e^{0.587M}), \quad (3)$$

where X is the hypocentral distance from the source in km and other parameters are same as above.

$$\log(a) = -1.5232 + 0.3677M - 1.0047\log(r + e^{0.41M}) + 0.2632\sigma, \quad (4)$$

where r is the hypocentral distance in km and all other parameters are same as above. P is 0 for median 50-percentile hazard and 1 for 84-percentile value.

(iii) At each grid point, only those accelerations are considered which exceed 0.005 g (which is the minimum value considered). These values of PGA at a given point can be viewed as a set of random numbers following Poisson distribution, since (a) these PGAs occur randomly, (b) each value is an independent event, unrelated to any of the past or future values, and (c) the probability of two PGA values occurring simultaneously is small enough to be safely neglected. The PGAs at a given point can be considered to be random events. These are caused by earthquakes occurring at irregular intervals and are dominated by earthquakes having magnitudes greater than 5.0. Since earthquakes with magnitudes greater than 5.0 can be considered to be random events, no two of which can occur simulataneously and are mutually independent, the same properties can also be assigned to compute PGAs. Thus, the ensemble of such PGA values at individual grid points can be assumed to follow a Poisson process characterized by the parameter λ, known as mean rate. λ is computed by counting all PGAs which are equal to or greater than a pre-assigned value and dividing this number by the duration over which earthquake data are available.

(iv) The number of times a prescribed value of PGA (a_0) is equal to or exceeded at each grid point is determined. Let it be denoted by n.

(v) If the period over which the earthquake data are known is denoted by T, the mean rate, $\lambda(= n/T)$, is calculated. Thus parameter λ is computed by counting all PGAs which are equal to or greater than a pre-assigned value (0.005g) n and dividing this number by the duration over which earthquake data are available.

(vi) The probability that the specified acceleration a_0 is exceeded during the time Δt is proportional to Δt and can be written as $\lambda\Delta t$. The probability that a_0 will not be exceeded during Δt is $1 - \lambda\Delta t$ to first order of approximation, provided Δt is smaller. Let $P_0(t)$ be the probability that a_0 is not exceeded even once during a time interval t prior to Δt. Then, $P_0(t + \Delta t)$ is the probability that a_0 will not exceed even once during $t + \Delta t$. Since PGAs have been assumed to be independent events:

$$P_0(t+\Delta t) = P_0(t)P_0(\Delta t) = P_0(t)[1-\lambda\Delta t].$$

Hence

$$\lim \Delta t \to 0 \quad \frac{[P_0(t+\Delta t) - P_0(t)]}{\Delta t} = -\lambda P_0(t),$$

i.e.

$$\frac{dP_0}{dt} = -\lambda P_0.$$

Integrating the above equation,

$$\ln P_0 = -\lambda t + C, \quad P_0 = c\exp(-\lambda t).$$

At $t = 0$, $P_0 = c$ is the probability that a_0 is not exceeded even once in time zero which is equal to unity. Hence $c = 1$, and the probability that during t, a_0 will not be exceeded is:

$$P_0 = \exp(-\lambda t).$$

Thus the probability that during t, a_0 will be exceeded at least once is

$$1 - \exp(-\lambda t).$$

Designating t as D, the design life of any structure or the return period of earthquake or total time period considered for seismic hazard estimation, and R the seismic risk or seismic hazard defined as the probability that a_0 is exceeded at least once during D years can be written as:

$$R = 1 - \exp(-\lambda D).$$

(vii) This procedure is repeated over all grid points and the values of R determined and contoured to give a map of exceedance probabilities. The map denotes the probability that the acceleration a_0 will be exceeded at least once due to an earthquake occurring anywhere in the region under investigation.

(viii) To estimate PGA for a prescribed exceedance probability, a value of n is determined as follows:

The above equation can be written as

$$\exp(-\lambda D) = 1 - \mathrm{R}$$

$$-\lambda D = \ln(1 - R)$$

$$\lambda = -\ln(1 - R)/D$$

$$n/T = -\ln(1 - R)/D$$

$$n = -(T/D)\ln(1 - R),$$

where D is the total time period for hazard estimation and T the period over which the earthquake data are known.

(ix) From the set of values of PGAs at each grid point, that PGA is determined which is exceeded n times.

(x) Knowing these PGA values at each grid point, a contour map of such PGA values can be prepared.

In order to estimate the potential faults or areas from where the earthquake may emanate, it is important to first consider the earthquake database for the area and plotting the epicentral maps along with all the possible faults, lineaments, etc. The earthquake catalogue used here is the latest till 2004 and is extracted from USGS earthquake catalogue and ISET catalogue. The epicentral map of the earthquakes is also shown in Figure 1.

Seismic hazard is the potential of earthquakes to cause damages; this could be in terms of ground accelerations, liquefaction, slope failures, etc. For example, one may state that seismic hazard as maximum peak horizontal ground acceleration at a particular location is 0.15 g and there is 10% chance that in next 50 years the location will experience peak horizontal ground acceleration exceeding

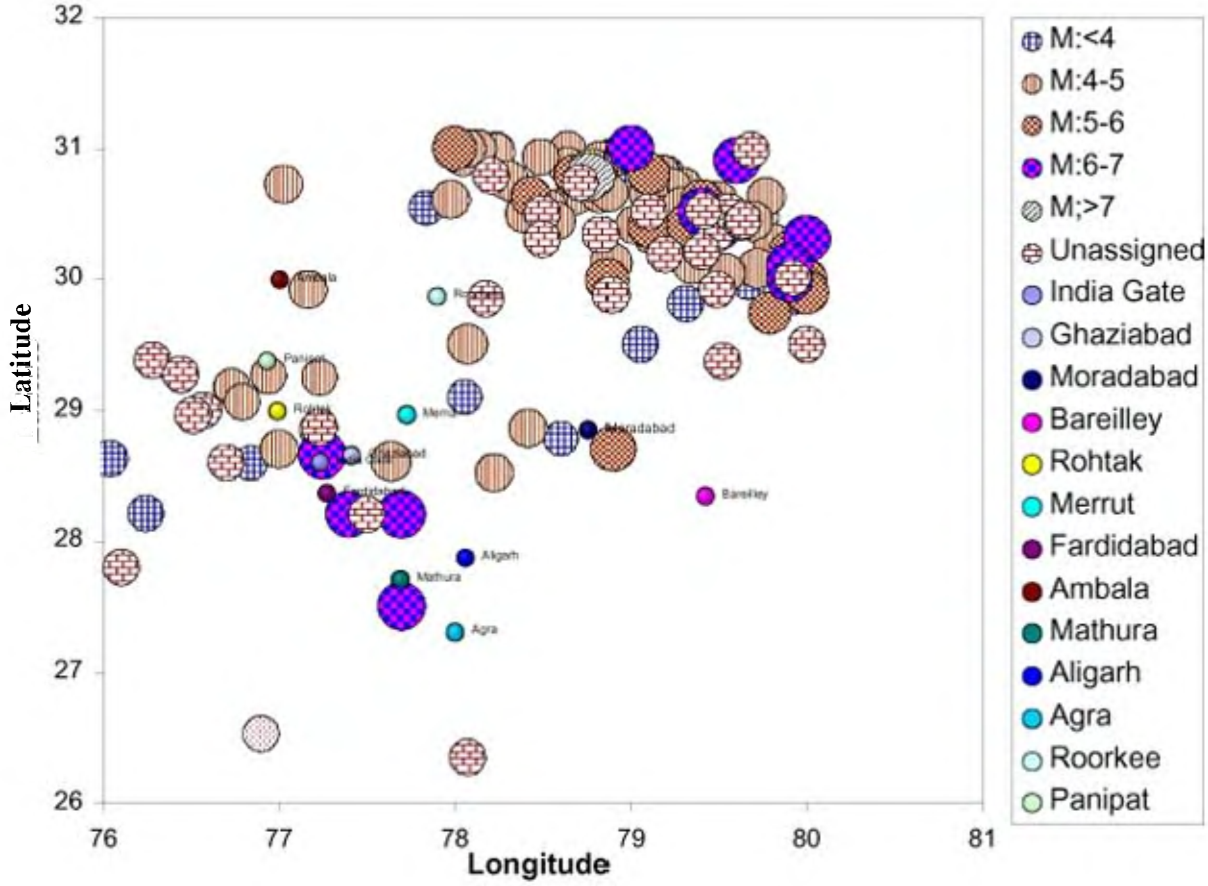

Figure 1. Epicentral map of earthquakes considered in the study.

0.15 g. Vice versa, seismic hazard may be defined in terms of probability of exceedance, i.e. say there is 20% chance that in next 50 years, a particular location will experience peak horizontal acceleration exceeding 0.15 g. In this communication, both the results are generated, i.e. seismic hazard maps in terms of peak horizontal acceleration and also in terms of exceedance probability maps.

Seismic hazard is normally defined as PGA corresponding to 10% of probability of exceedance in 50 years. Therefore, in the present analysis, the return period is taken as 50 years and probability of exceedance is taken as 0.10. The methodology described above is programmed in C^{++} and PGA is computed at each grid point, which is later presented in the form of contour maps for the entire region considered. The entire Delhi region is situated between lat. 28°24′01″N–28°53′00″N and long. 76°50′24″E–77°20′37″E. Therefore, to make the study relevant to Delhi region only, the contour maps are also plotted for 28–30°N lat. and 76–78°E long. Also, seismic hazard maps for the entire northern region between 26° – 32°N lat. and 76–81°E long. are also generated. The northern region covers the area up to the Himalayan region. The important locations of Delhi and other cities are also shown in these maps. The PGAs shown can be straightaway used for calculating the earthquake forces for which structures are to be designed. For calculating probability of exceedance, the specified acceleration (a_0) is considered to be $0.15g$ and the return period is considered to be 50 years. These maps are also shown in form of contours for the Delhi region and the entire northern region as well. Since there are four attenuation relations used in the present study, the results are shown only for the case which gives the maximum values, i.e. Sharma[11] and Iyengar and Ghosh[5].

Figure 2 *a* presents the seismic hazard map for Delhi region in terms of peak horizontal acceleration (in fractions of g) with 10% probability of exceedance in 50 years. The values vary from $0.12g$ to $0.16g$. Figure 2 *b* shows the seismic hazard map for the entire northern region covering Delhi to Himalayas. Considering northern region seismicity, the peak horizontal acceleration in Delhi is 0.14 g. It corroborates the fact that Delhi is vulnerable to far distant earthquakes originating from the Himalayan region.

The probability of exceedance maps is given in Figure 3 *a* and *b* for Delhi and the northern region respectively. Figure 3 *a* shows that there is 20% probability that Delhi will experience PGA of 0.15 g or more in next 50 years. Figure 3 *b* on the other hand, gives the probability

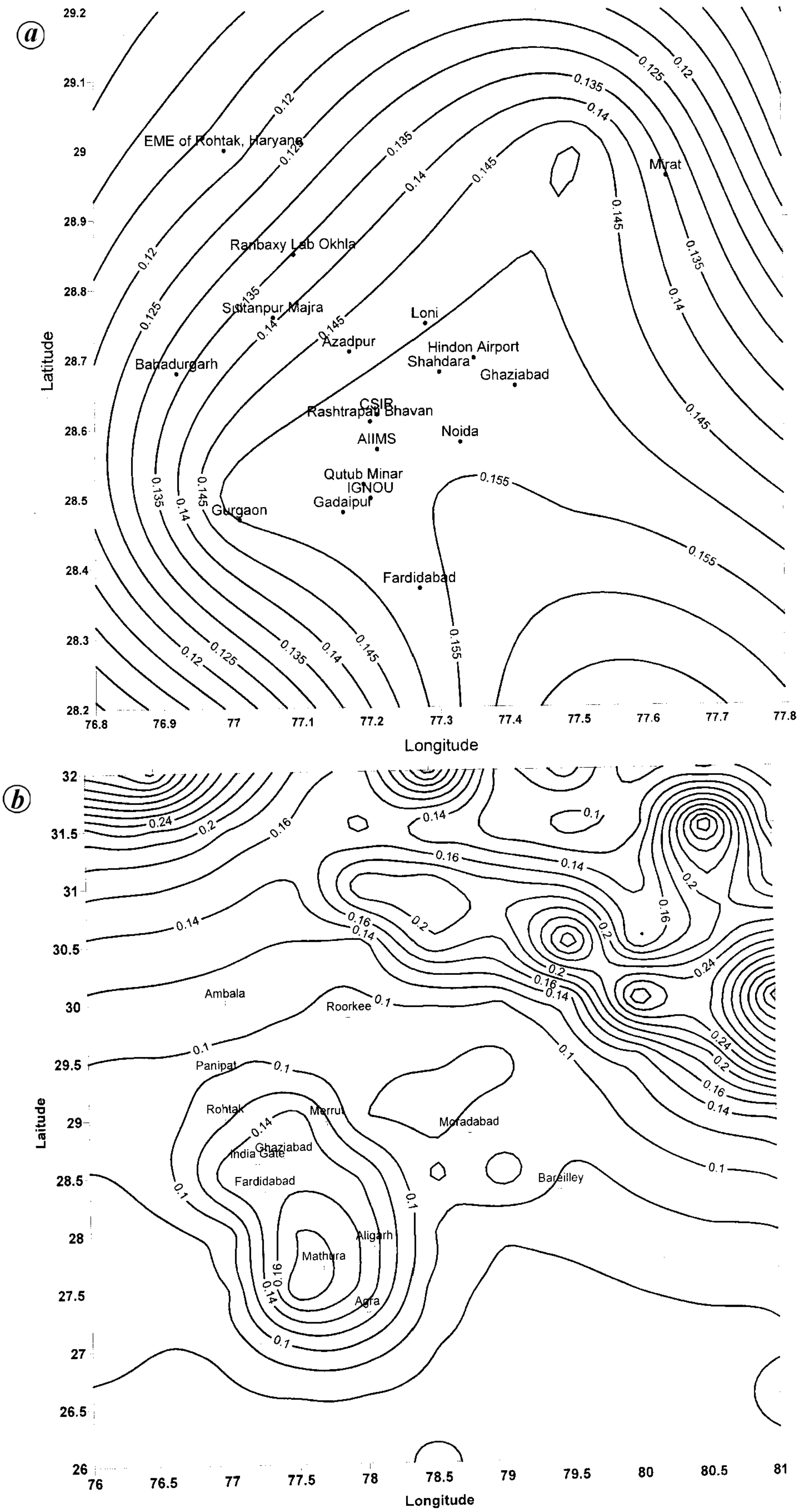

Figure 2. Peak horizontal acceleration map with 10% probability of exceedance in 50 years for Delhi region (*a*) and the northern region (*b*).

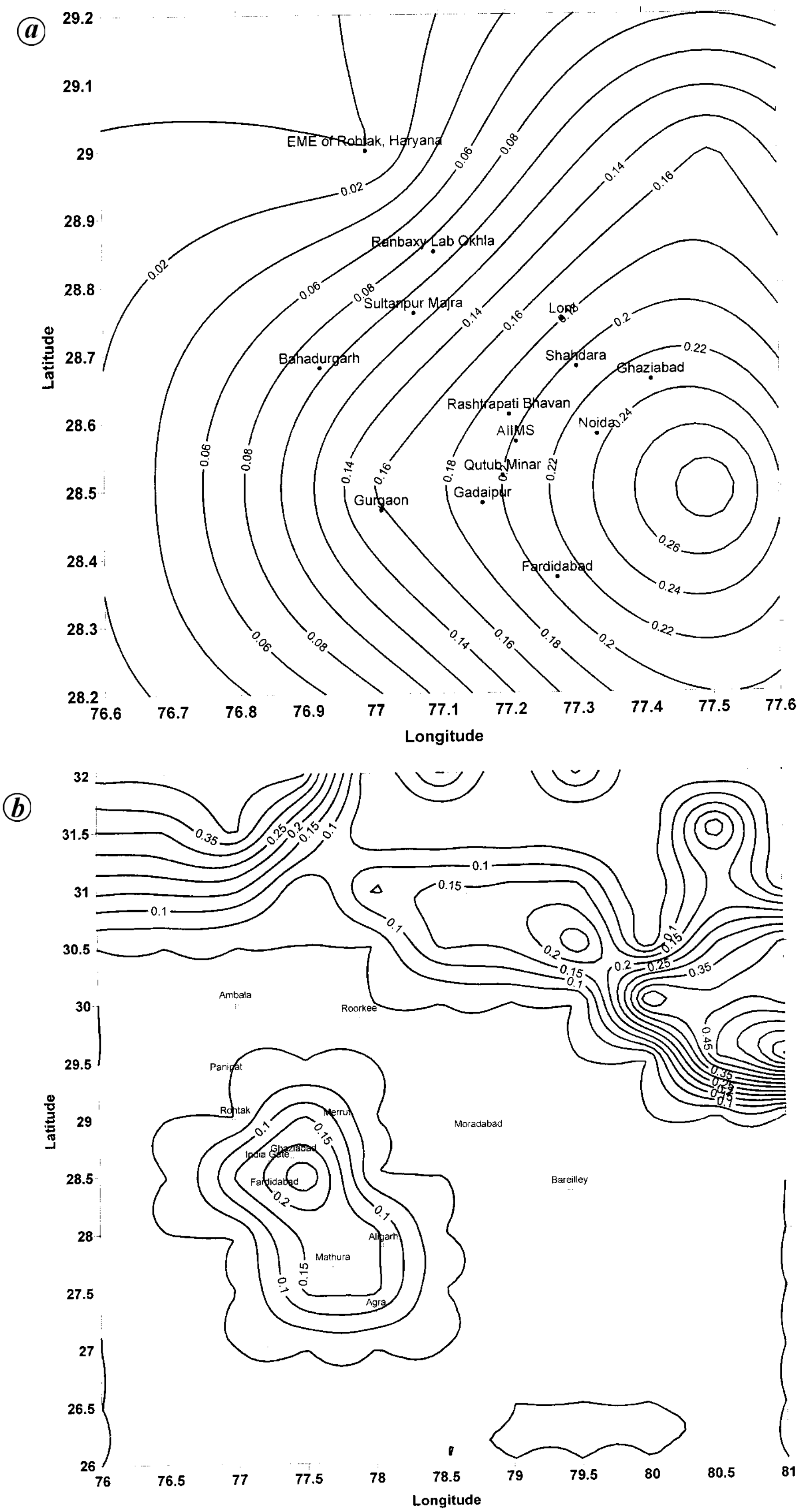

Figure 3. Exceedance probability map of 0.15 g peak horizontal acceleration in 50 years for Delhi region (***a***) and the northern region (***b***).

of exceedance considering regions up to the Himalayas. Here also, there is 20% probability that Delhi region will experience PGA of 0.15 *g* or more in the next 50 years.

The present communication presents a quantitative approach in probabilistic framework for estimation of seismic hazard of Delhi and the northern region. Seismic hazard can be expressed in a number of ways, i.e. peak ground horizontal accelerations, probability of exceedance, etc. These values can be straightaway used for earthquake-resistant design of structures. One may also use these values to generate synthetic accelerograms for a particular site. These seismic hazard maps are the basic unit for seismic microzonation and can be used to prepare seismic risk maps if data on population density, type of buildings, etc. are known.

The PGA values for Delhi region vary from 0.12 to 0.17 *g* considering all past earthquake data and seismicity of the area. The values are higher in SE region which is known as trans-Yamuna area consisting of soft soil, i.e. alluvium. According to IS 1893–2003, the Delhi region falls in zone IV of the seismic map of India and the corresponding value of PGA is 0.24 *g*. It means that the values given in codes are on the conservative side. The corresponding MMI intensity is between VIII to IX, which means that there will be considerable damage to the structures which are not designed for earthquake forces. It indicates that Delhi falls in the severe earthquake zone and therefore, aseismic design of structure is called for. Now, if the seismicity of the entire northern region is considered, including the Himalayas, the peak horizontal ground accelerations for Delhi seem to vary from 0.10 to 0.16 *g*, which demonstrates the vulnerability of Delhi due to far distant earthquakes. It was also noticed during the past earthquakes such as Uttarkashi earthquake of 1991, Chamoli earthquake of 1999, Bhuj earthquake of 2001 and the recently occurred earthquake in Pakistan during 2005 that some buildings in Delhi had structural and non-structural damages and the people felt the earthquake. It brings out the necessity to assimilate knowledge of seismicity of the entire northern region before carrying out seismic hazards assessment of Delhi. However, the exceedance probability maps for Delhi indicate that there is about 30% probability that in next 50 years, there will be an earthquake causing more than 0.15 *g* PGAs in horizontal directions. This probability is on the lower side. However, if we construct the exceedance probability maps for 0.10 *g*, the probability goes as high as 90%.

Seismic hazard maps thus produced in the study can be further refined taking into account the variations of surface geology, geotechnical characteristics, seismic sources and their damage potential and more realistic statistical models.

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