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First Order Seismic Microzonation of Delhi, India Using Geographic Information System (GIS)

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Abstract. A first order seismic microzonation map of Delhi is prepared using five thematic layers viz., Peak Ground Acceleration (PGA) contour, different soil types at 6 m depth, geology, groundwater fluctuation and bedrock depth, integrated on GIS platform. The integration is performed following a pair-wise comparison of Analytical Hierarchy Process (AHP), wherein each thematic map is assigned weight in the 5-1 scale: depending on its contribution towards the seismic hazard. Following the AHP, the weightage assigned to each theme are: PGA (0.333), soil (0.266), geology (0.20), groundwater (0.133) and bedrock depth (0.066). The thematic vector layers are overlaid and integrated using GIS. On the microzonation theme, the Delhi region has been classified into four broad zones of vulnerability to the seismic hazard. They are very high (>52%), high (38–52%), moderate (23–38%) and less (<23%) zones of seismic hazard. The "very high" seismic hazard zone is observed where the maximum PGA varies from 140 to 210 gal for a finite source model of M_w 8.5 in the central seismic gap. A site amplification study from local and regional earthquakes for Delhi region using Delhi Telemetry Network data shows a steeper site response gradient in the eastern side of the Yamuna fluvial deposits at 1.5 Hz. The 'high' seismic hazard zone occupies most of the study area where the PGA value ranges from 90 to 140 gal. The 'moderate' seismic hazard zone occurs on either side of the Delhi ridge with PGA value varying from 60 to 90 gal. The 'less' seismic hazard zone occurs in small patches distributed along the study area with the PGA value less than 60 gal. Site response studies, PGA distribution and destruction pattern of the Chamoli earthquake greatly corroborate the seismic hazard zones estimated through microzonation on GIS platform and also establishes the methodology incorporated in this study.

Key words: seismic microzonation, GIS integration, PGA, AHP, seismic hazard

1. Introduction

The cost of life, property, economic and social disruption caused by the earthquakes in India is enormous. Rapid urbanization due to population outburst, coming up of mega cities in potential seismic zones is the main

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reason for such damages. The ultimate accomplishment which would potentially minimize our vulnerability to earthquake hazard, should readily be available and assimilable knowledge products about expected ground motion quantities that would empower planners, designers, builders, regulators and disaster managers to adopt safe land-use planning and building codes, and sound construction practices. Since the occurrence of earthquake is inevitable, it is necessary to take proper mitigation measures against the probable earthquake damage. Though, India is broadly divided into four seismic zones (BIS, 2002), it is insufficient to predict how each zone will behave in the event of an earthquake. There is a wide variation in the intensity of ground motion, which depends largely on the local geological conditions, and the frequency of occurrence as well as the magnitude of earthquake. Some areas are exposed to big shocks, some moderate while the others have no known history of occurrence. Some areas are subjected to regular earthquake phenomenon, while others only after long intervals. As a result, no location can be described as “not susceptible” to earthquake occurrence. Hence, it is necessary to delineate zones that will likely be more vulnerable to future great earthquakes and thus reduce the loss of human life and property, because it will be uneconomical to construct structures everywhere to withstand strong earthquake ground motion.

Seismic microzonation is an approach to identify zones of vulnerability so as to adopt safety measures during an earthquake. Seismic microzonation is the subdivision of a seismic zone into smaller zones that have relatively similar exposures to various earthquake effects. The necessity of seismic microzonation was introduced as a result of the loss of life and property due to an earthquake event. The importance of seismic microzonation is that it can be used both for engineering structures, mitigation of disaster and for insurance purposes.

2. The Study Area

The present study area, Delhi, the capital city of India, lies between the latitude 28°24′01″N to 28°53′00″N and longitude 76°50′24″E to 77°20′37″ with an altitude of 239 m. It covers an area of 1485 km^2. Delhi is seismically active since historical times (Chandra, 1992). The earthquakes of 1720, 1803, 1842, 1934, 1956 and 1960 (Kamble and Chaudhury, 1979) is there to name a few. Besides its own seismicity (Verma *et al.*, 1995; Mohanty, unpublished Ph.D. Thesis), Delhi has been affected by the earthquakes from the Himalayas, which is still very active and is a major contributor to the seismic hazard in the north and north-eastern part of India (Bilham *et al.*, 2001). Delhi lies approximately 200 and 300 km from Main

Boundary Thrust (MBT) and Main Central Thrust (MCT) respectively, which are the two most active thrust planes of the Himalayas. The Himalayan region has experienced several great earthquakes in the past hundred years or so (1897 Assam; 1905 Kangra; 1934 Bihar–Nepal; 1950 Assam). The importance of seismic microzonation of Delhi is that –

- Delhi is the Capital as well as a mega city with a population of 14 million people, which is increasing rapidly with time.
- Besides its own seismicity, it lies in the vicinity of the Himalayan region and comes under zone IV of the Seismic Zonation map of India (BIS, 2002).
- Plays an important role in terms of economic and industrial development of the country.
- It lies over the thick soft alluvium soil of Yamuna sedimentary Basin that is subjected to relatively high site amplification during an earthquake.
- Faces severe seismic threats from the Central Himalayan seismic gap, which is approximately 300 km away from it (Bilham, 1995; Khattri, 1999; Rajendran and Rajendran, 2005).
- Because of its superstructures, like high-rise buildings and the shopping malls, death toll and damage to property can be large.
- The most recent development of all, in Delhi, is the introduction of metro rail.

3. Database

A mosaic of four toposheets in the scale 1:25,000 covering the area 53H/2 NE, 53H/2 SE, 53H/2 SW and 53H/2 NW, was used as the base map. Five thematic layers were selected for the generation of the seismic microzonation map of Delhi city. Those are Peak Ground Acceleration (PGA) contour, soil, geology, groundwater fluctuation and bedrock depth. The data maps were obtained from Geological Survey of India (GSI), Central Ground Water Board (CGWB) and Central Soil Research Institute (CSRI). Since the data maps were from different sources, they covered different parts of Delhi and the study area was restricted to a limited region as shown in Figure 1.

3.1. PEAK GROUND ACCELERATION (PGA)

Delhi is more vulnerable from the earthquakes from the Himalayan region in comparison to the nearby seismic sources. The geodynamics and occurrences of great earthquakes in the Himalayas are discussed by Seeber and

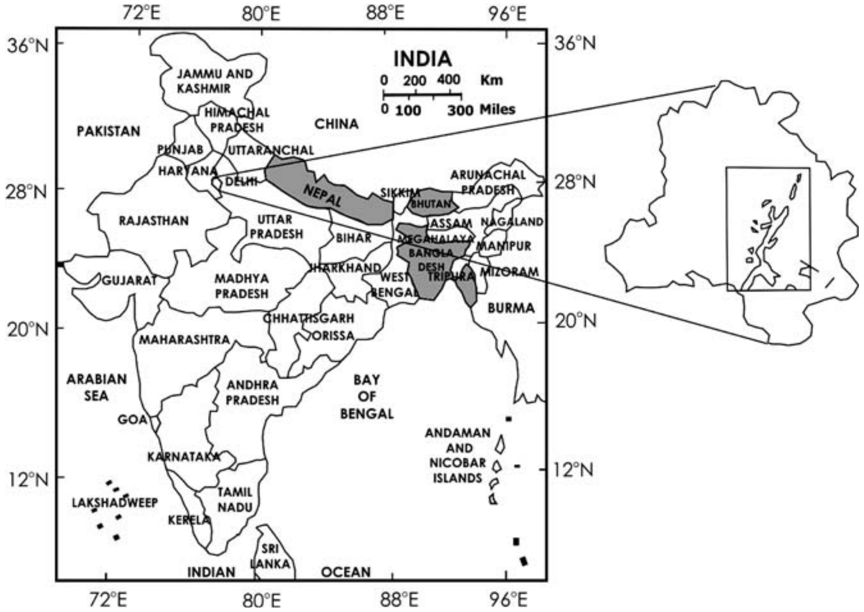

Figure 1. Map showing the area of interest for the work (in box) with respect to the Delhi map.

Armbruster (1981), Khattri (1999), Bilham and Gaur (2000), Rajendran *et al.* (2000) and Rajendran and Rajendran (2005). The Himalayan mountain range is an outcome of the collision of the Indian plate and Eurasian plate (70–40 Ma). The relative velocity of Indian plate with respect to the Eurasian plate near Delhi is about 5 cm/year in the direction of N13°E (NUVEL-1A model of DeMets *et al.*, 1994). The collision of these continental plates results in crustal shortening along the northern edge of the Indian plate and has given rise to three major thrust planes (Gansser, 1964; Molnar and Chen, 1982): the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) (Figure 2).

A 750 km long segment, which lies between the eastern edge of the 1905 rupture zone and the western edge of 1934 earthquake remained unbroken (Figure 2). This segment is called Central Seismic Gap, which continues to be under high strain. In the recent past, two moderate earthquakes of 1991 Uttarkashi earthquake (M_w 6.8) and 1999 Chamoli Earthquake (M_w 6.5) occurred from this region. These earthquakes were largely felt in Delhi. A few buildings in Delhi sustained non-structural damages (Jain *et al.*, 1999). There are also earthquakes from this region during 1803 and 1883. These earthquakes have magnitude less than 8, hence they were not gap filling event (Bilham, 1995; Khattri, 1999). Based on this considerations and a shortening rate of 20 mm/year across the Himalayas (Lyon-Caen

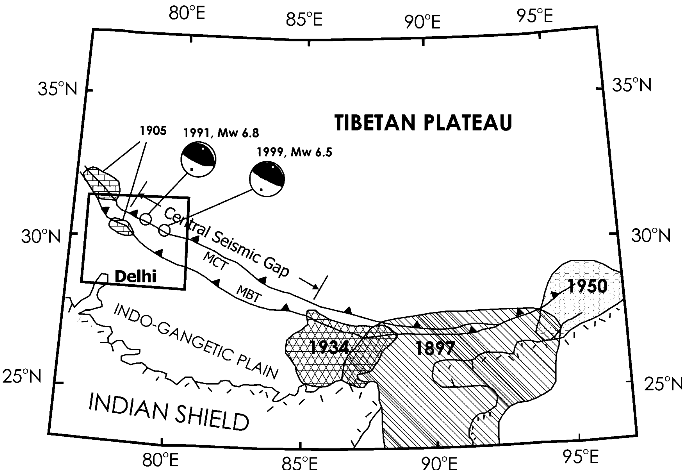

Figure 2. Tectonic map of the Himalayan region showing the Central Seismic Gap (modified after Seeber and Armbruster, 1981).

and Molnar, 1985; Avouac and Tapponnier, 1993; Gahalaut and Chander, 1997; Bilham *et al.*, 1998), Khattri (1999) has estimated the probability of occurrence of a great M_w 8.5 earthquake in the gap in the next 100 year to be 0.59.

Delhi, which is at the closest distance of 200 km from the Central Seismic Gap, is likely to be greatly affected by the earthquake of these regions. During 1999 Chamoli earthquake, isoseismal map shows Delhi was in the intensity of VI on MSK scale (GSI Report, 2000).

Singh *et al.* (2002) estimated ground motions in Delhi for probable future great earthquakes from the central seismic gap in the Himalayan arc. They used two methods to estimate ground motion in Delhi due to earthquake of M_w 8.5: one is the Empirical Green's Function (EGF) and the other the stochastic approach. The 1999 Chamoli earthquake (M_w 6.5; epicentral distance ~300 km from Delhi), which was located in the gap, is used as EGF. Chamoli earthquake was well recorded at Ridge observatory (RO), University of Delhi South Campus (UDSC), Council of Scientific and Industrial Research (CSIR), Rafi Margh, India Habitat Centre (IHC), Lodhi Road and Central Pollution Control Board (CPCB) observatories.

Recording of Chamoli earthquake and its aftershock at these observatories were used to predict the ground motion for higher magnitude earthquakes from Chamoli region. RO and UDSC observatories are situated on hard rock sites and CSIR, IHC and CPCB are on the soft sites. For an expected earthquake of M_w 8.5, the value of maximum acceleration (A_{max}) and maximum velocity (V_{max}) at RO are about 52 gal and 13 cm/s and the corresponding values at softer sites range between 174–218 gal and

17–36 cm/s. $A_{\max}$ at the hard sites are 3–4 times less than those at the soft sites.

The PGA values are contoured. Since the number of recording stations is limited, the PGA values are extrapolated for the other parts of Delhi where there is no seismic recording coverage. The extrapolation has been done on the basis of similar soil types and the basement rock depth. The expected PGA value in the study area is found at IHC, which is overlain by a thick clay deposit. The minimum expected PGA is at RO and UDSC. The PGA contours are generated and is classified into 17 categories, as depicted in Figure 3a with PGA ranging from 50 to 210 gal.

A site amplification studies have been undertaken from local and regional earthquakes for greater Delhi region using VSAT-based 24-bit digital Delhi Telemetry Network of the India Meteorological Department (Nath *et al.*, 2003). The site response gradient is found to be steeper towards east Yamuna fluvial deposit at 1.5 Hz (Figure 4), which is a very high seismic hazard zone and this is also evident from the PGA contour generated from Singh *et al.* (2002). At high frequency the site response is mild.

3.2. SOIL

It is well known that unconsolidated soil amplifies ground motion that may cause considerable damage to man-made structures, while on hard rock exposures, the amplification of ground motion is not observed. Therefore, the amplification of seismic energy will decrease away from the ridge. For a given magnitude of earthquake, it will have different effects on an area depending on its local soil condition. The soil types that are present within the study area are: silt with low plasticity; sand with fines; sand with no fines; clay with low plasticity; clay with medium plasticity and alluvium. The thematic map showing various soil types at 6 m depth is shown in Figure 3b.

3.3. GEOLOGY

Delhi is well covered by old and recent alluvium all over the region except in the southern and central part where the Delhi Super Group of rock Alwar Quartzite is exposed aligning in a direction NE–SW. The quartzite occupies the central and southern part of Delhi while the Quaternary alluvium sediments cover the remaining area and comprises of Older and Newer Alluvium (Kumar *et al.*, 1997). Thickness of alluvium overlying the quartzite increases away from the outcrops. Towards the eastern part, it is covered by flood plains of Yamuna River which are overlain by unoxidized clay and sand. Delhi region is characterized by tectonic features like the Delhi-Hardwar Ridge, Delhi–Lahore Ridge, the Aravalli–Delhi Fold, the

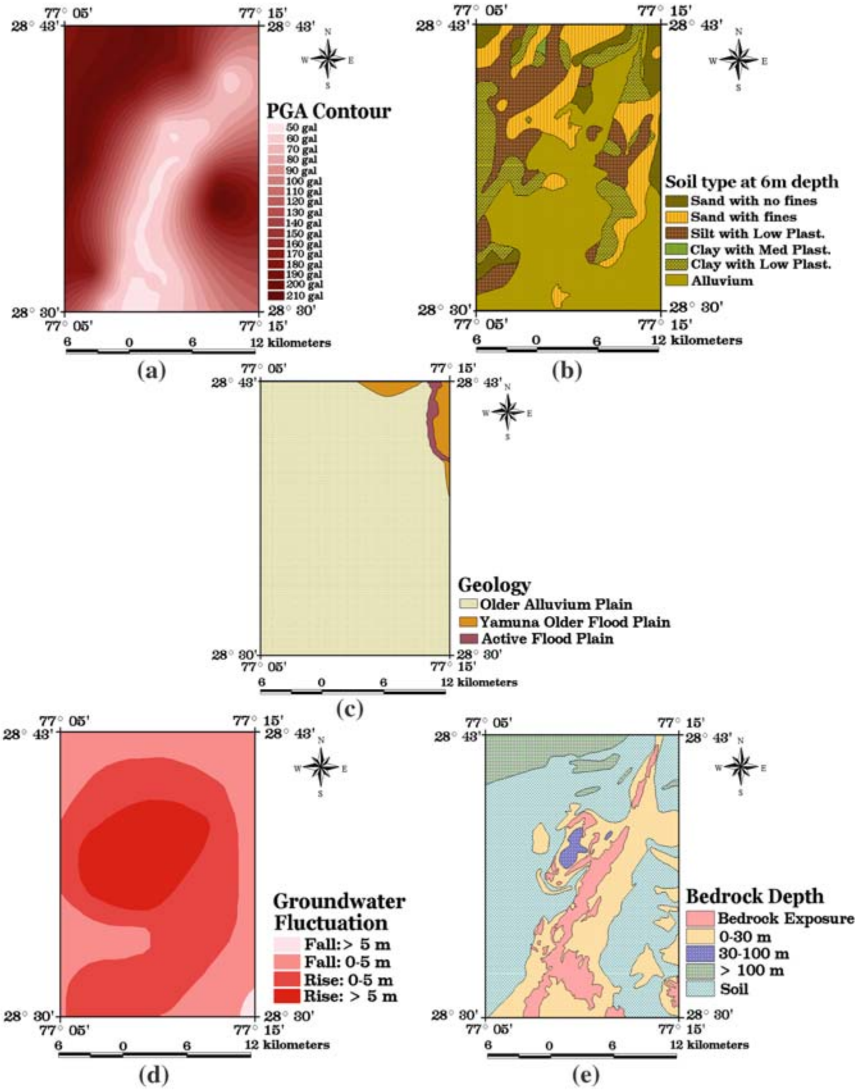

Figure 3. Thematic map of the study area of Delhi showing the (a) PGA contour ranging from 50 to 210 gal (modified after Singh *et al*., 2002); (b) Different types of soil (modified after Kumar *et al*., 1997); (c) Different geological features (modified after Kumar *et al*., 1997); (d) Different zones of groundwater fluctuation (modified after Kumar *et al*., 1997); (e) Bedrock depth at different levels at the subsurface (modified after Kumar *et al*., 1997).

Sohna Fault, the Mathura Fault and the Moradabad Fault (Verma *et al*., 1995; Chauhan *et al*., 1998) (Figure 5). One major lineament passing close to the Rohtak coincides with the gravity high.

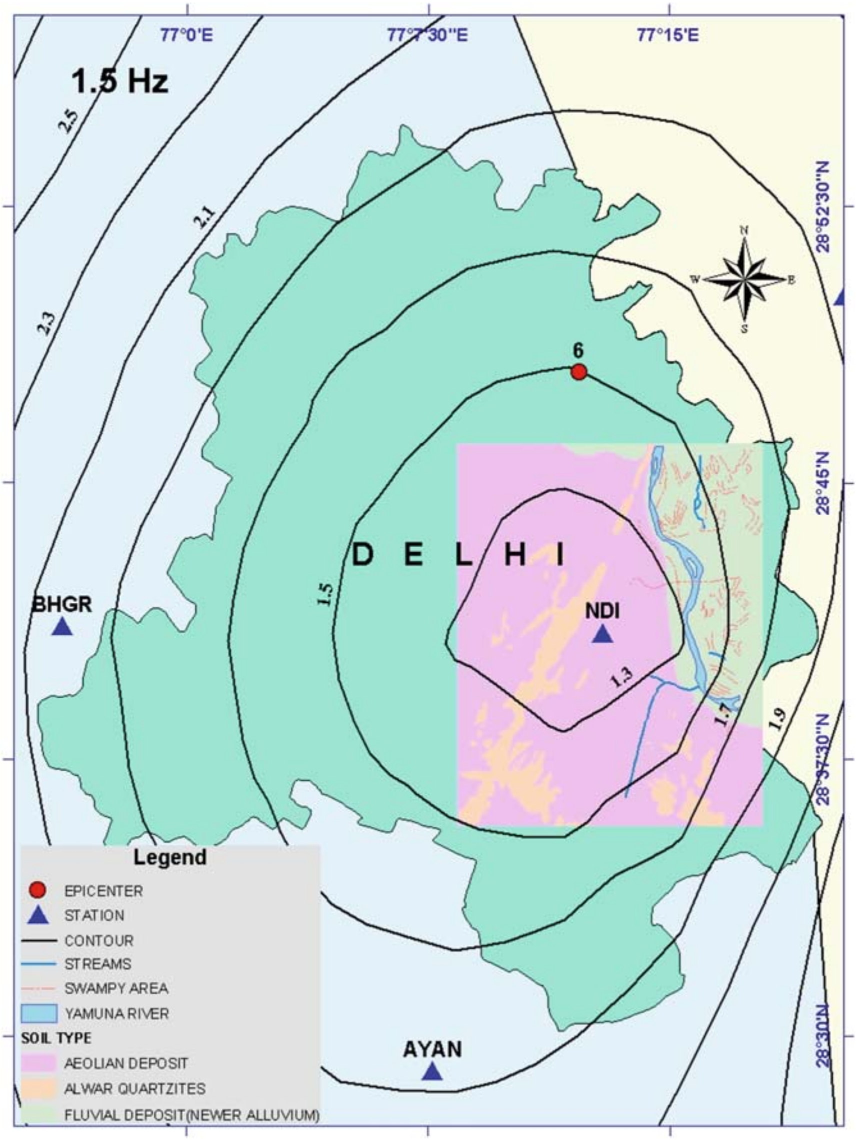

Figure 4. Site response contour map in the Delhi region at 1.5 Hz (after Nath *et al*., 2003).

The geology of the study region includes the Old Alluvium Plain, Old Alluvium Flood Plain and the Active Flood Plain as shown in Figure 3c. The highest seismic hazard in Delhi is the Active Flood Plain. It is located to the east of the Yamuna River, which is underlain by recent fluvial

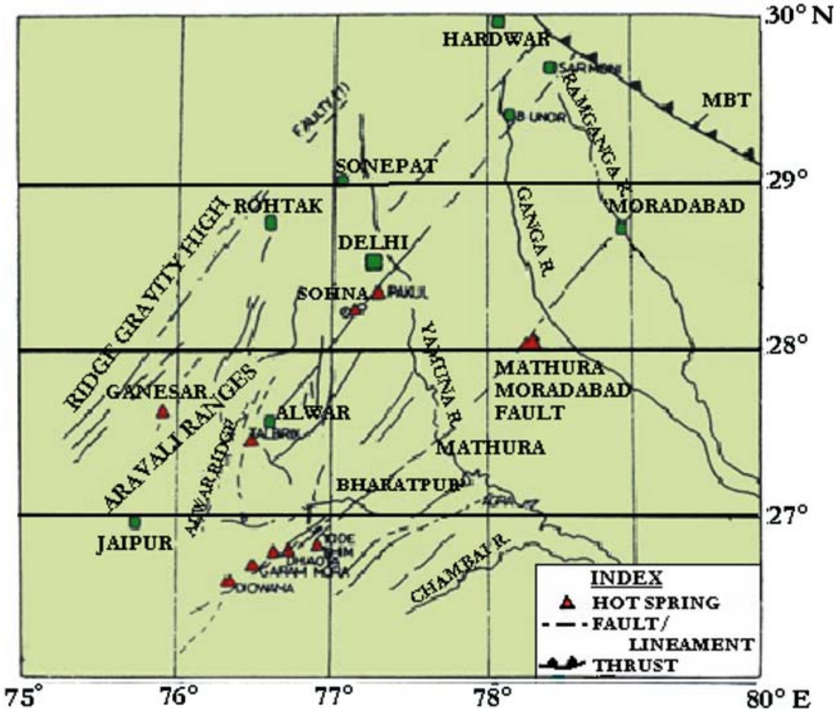

Figure 5. Structural features of Delhi and the surrounding regions (modified after Verma *et al*. 1995).

deposit, and is more prone to seismic hazard. The Old Alluvium Flood Plain is more stable in comparison to the Yamuna Older Flood Plain.

3.4. GROUNDWATER FLUCTUATION

The groundwater depths of Delhi area can be used to check the liquefaction potential of different parts of the city, since liquefaction is a factor of water saturated soil. The Delhi Ridge forms a watershed to the flow of groundwater towards west or east. Occurrence of groundwater is known in both confined and unconfined conditions with the water depth generally varying from 1 to 10 m below ground level (b.g.l.) (Kumar *et al*., 1997). There is a lot of variation in the rise and fall of the water level and has been mapped accordingly. For this study, the ground water fluctuation has been broadly classified into four zones as, fall of more than 5 m, fall of 0–5 m, rise of 0–5 m and rise of more than 5 m (Figure 3d). The rise of groundwater for more than 5 m is given more importance in regards to seismic hazard as it is directly related to liquefaction. Less weightage is given to the fall of more than 5 m.

3.5. BEDROCK DEPTH

The residual gravity map with the results of seismic and resistivity surveys were used to get the bedrock contour pattern (Kumar *et al.*, 1997). The area is divided into four following major zones depending upon bedrock depths (Figure 3e):

(1) Zone A: It represents the bedrock depth < 30 m b.g.l. The prominent area falling under this group lies in the vicinity of the exposures along the main ridge namely, Anand Parbat, Greater Kailash-Kalkaji, Nehru Nagar and in regions near Shakurpur Khas, Lal Qila, South of India Gate, North of Connaught Place, Greater Kailash-I, West of Nizamuddin, Nehru Park and Moti Bagh localities.
(2) Zone B: It comprises of the areas with bedrock depth varying from 30 to 100 m b.g.l. The important areas under this zone lies around India Gate along Prithvi Raj Road, along Aurbindo Marg, near Khanpur east of Geeta Colony, west of Khajuri Khas, west of Rangpur, west of Palam, Gulabi Bagh around the course of Najafagarh drain.
(3) Zone C: This zone consists of the bedrock depth > 100 m b.g.l. The prominent localities under this zone are Sastri Nagar, Palam Village, areas lying west of Najafagarh drain and to the west of Palam village etc.
(4) Zone D: This consists of the bedrock exposure and is aligned in the direction of NE–SW.

4. Methodology

The analysis has been carried out following Saaty's Analytical Hierarchy Process (AHP). The AHP is a multi-criteria mathematical evaluation method in decision making process. It uses hierarchical structures to quantify relative priorities for a given set of elements on a ratio scale, which is based on the discernment of the user. From the judgments between two particular elements, a pairwise comparison matrix is constructed on a scale of 1–5, 1 indicating that the two elements are equally important, and 5 implying that one element is more important than the other. If an element is less significant than the others then it is indicated by reciprocals of 1–5 values (i.e., 1/1 to 1/5). The pairwise comparison matrix prepared is used to derive the individual normalized weights of each element. It is carried out by computing the principal Eigen vector of the matrix which results in a matrix that range from 0 to 1 and adds up to 1 in each column. The weights of each criterion are calculated by averaging the values of each row of the matrix. These weights also add up to 1 and can be used in deriving the weighted sums of rating for each region of polygons of the mapped layers.

The features of each thematic map are also normalized between 0 and 1 (Nath, 2004) to ensure that no layer exerts an influence beyond its determined weight. Normalization is carried out for the features using the relation:

$$x_i = \frac{R_j - R_{\min}}{R_{\max} - R_{\min}}$$

where R_j is the raw rating, $R_{\max}$ and $R_{\min}$ are the maximum and minimum ratings of a particular layer.

From AHP, a spreadsheet package called EXPERT CHOICE is designed which is used in calculating weights in each layer. It has an ability to calculate weights for multiple criteria with pair wise comparisons. Hence, fuzzy set maps are created, showing that the AHP can handle fuzziness factor diversity and problem complexity. The calculations of the weights are done outside the GIS platform.

For the study the paired comparison matrix is prepared for the five themes (PGA contour, soil, geology, groundwater fluctuation and bedrock depth) as shown in Table I. Following the AHP, the thematic maps are assigned weights on a scale of 1–5 depending on their contribution to seismic hazard. The higher weight is assigned to the theme that contributes more to the hazard and in this case the highest weight is given to the PGA contour theme. Calculating the principal Eigen vector and averaging the values of each row matrix, the weights obtained for each theme are: PGA (0.333), soil (0.266), geology (0.20), groundwater (0.133) and bedrock depth (0.066).

The normalized values of the features of each thematic layer are given in Table II. The values obtained are then incorporated on a GIS platform for the integration of all the thematic maps to obtain the seismic microzonation map of Delhi. The integration of five thematic layers is done following the UNION and overlay operation in GIS.

Table I. Weights assigned to the thematic maps for the GIS integration.

Themes	PGA	Soil	Geology	Groundwater	Bedrock	Weightage
PGA	1	5/4	5/3	5/2	5/1	0.3333
Soil	4/5	1	4/3	4/2	4/1	0.2666
Geology	3/5	3/4	1	3/2	3/1	0.200
Groundwater	2/5	2/4	2/3	1	2/1	0.1333
Bedrock	1/5	1/4	1/3	1/2	1	0.0666

Table II. Normalized ratings of the features of the thematic layers.

Theme	Weight	Rating	Feature	Normalized rating
PGA (gal)	0.3333	1	50	0.0000
		2	60	0.0625
		3	70	0.1250
		4	80	0.1875
		5	90	0.2500
		6	100	0.3125
		7	110	0.3750
		8	120	0.4275
		9	130	0.5000
		10	140	0.5625
		11	150	0.6250
		12	160	0.6875
		13	170	0.7500
		14	180	0.8125
		15	190	0.8750
		16	200	0.9375
		17	210	1.0000
Soil type	0.2666	1	Silt with low plasticity	0.0000
		2	Sand with fines	0.2000
		3	Sand with no fines	0.4000
		4	Clay with low plasticity	0.6000
		5	Clay with medium plasticity	0.8000
		6	Alluvium	1.0000
Geology	0.2000	1	Old Alluvium Plain	0.0000
		2	Old Alluvium Flood Plain	0.5000
		3	Active Flood Plain	1.0000
Groundwater	0.1333	1	Fall: >5 m	0.0000
		2	Fall: 0–5 m	0.3333
		3	Rise: 0–5 m	0.6667
		4	Rise: >5 m	1.0000
Bedrock	0.0666	1	Quartzite Exposure	0.000
		2	0–30 m	0.250
		3	30–100	0.500
		4	>100 m	0.750
		5	Soil	1.000

5. Discussions and Conclusion

Delhi has been seismically active since historical times that are evident from the earthquakes of 1720, 1803, 1842, 1934, 1956 and 1960 (Kamble and Chaudhury, 1979). It has been affected by the earthquakes from the Himalayas. Delhi lies approximately 300 km from the central seismic gap and in the event of occurrence of any great earthquake in the central seismic gap, there will be immense threat to the human population and property of Delhi. Delhi is well covered by old and recent alluvium all over except in the southern and central parts. Towards the eastern part, it is covered by flood plains of Yamuna River that are overlain by unoxidized clay and sand. The present population of Delhi is about 14 million, which puts direct pressure on civil construction and transportation. As a result, many flyovers, metro rails and high rise buildings have come up. In the recent past, earthquakes like the Uttarkashi (1991) and the Chamoli (1999) have caused lots of damage to the high rise buildings in the Trans Yamuna area. Delhi lies in the seismic zone IV of the seismic zonation map of India which suggests that a moderate to high magnitude earthquake can strike Delhi. Due to its rapid growth in civil construction, industry etc., a thorough knowledge on seismicity is needed for adopting mitigation measures. This study aims at identifying tiny zones that can be vulnerable during earthquakes. Seismic microzonation is aimed for this reason. Based on AHP, the weightage assigned to each theme are: PGA (0.333), soil (0.266), geology (0.20), groundwater (0.133) and bedrock depth (0.066). The PGA contour has been extrapolated from the available four recording station data based on different soil types. The PGA values increase away from the ridge on both sides reaching a maximum of 210 gal. The PGA value is aligned about NE–SW direction (Figure 3a). The increase in PGA value can be correlated with the alluvium thickness, which increases away from the ridge. The groundwater fluctuation shows the maximum rise on the west of the Delhi ridge. The feature of each theme was also normalized between 0 and 1.

Delhi has been broadly classified into four zones, as very high, high, moderate and less in terms of seismic hazard in an event of future earthquakes (Figure 6). The ‘very high’ seismic hazard zone is observed on either sides of the Delhi ridge and coincides with the zones of maximum PGA value contours where the PGA value ranges about 140–210 gal. The soil type includes the clay and the silt. The active flood plain also comes under the ‘very high’ seismic hazard zone.

The ‘high’ seismic hazard zone covers most of the study area and the PGA for this zone ranges from 90 to 140 gal and occurs mostly over the alluvium deposit.

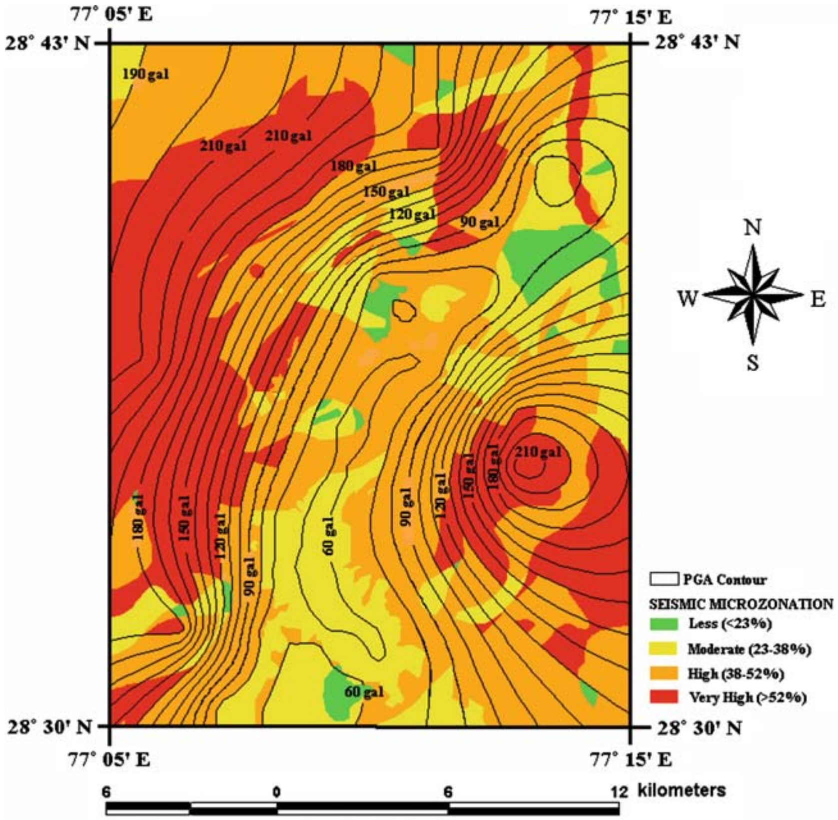

Figure 6. Seismic microzonation map of Delhi after integration of the five thematic maps in GIS. The legend shows the relative seismic hazard zones of Delhi.

The 'moderate' seismic hazard zone occurs along the flanks of the Delhi ridge on both sides and the PGA value ranges from 60 to 90 gal and mostly overlies the sandy soil.

The 'less' seismic hazard zone occurs in small patches scattered within the vicinity of the Delhi ridge with PGA value less than 60 gal. It covers a small area.

Site response, PGA distribution and destruction pattern due to the Chamoli earthquake greatly corroborate the seismic hazard ratings estimated through microzonation on GIS platform thus establishing the methodology incorporated in this study.

From the above results we can conclude that almost the entire Delhi region is exposed to high seismic hazard, while a small part lies within the safe zone. This small part lies in the Delhi and is mainly of forest areas and Delhi ridge. The seismic microzonation map thus generated will be of immense help for the Urban Development Authorities for planning of future construction projects. It will also be of use for assessment of seismic risk to the existing construction, defense installation, heavy industry, and important structures like dams, nuclear power stations and other public utility services.

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