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COMPREHENSIVE SEISMIC MICROZONATION OF LUCKNOW CITY WITH DETAILED GEOTECHNICAL AND DEEP SITE RESPONSE STUDIES

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ABSTRACT: Earthquake induced damages can be manifold in case of poor construction practise and very high population density areas. Studies of seismic microzonation focuses on estimation of seismic hazard considering the seismotectonic province of the study area and also deals with quantification of induced effects such as ground shaking, site response and liquefaction. In this paper, the seismic microzonation of Lucknow in light of on-going seismicity of the Himalayan region and local seismicity of the Lucknow region considering the deeper lithology of Indo-Gangetic basin (IGB) is presented. Issues such as lack of regional ground motion prediction equation, subsoil lithology details, suitability of seismic site classification system for deep basins, site response for deep basins and ground motion selection for deep basins, liquefaction etc. have been attempted.

INTRODUCTION

The collision of Indian and Eurasian plate had given birth to the Himalayas. The entire collision process was initiated about 50 million years ago (during the Cenozoic era). The building up strains due to such collision had resulted in many of the devastating earthquakes of the history of the humanity. Some of the deadly earthquakes occurred as a result of this collision include 1255 Nepal EQ (earthquake), 1555 Srinagar EQ, 1737 Kolkata EQ (then Calcutta), 1897 Shillong EQ, 1905 Kangra EQ, 1934 Bihar-Nepal EQ, 1950 Assam EQ and 2005 Kashmir EQ etc. Many of the above events caused casualties up to 1 lakh and total destruction of the utilities all around. Even though these events are wide scattered in time, a closer observation in the recent past shows continuous occurrence of moderate size earthquakes at different segments along the entire Himalayan belt. Example include 1991 Uttarkashi, 1999 Chamoli, 2005 Uttarkashi, 2007 Chamoli, 2008 Pithoragarh EQ, 2011 India-Nepal, 2011 Sikkim EQ and many more. Based on geodetic measurements, a collision rate of 5 cm/ year between the two plates has been found. Also, the building up strains at many locations in the Himalayan region has been highlighted as the possible locations of seismic gap. Combining all the observations above, continuous records of the seismic activity of the Himalayas since its origin and present increased seismicity can be found. Such a condition makes the areas surrounding in and around the Himalayas seismically vulnerable. The inefficiency of the present seismic code in capturing the regional seismicity has been highlighted by many previous researchers. In addition to this, merging the poor construction process followed in these areas and very high population density can enhance the seismic vulnerability manifold. It is well established fact that the earthquakes cannot be avoided nor can be predicted in advance but with serious efforts, post effects of earthquakes can be minimized. In the present work, attempts have been done to quantify the effects of the Himalayan seismicity and the local seismicity of Lucknow for a detailed seismic microzonation of Lucknow urban centre.

STUDY AREA

The Indo-Gangetic basin covers an area about 2, 50, 000 km^2. It extends between the latitude 24^o N to 30^o N and longitude 77^o E to 88^o E. Approximately 200 million live in the basin which defines the area as one of the most densely populated regions of India. Origin of this basin is related with the collision between Eurasian and Indian plate which has caused the rise in the Himalayas since Cenozoic era. It has been the same time since the collision started that weathering by the river Ganga during its course of flow also has place. Further, these sediments caused gradual deposition in the lower courses. Continuous depositing of sediments for long time has resulted in layers of sediment layers having thickness beyond several kilometers (Sinha *et al.*, 2005). Many important urban centers are located in various parts of IGB such as Lucknow, Meerut, Agra, Allahabad, Gorakhpur, Ghaziabad, Jhansi etc. Based on strain accumulation at different segments of the Himalayan belt, Khattri (1987) highlighted possible seismic gap between 1905 Kangra EQ location and 1934 Bihar-Nepal EQ location (called as Central Seismic Gap). Also, Khattri (1987) mentioned the possibility of great seismic event in the near future in this gap. Since, the IGB lies close to seismically active Himalayan belt, most of the urban centers of IGB listed above are vulnerable to great earthquakes in the Himalayan belt. In addition to the seismicity of the Himalayan region, IGB itself consists of many active tectonic features such as Delhi-Haridwar ridge from Delhi to Gharwal Himalayas, Delhi-Muzzafarabad ridge running from Delhi to Kathgodam, Faizabad ridge from Allahabad continuing towards Kanpur, Lucknow ending in Nepal and Monghy-Saharsa ridge. Some of the earthquakes which have occurred in IGB include 1833 Bihar, 1934 Bihar-Nepal, 1988 Bihar and 2011 Delhi. Thus, urban centres in IGB are under high seismic hazards due to the Himalayan seismicity and the local seismicity as well. Further, in the light of thick overburden, local site effects will be dominating in IGB which has not been addressed in any other previous studies.

LUCKNOW AND ITS SEISMICITY

The study area of "Lucknow" lies in the central part of IGB. Lucknow, the capital of Uttar Pradesh, also known as the "City of Nawabs,". It is a multicultural city, famous for beautiful gardens, music and architectural styles. The study region of Lucknow city covers an area of about 370 km2 and with center point at Vidhan Sabha having latitude 26^{o} 51.6' N and longitude 80^{o}54.6' E. Figure 1 shows the study area of Lucknow with Himalayan belt and IGB. The elevation difference in the entire study area is about 29 m from its highest elevation of 129 m in the area of the Sarda canal and its

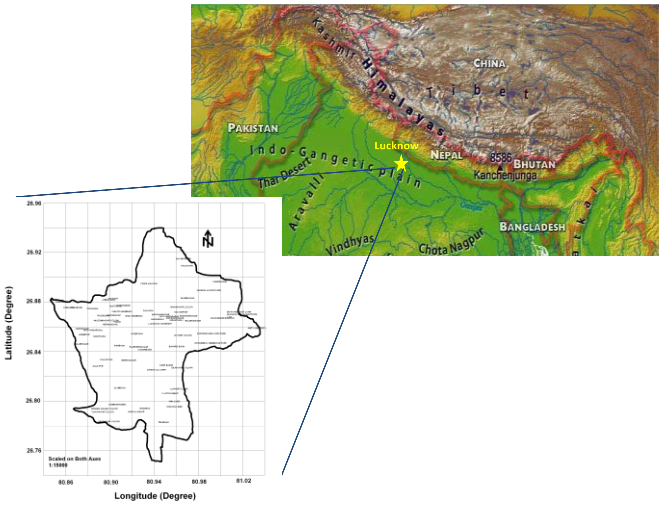

Fig. 1 Study area of Lucknow in close proximity to the Himalayan region and Indo-Gangetic basin

lowest elevation of 100 m on the southeastern Dilkusha garden. The River Gomati flows in the middle of Lucknow in northwest-southeastern (Husainabad-Dilkusha garden) direction. The study area covers most part of River Gomati in Lucknow city. As per Geological Survey of India (DRM, 2001) report, the entire area is composed of thick Quaternary sediments uncomfortably overlying the basement of Bundelkhand Granitoids and sedimentary rocks of the Vindhyas. As per the Central Ground Water Board (CGWB) the bedrock is not present at a depth of 298 m and 445 m in southern and western parts of the urban center (DRM, 2001). The study area of Lucknow lies in the Seismic zone III in current Seismic Zonation map of India (IS: 1893, 2002), with zone factor of 0.08. Till date, the State of Uttar Pradesh has faced a number of earthquakes. These include the 1925 Rae-Bareili, 1956 Bulandshahar, 1965 Gorakhpur, and 1966 Muradabad earthquakes. Magnitudes of these earthquakes are in the range of 5.0 to 6.3 on the Richter scale. The disaster risk management program of the Ministry of Home Affairs in association with United Nations Development Program (UNDP) has highlighted that Lucknow city lies within the Faizabad Fault (Nadeshda, 2004). This fault has been inactive for 350 years. Researchers have highlighted that this fault has been under heavy stress for a long time and has the potential to cause a great earthquake in the future. With the Himalayas rising due to the subduction of Indian plate under Eurasian plate, a movement of the Indian plate by 5.25 m could cause an earthquake as high as magnitude 8 on Richter scale on Faizabad fault as per Earthquake Mitigation Department of Uttar Pradesh (Nadeshda, 2004). This fault passes through the Lucknow district. Apart from the local seismic activity around Lucknow, the area also lies within a radial distance of 350 km from Main Boundary Thrust (MBT) and Main Central Thrust (MCT), where many major earthquakes have been reported. Considering the above seismic aspects of areas in and around Lucknow, the city of Lucknow can be considered under high seismic risk due to any future earthquakes. Thus in present work, an attempt has been made to estimate the possible seismic hazards for Lucknow city.

GROUND MOTION PREDICTION EQUATIONS (GMPES)

Ground shaking during an earthquake is responsible for structural damages and ground failures within the epicentral region as well as at far distances. Seismic hazard analysis of any region estimates these ground shaking in terms of PGA (Peak Ground Acceleration) for the area. The region specific GMPE (Ground Motion Prediction Equation) is an important component of seismic hazard analysis for seismic macro and microzonation.

Developed countries are in the process of arriving the Next Generation ground motion Attenuation (NGA) for the better prediction of ground shaking due to any future earthquake events (Campbell and Bozorgnia, 2006; Kaklamanos and Baise, 2011). However, studies towards developing regional representative GMPEs in India are very limited. Also limited GMPEs are available to estimate the representative seismic hazard both at bedrock as well as at surface by accounting local site effects in India and other parts of the world (Atkinson, and Boore, 2006; NDMA, 2010; Anbazhagan *et al*., 2011). Many recent studies have highlighted that macro level zonation factor (or PGA) given in Indian standard code (IS:1893:2002) is either higher or lower than that of the micro level PGA obtained after seismic hazard studies at regional scale (Anbazhagan *et al*., 2009; Menon *et al*., 2010; NDMA, 2010). Thus, the zonal values given in IS code are required to be updated after such micro level findings. Such micro level ground motion estimation studies should be based on regional past seismicity and region specific GMPE. Several seismic hazard maps are being produced in India using available GMPEs with limited validity on the degree of suitability of representative GMPEs for the regions.

Region specific ground motion prediction equation for the Himalayan region

A large number of region specific GMPEs which are developed based on data from the Himalayan region are available. Anbazhagan *et al.,* (2013) presented summary on the standard form of regional GMPEs, zero period coefficients, range of magnitude and hypocentral distance each of the regional GMPE valid for the Himalayan region. Most of these GMPEs were applicable for hypocentral distance of within 200 km and for a magnitude range of 7.0. These include GMPEs by Singh *et al*.(1996), Sharma (1998), Nath *et al*. (2005, 2009), Sharma and Bungum (2006), Das *et al*., (2006), Baruah *et al*. (2009), Sharma *et al.* (2009), Gupta (2010) and NDMA (2010). Due to limited length of paper, further details about each of the above GMPE has not been given here and can be found in Anbazhagan *et al.,* (2013). Out of all the above GMPEs, NDMA (2010) was only found to be applicable up to 500 km hypocentral distance and up to magnitude of 8.5 (Mw). In addition to region specific GMPEs, there are several GMPEs developed for similar tectonic condition which can also be applicable to the Himalayan region. GMPEs developed elsewhere and applicable to Himalayan regions are Youngs *et al.* (1997), Ambraseys *et al*. (2005), Kanno *et al.* (2006), Zhao *et al.* (2006), Campbell and Bozorgnia (2008), Idriss (2008) and Akkar and Bommer (2010). All these equations were developed for other regions of the world and are being used for seismic hazard studies of Himalayan region.

In order to compare GMPEs in single plot, the PGA values are estimated considering distance used to develop respective GMPEs and simultaneously hypocenter distance is also estimated. Estimated PGA as per GMPE distance is plotted with hypocentral distance. It can also be noted here that the use of multiple distances for GMPE comparison only affects short distance <20 km and above 20 km, the effects are negligible (Bommer *et al*., 2005). Figure 2 shows the plot of region specific available GMPEs and applicable GMPEs for Mw 6.8 and hypocenter distance of 10 to 300 km. From Figure 2, it is very difficult to assess applicability of the particular GMPE for the region. Also it is very difficult to identify the appropriate region specific GMPEs for the hazard analysis and microzonation purposes. Nath and Thingbaijam (2011) was identified higher ranked best suitable GMPEs for Himalayan region by efficacy tests proposed by Delavaud *et al*., (2009). Nath and Thinbaijam (2011) listed higher ranked GMPEs for Himalayan region and among this first five are best suitable GMPEs. First five GMPEs suitable for Himalayan regions are Kanno *et al*., (2006) [KAN06]; Campbell and Bozorgnia, (2008) [CABO08]; Sharma *et al*., (2009) [SHAR09]; Akkar and Bommer, (2010) [AKBO10] and Idriss, (2008) [IDR08]). In order to make comparison, these five GMPEs are combined and average value is considered. PGA for MW of 6.8 and up to hypocentral distance of 300 km was estimated considering five highly rankled GMPEs [HRGMPE] and average values are plotted as shown in Figure 3.

From Figure 3 it can be observed that GMPEs given by Iyenger and Ghosh (2004) overestimates the hazard values when compared to average of HRGMPEs throughout the hypocentral distance of up to 300 km. Further, GMPE by Nath et al., (2005) under predicts the PGA values till 100 km distance as this GMPE is valid up to 100 km only. Comparison of GMPE by Das et al., (2006) with average of HRGMPEs shows close matching till 40 km and highly over predicts beyond 40 km. GMPE by Sharma and Bungum (2006) on comparison with average of HRGMPEs shows close matching upto 70 km while over predicts beyond 70 km till 200 km beyond which this GMPE is not applicable. Comparing the GMPE by Baruah *et al*., (2009) with the average of HRGMPEs shows over prediction throughout the

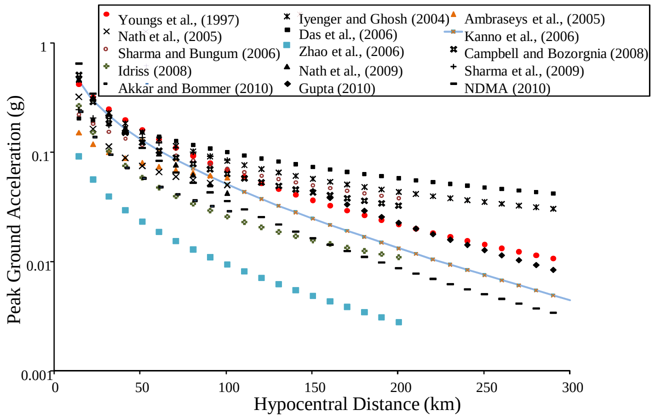

Fig. 2 Comparison of ground motion prediction equations applicable to Himalayan region for 6. 8 (Mw) earthquake.

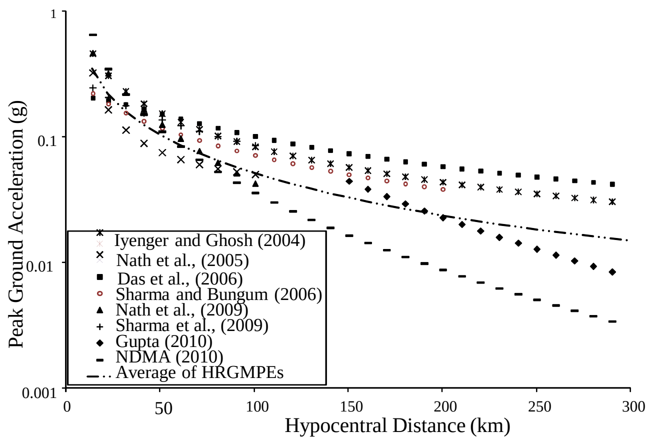

Fig. 3 Comparison of region specific ground motion prediction equations with the average of first five High Ranked Ground Motion Prediction Equations (HRGMPEs) for an 6.8 (Mw) earthquake.

distance range. GMPE by Nath *et al.,* (2009) matches closely with the average of HRGMPEs up to 100km distance beyond which this GMPE is not applicable. GMPE by Sharma (2009) is applicable up to 100 km distance range. Comparison of this GMPE with average of HRGMPEs shows over prediction up to 40 km. GMPE by Gupta (2010) is applicable only after 150 km distance. Comparison of this GMPE with the average of HRGMPEs shows close matching between 150 km and 200 km beyond which GMPE by Gupta (2010) under predicts the PGA values. Comparison of GMPE by NDMA (2010) for Himalayan region and HRGMPE is shown in Figure 3, which show that up to a hypocentral distance of 70 km, both the GMPEs are predicting closer PGA values. However, beyond 70 km, NDMA (2010) underestimates the PGA values when compared to HRGMPE.

From the above discussion, it can be concluded that the region specific GMPEs are incapable of predicting hazard values at higher magnitude and for entire hypocentral distance range of interest. Thus, there is demand of a new attenuation relation for the Himalayan region.

Database and development of the proposed GMPE

Instrumented ground motion data are best suitable to develop a most appropriate GMPE for any region. But unfortunately available recorded earthquakes are very limited for such studies. In India, very few recorded ground motions are available. The Dharamshala earthquake of 1986 was the first event in the highly active western Himalayan region. Three arrays namely Kangra array, Uttar Pradesh array and the Shillong arrays were installed by the Department of Science and Technology (DST), Government of India to record ground motions of the Himalayan earthquakes and maintained by the Department of Earthquake Engineering, Indian Institute of Technology, Roorkee. The database provides the epicentre location, recording station detail and recorded ground motion in terms of acceleration, velocity and displacement time histories.

In order to develop new GMPE, recorded ground motions were collected from Shrikhandre (2001) for earthquakes up to 2001 and from PESMOS for earthquakes happened after 2001. This database shows lack of recorded ground motions both in terms of near field region as well as far field region. In order to fill this gap in the existing database, synthetic ground motions were developed using Finite Fault Simulation Model (FINSIM; Beresnev and Atkinson, 1997). Source and propagation path details have been collected from the published literature for each event. Model parameters such as strength factor and the stress drop have been obtained from parametric study by comparing between the simulated and recorded

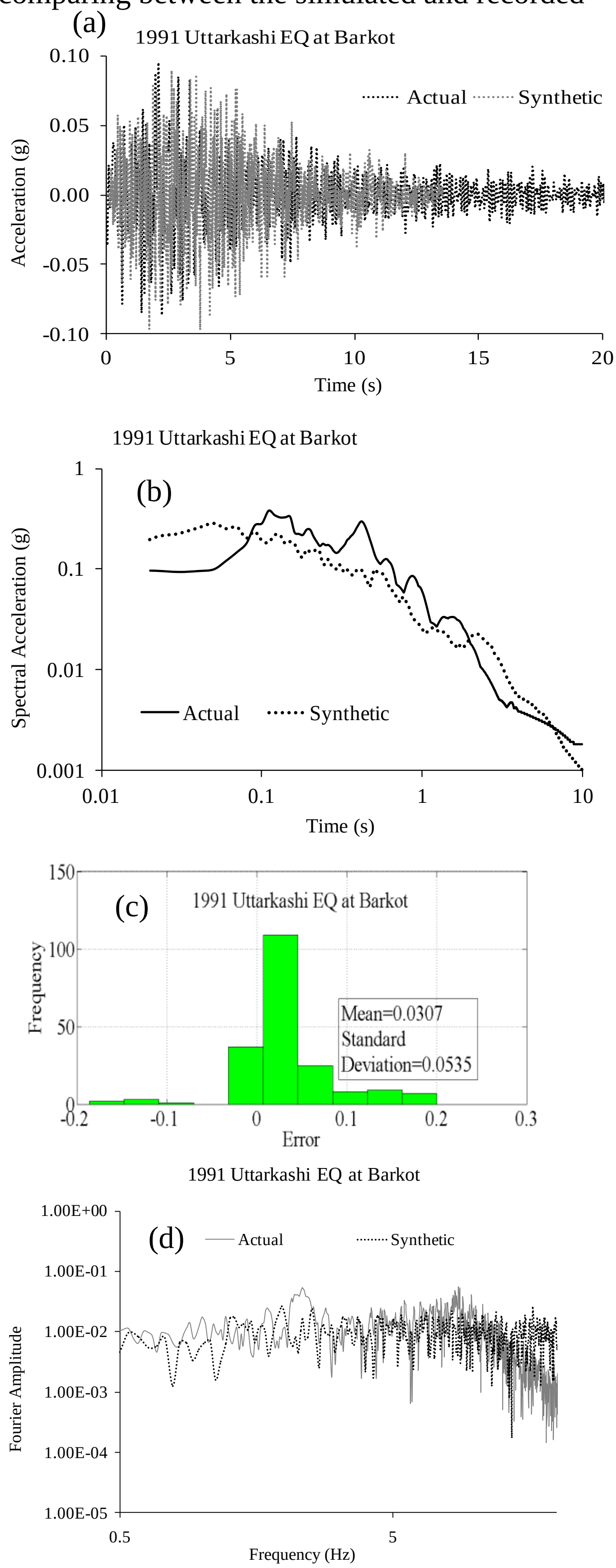

Fig. 4(a-d) Various comparisons between actual and synthetic data

data. In order to validate the simulated ground motions with the recorded data, comparison between the two in terms of acceleration time history, Fourier spectra, response spectra and error versus frequency plots for large number of stations where recorded data was done have been obtained. Figure 4 (a-d) shows the comparison for 1991 Uttarkashi EQ at Barkot. Further, same model parameters for each event have been developed to generate synthetic ground motion for addional locations. The concept of apparent station which has been developed by Anbazhagan *et al*., (2013) has been used. In total 9 recorded earthquakes were considered with each event simulated at 30 stations at bedrock. Recorded data are available since 1986 and since then no great seismic event has been reported in the Himalayan region. Thus, in order to incorporate large magnitude data in the database, historic earthquakes with no ground motions have been considered using isoseismal map of each of them. Isoseismal maps show the level of ground shaking in terms of MMI (Modified Mercalli Intensity) due to a particular event. 5 historic events namely 1897 Shillong EQ, 1905 Kangra EQ, 1934 Bihar Nepal EQ, 1950 Assam EQ and 2005 Kashmir EQ were simulated. PGA-MMI relation by Murphy and O'Brien (1977) was used to convert surface MMI to surface PGA values. Further, these surface PGA were converted to bedrock PGA based on average values of amplification factors for the Himalayan region. These bedrock PGA values were compared with simulated PGA at those locations. Once, both the MMI induced PGA and simulated PGA are found matching, same model parameters for each event were used to develop additional ground motions at apparent stations at bedrock level.

In total 14 earthquakes each having 420 ground motions (30 for each event either recorded at bedrock or simulated at bedrock) were used for the database. Further, with this developed database, multi-regression using two step stratified procedure of Fukushima and Tanaka (1990) was carried out and compared with many of the earlier GMPEs for the Himalayan region. The following form of the GMPE is used for the analysis;

$$log\ (y) = c_1 + c_2 M - b\ log(X + e^{c_3 M}) + (\sigma) \qquad (1)$$

Where, y is SA in g, M is moment magnitude, X = , where R is the closest distance to the rupture in km, h is the focal depth in km, b is decay parameter as estimated above, c1, c2 and c3 are regression coefficients and (σ) is the standard error term. Since, the matching between the recorded and simulated ground motions are found till 2 sec, coefficients for the proposed GMPE are given till 2 sec. Table listing the coefficients of the proposed GMPE can be found in Anbazhagan *et al*., (2013). Further, the proposed GMPE is validated for three recent earthquakes which were not considered in the database for developing the GMP. Figure 5 shows the comparison of PGA proposed based on the new GMPE with other highly ranked GMPEs and recorded data for 2011 Nepal-India EQ (Mw=5.7). It can be observed from Figure 5 that PGA values based on the proposed GMPE matches well with recorded values up to 300 km. The PGA obtained from KAN06 and CABO08 matches with recorded PGA values up to 200 km, beyond 200 km KAN06 under predicts when compared to recorded and proposed GMPE. PGA values from and IDR08 GMPE is slightly lower than recorded values and proposed GMPE predictions. PGA values are over- predicted by SHAR09 GMPE and are under predicted by AKBO10 GMPE for applicable distance range of 100 km, when compared to PGA records of 2011 Nepal India Border EQ and proposed GMPE. Moreover, these two GMPEs are not following prediction value of other three highly ranked GMPEs and GMPE proposed in this study. For the same event, Figure 6 shows the comparison between the response

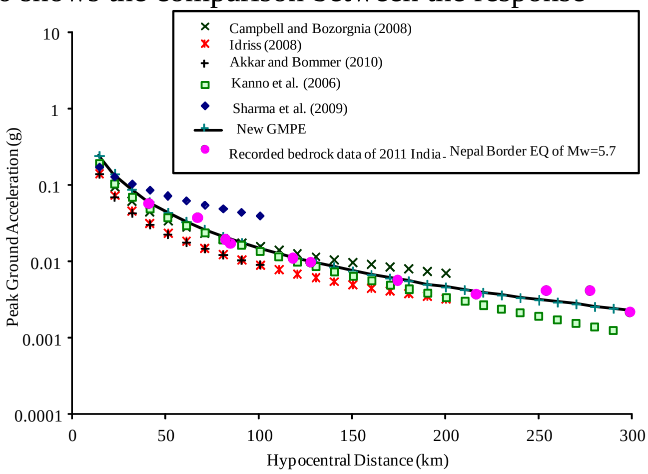

Fig. 5 PGA comparison of new GMPE with recorded data and other highly ranked GMPs

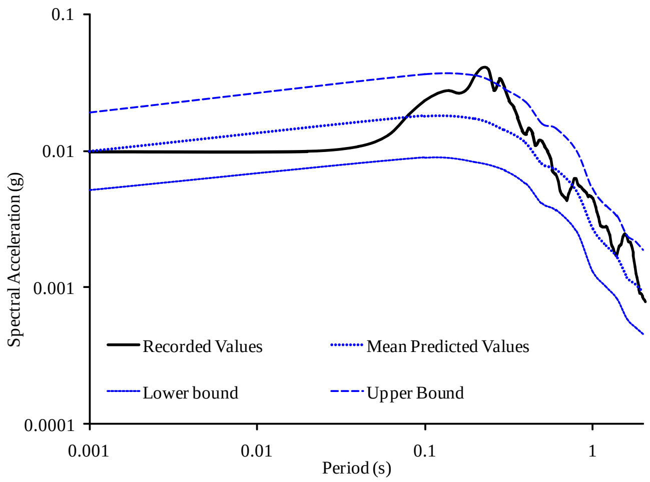

Fig. 6 Comparison of response spectra based on proposed GMPE and recorded ground motion

spectra from recorded data and the response spectra from the proposed GMPE. It can be observed that Figures 6 that up to a period of 0.06 seconds, the response spectra based on recorded data match well with mean predicted response spectra. Beyond 0.1 seconds, the recorded response spectra matched well with mean predicted response spectra.

SEISMIC HAZARD ANALYSIS OF LUCKNOW

Estimation of the level of ground shaking at bedrock level for Lucknow will be a governed both by the seismicity of the Himalayan region due to its close proximity from Lucknow and the local seismicity of Lucknow-Faizabad fault. In order to perform the seismic hazard of Lucknow, past events along with the active sources need to be collected within the seismotectonic province of Lucknow. As per Gupta (2002), the extent of the seismotectonic region should be 300 km in case of moderate seismicity region which can be extended to 500 km in case of highly active regions. For the present work, considering 350 km as the radial distance between the Lucknow and the MBT (main Boundary thrust), the radial extent of seismotectonic region has been considered as 350km. A source map, showing all the faults, lineaments, shear zones which lie within 350 km from Lucknow center as per SEISAT (2000) is prepared. Past event details are collected from various sources such as United State Geology survey (USGS), Northern California Earthquake Data Centre (NCEDC), India Meteorological Department (IMD) and Geological survey of India (GSI) etc. A total of 1831 events have been collected and data consist of epicentre coordinates, focal depth, date, month, year, and magnitude in different magnitude scale. In order to achieve homogeneity in magnitude scale, all the collected events were converted to moment magnitude (Mw) using Scordilis (2006) correlations.

Declustering of earthquake data and G-R relation

Declustering of earthquake events are required to remove dependent events from the earthquake catalogue which can overestimate the actual seismicity. For the present work, static window method is used. Thus, after declustering and removal of events <4.0 (Mw), a total of 496 events in the whole seismotectonic province are left. These events were overlapped on the source map thus generating the seismotectonic map of Lucknow. Figure 7 shows the seismotectonic map of Lucknow. Based on the event distribution on the seismotectonic map (shown in Figure 7), the entire area is divided into two parts; Region I which belong to events inside the rectangle while Region II represents event outside the rectangle. Earthquake data in each region are separately analyzed to check data

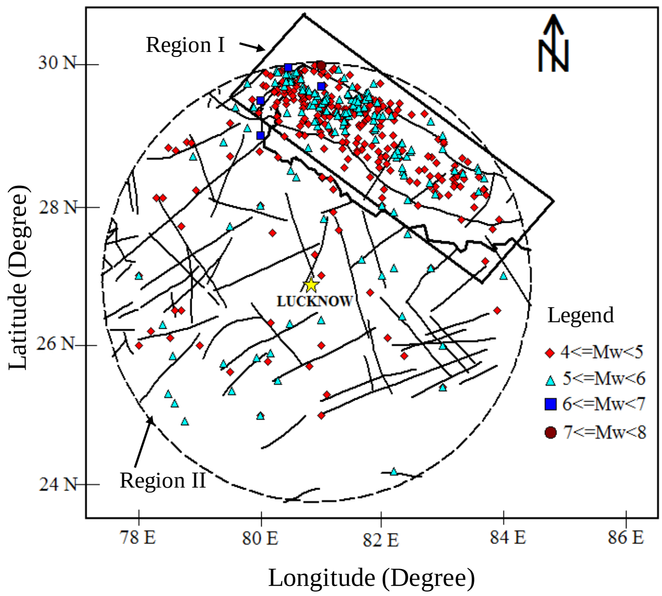

Fig 7 Seismotectonic map of Lucknow

completeness and estimation of Guternberg-Ritcher recurrence (G-R) relation parameters.

Available earthquake catalogue only shows events within last one or two centuries and thus may not be representing the actual seismic activity of the region. Thus, in order to use the prepared earthquake catalogue for the estimation of seismotectonic parameters and seismic hazard, the data from both the regions are analysed for their completeness. Stepp (1972) method is used to check for data completeness in this work. Due to limited length of paper, details about the analyses are not presented here and can be found in Abhishek *et al.*, (2013). Based on the completeness analysis, data from both the region are found complete for the last 80 years. Using the complete earthquake catalogue for both the regions, G-R recurrence relation parameters (a resembles number of earthquakes of magnitude zero and b resembles the relative abundance of large to small shocks) are estimated for both the regions. The 'b' values for Region I and Region II are 0.86 and 0.90 respectively. These values were found matching with other studies available for Region I and Region II. For further analysis, the above values of 'b' parameter are used.

M_{max} Estimation

Evaluating the maximum possible magnitude is a very crucial step in any seismic hazard analysis. Since, the complete earthquake catalogue for any region represents a very small portion of its total seismic activity. Thus, based on complete catalogue, it is very difficult to understand the complete potential of any region or source for future seismicity. The maximum magnitude (M_{max}) is defined as the upper limit of magnitude or the largest possible earthquake in any region or seismic source. The maximum observed magnitudes on each fault may not represent the full potential of that fault, since the earthquake catalogue has been found to be complete only for the last 80 years. Thus, M_{max} in this work is estimated by two ways for each fault namely: 1)Kijko and Sellvolle (1989) and 2) increamental method. Maximum of the above two M_{max} is used in the seismic hazard analysis. Further details can be found in Abhishek *et al*., (2013).

DSHA and PSHA of Lucknow

Once, source details, M_{max} and G-R recurrence relation parameters are estimated, seismic hazard is carried using Deterministic seismic hazard analysis (DSHA) and Probabilistic seismic hazard analysis (PSHA). Three GMPEs namely Kanno et al., (2006), NDMA (2010) for the Himalayan region and GMPE by Anbazhagan *et al*., (2013) are used with weightage factors of 0.3, 0.3 and 0.4 respectively. Separate MATLAB codes are developed for DSHA and PSHA dividing the entire study area into grids of 0.15^{o} x 0.15^{o}. Figure 8 presents the DSHA map of Lucknow. The PGA variation was found from 0.05g in the eastern periphery of the city to 0.13 g in the northern part of Lucknow. DSHA analysis shows that north-western part of the city is expected to have PGA values of 1.8 to 2.6 times PGA of south eastern part of the city. North-western part include areas like Aliganj, Hasanganj, Butler colony, Indiranagar and surrounding areas which are more prone to earthquake induced ground shaking. However, areas which fall in south and eastern part of the city such as Vikram Khand, Gomati Nagar, Telibagh, Hudson lines and their nearby areas are less susceptible to earthquake shaking. Further, the Figure 9 shows the obtained response spectra at bedrock for Lucknow urban centre obtained from DSHA. It can be observed from the figure that spectral acceleration at the city centre is0.10g at zero seconds which has reached to 0.20 g at 0.05 seconds. Thus there has been a two fold increase

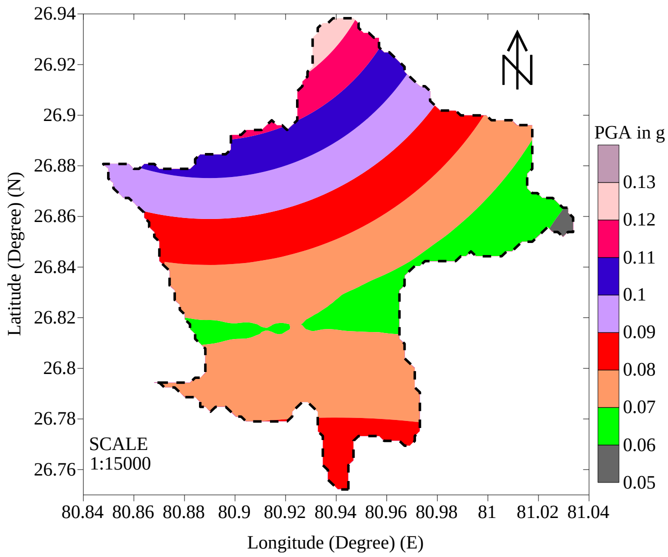

Fig 8 DSHA map of Lucknow

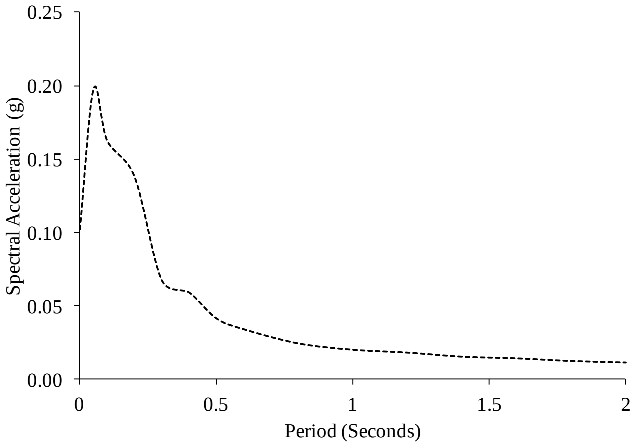

Fig 9 response spectra at Lucknow city centre based on DSHA

in the spectral acceleration from zero to 0.05 seconds change in period of motion. Beyond 0.05 seconds however, the spectral acceleration suffered a rapid drawdown till 0.3 seconds where spectral acceleration reached a value of 0.07g.

DSHA evaluates seismic hazard considering the maximum magnitude earthquake happening at closest distance to the site. Thus, DSHA will produce consider worst scenario without considering its possibility of occurrence during the design life of the structure. Overcoming these limitations of DSHA, PSHA (Cronell, 1968) accounts for the probability of occurrence magnitude, hypocentral distance and ground motion exceeding a particular value. For present work, all the uncertainities related to magnitude exceedence, hypocentral distance and ground motion exceedence are evaluated as can be seen in Abhishek *et al.*, (2013) to produce the PSHA map of Lucknow. Two PSHA maps for 2 % and 10% probability of ground motion exceedence in 50 years are produced as shown in Figure 10 and 11. These maps will have return period of 2500 years and 475 years respectively. It can be observed from Figure 10 that PGA varies from 0.07g in the eastern periphery to 0.13 g towards the north, while southern part of the city encounters PGA of 0.08 g. Aliganj, Hasanganj, Butler colony, Indiranagar and surrounding areas are more prone to earthquake induced ground shaking. Further Figure 11 shows the PSHA map for Lucknow for 10 % probability of exceedence in 50 years. There is a large variation in the PGA across the city from 0.035 g in the southern part to 0.07 g in the north and north-eastern part of the city. In this case also, the areas which come in north and northeast part of Lucknow urban center are susceptible to higher level of ground motions compared to the eastern part and the southern part of the city.

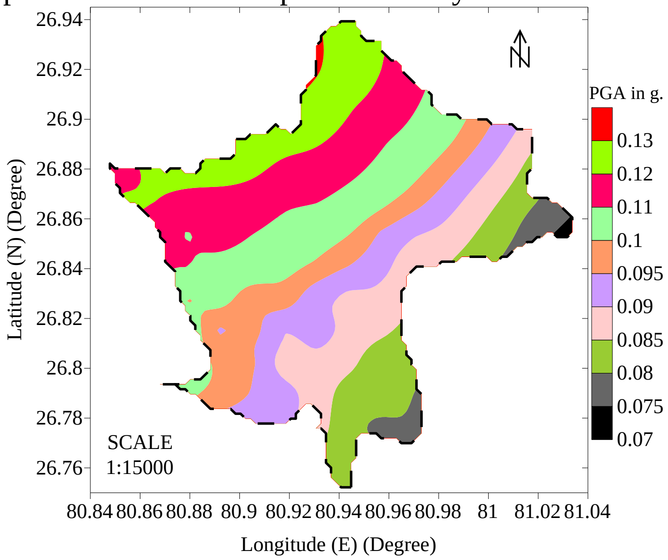

Fig 10 PSHA of Lucknow for 2% probability of exceedence in 50 years

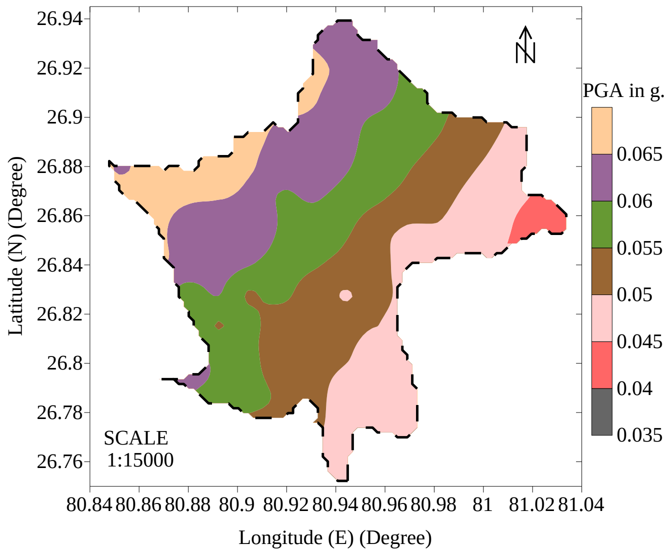

Fig 11 PSHA of Lucknow for 10% probability of exceedence in 50 years

FIELD INVESTIGATIONS AND SEISMIC SITE CLASSIFICATION

Subsurface profile above seismic bedrock plays very important role in the modification of earthquake waves and failure of surface layers. It is proved that shallow subsurface make considerable contribution towards earthquake damages to infrastructures. Geotechnical and geophysical methods are most widely used techniques to generate subsurface profiles for earthquake geotechnical engineering studies. Geotechnical methods include Standard Penetration Test, Cone Penetration Test (CPT), Vane Test, Dilatometer Test, etc. Common geophysical test methods to explore subsoil are Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW).

Subsoil geology of the IGB consists of several kilometer thick river deposited alluvium. As per Sastri *et al.* (1971), the sediment thickness in the Ganga basin reaches 6 km near the Himalayan foothills, decreasing gradually towards the south (Rao, 1973). Deep borehole reports carried out by ONGC was presented in Sastri *et al*., (1971). Shallow depths are occupied by the presence of alternate layers of sand and clay with few layers of Kankar in between until a depth of 360 m in Kasaganj,. This thickness further grows towards Raxual in east Uttar Pradesh from 360 m to 700 m and further down to a thickness of about 1500 m. The presence of limestone was found at 620 m in Kasaganj, which further dip down and reaching a depth of 4000 m in Raxual. At some locations, Vindhyan sediments were also found at depths exceeding 4500 m. Sastri *et al*., (1971) highlighted the presence of younger sediments at a depth of 620 m in Kasaganj to a depth of 2000 m near Raxual. Detailed literature of Lucknow reveals that no geological map for the study area of Lucknow is available at present. However geological setting of Lucknow district was published by the Geological survey of India in the name of District resource map for Lucknow (DRM, 2001). As per DRM (2001), the soil in the region is mainly comprises of both older and younger alluvium of Ganga-Ghagra interfluves (DRM, 2001). The older alluvium spreads over the vast area between elevations 115 m and 129 m, covering the areas like Chowk, Aminabad, Charbagh, and Kakori. Thus no quantitative information upon the subsoil properties of Lucknow was available. In order to explore subsoil properties quantitatively, field tests both geotechnical and geophysical are planned for Lucknow. The guidelines for field testing in case of microzonation studies as per NDMA (2011) are followed while planning for field studies. The entire city is divided into grids of 2km x 2km and 12 boreholes of 30 m depth with N-SPT at 1.5 m interval are drilled and 11 boreholes are collected from the same geotechnical firm. In addition, deeper boreholes (>150m) were collected from Jal Nigam Lucknow, Government of Uttar Pradesh. Based on 30 m borehole and deeper boreholes, 2D lithology cross sections for Lucknow are developed. In order to control the paper length, other details about the subsoil lithology are not discussed here and can be found from Anbazhagan *et al*., (2012). In general, borehole details reveal shows the presence of silty sand and poorly graded sand (SM-SP) in most part of the cross-section. Other portions of the cross-section are occupied by the presence of low to medium compressibility clay (CL-CI). Based on deeper boreholes also such similar observations can be made. Overall, no bedrock has been encountered till 150 m depth anywhere in Lucknow which is identical with the observation by CGWB (Central Ground Water Board).

In addition, 47 geophysical surveys using 24 channel geode using 4.5 Hz frequency geophones are performed across the Lucknow. MASW tests provide shear wave velocity (SWV) of the soil with depth. Further, the measured SWV can be used to classify the soil type as hard, soft stiff. At 17 locations, both the N-SPT and the SWV are available which are used to develop the empirical correlation between N-SPT and SWV for the Lucknow soil. In total three correlations namely for clayey, sandy and for all soil types. These are: $Vs = 106.63 (N)^{0.39}$ with R^2 of 0.74 for sand, $Vs = 60.17 (N)^{0.56}$ with R^2 of 0.86 for clay and $Vs=68.96\ (N)^{0.51}$ for all soil types re. These are the first types of correlations developed based on in-situ measurement of subsoil properties till 30 m depth. The proposed correlation is validated using normalized consistency ratio and scaled percent errors and found matching well with the recorded data. Comparison of the proposed correlation developed in this study with Indian researchers and JRA (1980) correlations is presented in Figure 12. It can be noticed in Figure 12 that the correlation proposed in this study matches very well with all correlations used in India up to N-SPT value of 25. Correlations above N-SPT of 25 are comparable with those reported in Hanumantharao and Ramana (2008). Maheshwari *et al.*, (2010), Anbazhagan and Sitharam (2008) and JRA (1980) have used N values from the shallow soil deposits (< 25 m), when compared to this study. Correlations developed in this study are comparable for all N-SPT values with Hanumantharao and Ramana (2008) correlation.

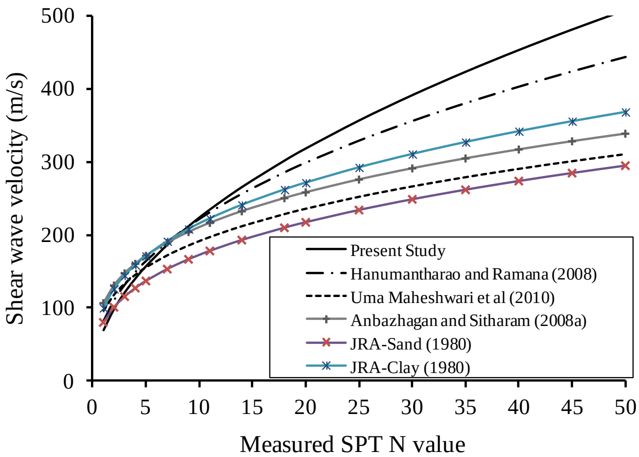

Fig 12 Comparison of proposed relation with other relations used and developed in India

Measured N-SPT and the SWV for all the test locations are further used for seismic site classification of Lucknow. The 30 m average values of N-SPT (N30) and SWV (VS30) are calculated and the sites are classified as per NEHRP (BSSC, 2003) classification system. Based on the classification, site class C and D are found based on VS30 and site class D and E are found based on N30 values. Most of the Lucknow city is found belonging to site class D with some mismatching. For further comment on the suitability of NEHRP classification system for IGB, large number of field data are needed which is not available at present stage.

The presence of local available geology at a site can modify the bedrock ground motions from seismic source. As a result, it will cause a complete change in the ground motion characteristics such as duration of motion, frequency content and amplitude at surface level in comparison to bedrock. Thus, the scenario will get completely changed as compared to the seismic hazard values obtained at bedrock. These modified motions are called as surface motions and are the actual ground motions that initiate phenomena such as liquefaction, ground shaking and landslides. Classical examples where the role of local soil played major role in site specific damages can be listed many, starting from the 2001 Bhuj earthquake (Mw=7.7) in India which is a classical example for many earthquake geotechnical damages due to thick soil deposit similar to the study area of Lucknow. 2011 Sendai earthquake (Mw=9.0) in Japan is an active tectonic earthquake resulted in far field damages due to local site effects. The Sendai earthquake was originated in the Pacific Ocean 130 km off from the eastern coast of Sendai. The event had caused massive ground failures such as liquefaction and differential settlements at many places such as Maihama, Tokai Mura which are located at more than 150 km from the epicentre (Nihon, 2011). The 2011 Sikkim earthquake (Mw=6.9) was of moderate size, however the induced ground shaking has caused collision of many buildings in Singtam, Gangtok, Lower Zongue, Mangam and Jorethang areas as far as 150 km from the epicentre. This earthquake had also triggered landslides on a massive scale in the areas near to Mangan, Chungthang and Lachung. These modified ground motions provide inputs for the seismically safe design of buildings and infrastructures. Hence, the effects due to local soil should be addressed completely while performing the microzonation studies for any urban center. Understanding and estimation of the response of different subsoil layers for the given seismic input motion at bedrock is called as site response study. Understanding the local geology for microzonation studies is always a challenging task. Hence, the effectiveness of any microzonation study is solely depending upon the accuracy in predicting the local site effects. In this work an attempt has been made to estimate change in bedrock motion due to local subsurface soil characteristics. Nonlinear site response model of DEEPSOIL (Hashash and park, 2001) is used in the analysis. Two crucial issues are addressed while performing the site response for the Lucknow subsoil. First is the selection of input bedrock motions and second is the depth of soil column to be used in the site response analysis of deeper basins such as IGB where overburden thickness is beyond several hundred meters.

Till now no recorded ground motions are available for Lucknow. In the absence of recorded ground motions, selection of standard ground motions from earthquakes such as 1940 El-Centro EQ, 1985 Mexico EQ, 1989 Loma Prieta EQ, 1994 Northridge EQ, 1995 Hyogoken-Nanbu EQ and 1999 Chi-Chi EQ etc. are usually used in many of the site response studies in India. These motions are directly used or scaled as per required PGA levels. Generation of synthetic ground motions compatible with uniform hazard spectra and hazard values were also followed worldwide for site response study. Further, selected ground motions should match with the site specific response spectra at rock level. However, in most of the cases, no reference spectra for the site are available for comparison. Hence, selections of number of ground motions are preferred to incorporate wide possible range of unavailable reference response spectra at rock level. In absence of recorded base motion at Lucknow, a wide range of ground motions recorded during various earthquakes in the Himalayan region are selected. The amplitude of bedrock motion obtained from DSHA of Lucknow urban centre has been considered as the first criteria in selecting the ground motions recorded at bedrock level. The entire PGA variation has been divided into 4 classes to select the input bedrock motion. These are 1) 0.05g to 0.07g, 2) 0.07g to 0.09g, 3) 0.09g to 0.12g and 4) >0.12g. Recorded ground motions are collected from combined dataset of Shrikhande (2001) and PESMOS corresponding to site class A. In accordance with first criteria, selected ground motions should also show a wide range of frequency and duration. In total 18 ground motions recorded at bedrock level are selected for the analyses. It can be observed from the Figure 13 that the predominant frequency of the input motions vary from as low as 3.15 Hz to as high as 12.5 Hz. Similar observations can also be made for the range of duration in selected motions. Loose to medium relative density soil deposits are more susceptible to high amplification when subjected to earthquake ground shaking. Most of the microzonation and hazard assessment programs in India determined the effect of local soil based on the top 30 m lithology characteristics.

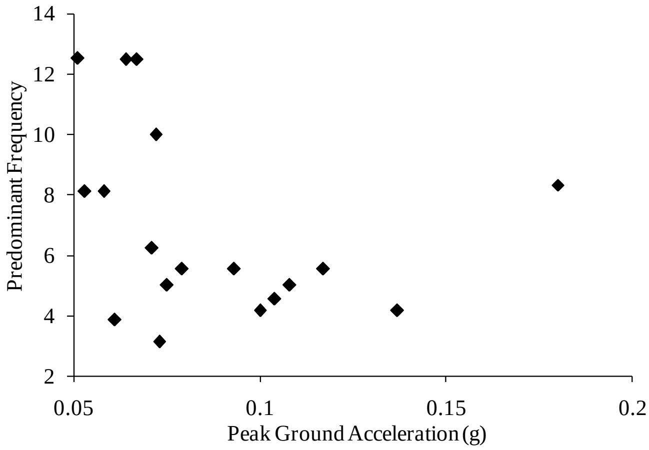

Fig 14 Variation of predominant frequency versus PGA in the input motion used

However, relevant depth to be taken either in case of shallow basin or deep basins equal to 30 m is still a question of debate. Anbazhagan *et al*., (2010) showed based on simulated ground motions and site response of one borehole that amplification is even possible beyond 50 m depth. Hence, consideration of 30 m depth as input level for site response study of the site having thick overburden need to be reviewed. Giving input at layer having shear wave velocity of more than 760 m/s is giving similar surface spectral values (Luke *et al*., (2001). Similarly Anbazhagan *et al*., (2013) shown as similar amplification spectrum for input at 1385 m/s, Lee *et al*., (2012) also performed site response analyses for Korean soil considering the depth of soil column up to SWV of 760 m/s. Such studies clearly indicate that applying base motion at or below soil layer having SWV 760 m/s layer can give representation surface response parameters. Hence in the present work uses soil layer having SWV of 760±60 m/s is considered as input depth overlain by elastic half space. Out of 47 MASW test locations, 29 locations are found where SWV is reaching 760 m/s value. For each test location, all the 18 input motions are applied and the maximum and average amplification factors of each soil column are obtained. Thus, in total 18 x 29=522 nonlinear analyses are conducted. G/Gmax and damping curves for sandy soil given by Seed and Idriss (1970) are used for sandy soil layers. For clayey soil G/Gmax curve for different Plasticity Index (PI) are taken from Sun *et al.*, (1988). The damping curve of clay used in the analysis is taken from Seed and Idriss (1970). For dense soil having SWV of 760±60 m/s, G/Gmax curves for soft rock as given by Schnabel (1973) are used (Anbazhagan and Sitharam, 2008). From the analyses, two maps are generated showing surface PGA based on average amplification factor and maximum amplification factor as shown in Figure 14 and 15 respectively. It can be observed from Figure 14 that the surface PGA is varying from 0.1g to 0.45g for the average amplification factor. The distribution of surface PGA indicate that the northern part of Lucknow may experience maximum PGA of 0.45 g while the southern, central and the eastern parts of Lucknow comes under a surface range of 0.1g to 0.35g. The western part of Lucknow is showing the surface PGA in the range of 0.20g to 0.35g. Figure 15 shows the surface PGA map for Lucknow based on maximum amplification factor from 18 input motions. It can be observed from the Figure 15 that the surface PGA is ranging from 0.12g to 0.72g with maximum PGA in northern parts of the city

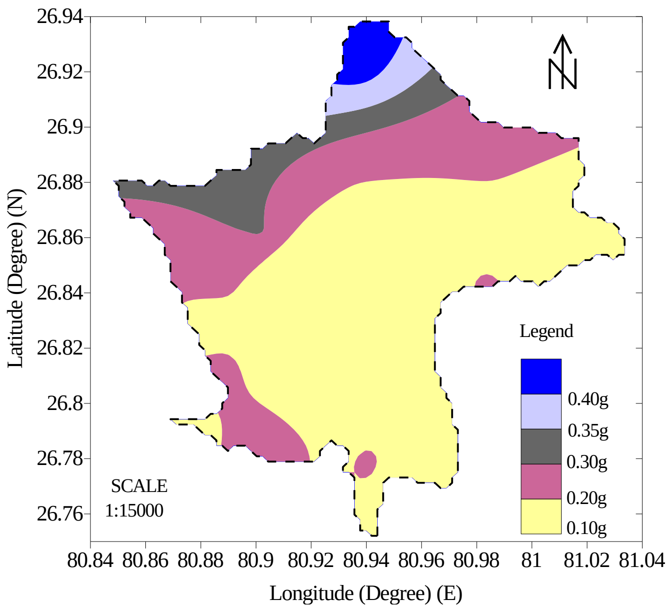

Fig 14 Surface PGA map based on average amplification for Lucknow

ranging from 0.60g to 0.72g. Further, the central, eastern and the southern parts are experiencing surface PGA of 0.12g to 0.36g. Other plots showing the variation of predominant frequency, amplification factor, period corresponding to maximum spectral acceleration are also determined. Due to limited length of the paper, all outputs have not been discussed here.

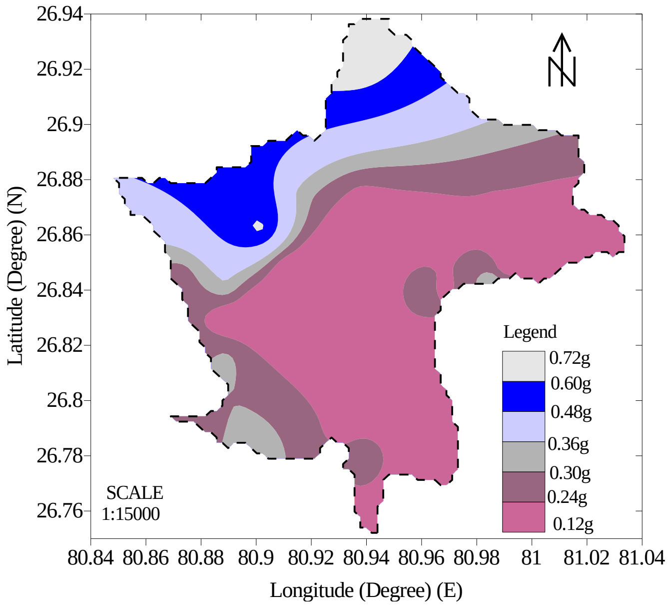

Fig 15 Surface PGA map based on maximum amplification for Lucknow

The final outcome of any site specific response analysis is the design response spectrum which provides the design acceleration for a particular building. In this design spectrum at Lucknow city center has developed considering amplified spectral parameters and compared with Eurocode 8(2002), International Building code (IBC, 2009) and IS1893:2002. Figure 16 shows average response spectrum at surface considering 18 input ground motion. It can be found from Figure 16 that within short period (≤0.25 s), the response spectra from the present study is closely matching with the design response spectra of codes. Similarly for higher periods (≥ 1 s), the response spectra is matching closely with IS1893:2002 and other codal provisions. However, for intermediate periods (0.25s to 1s), the response spectra based on present work is giving higher values. Most of the codal provisions have been developed based on 30 m site class information in the respective region. Moreover, IS1893:2002 design spectrum does not account the detailed geotechnical soil classification in design spectrum. Differences between proposed spectrum and codes spectrum may be attributed by the above reasons needs detailed study in this direction.

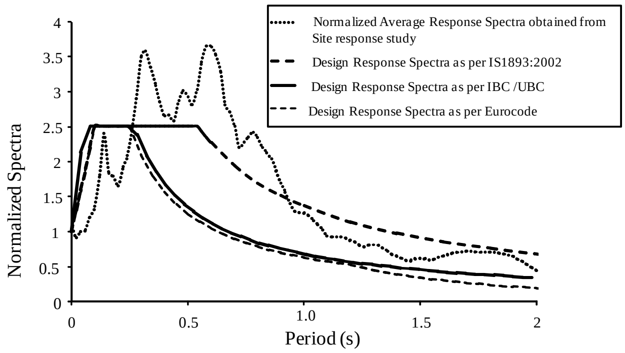

Fig 16 Comparison of typical normalized response spectra obtained from the present study with codal based design response spectra.

Estimation of Liquefaction potential of Lucknow

Ground shaking induced during an earthquake causes large amount of vibrations for buildings and for subsoil as well. Subsoil shaking results in differential settlement in building foundations, sinking of pavements, railway lines etc. Failure of soil during an earthquake usually happens due to loss in shear strength of soil. This phenomenon is termed as Liquefaction where the shear resistance of soil is reduced significantly in comparison to shear stresses induced by an earthquake. This reduction in shear strength causes the soil to behave almost like a liquid. Further, such subsoil cannot withstand any overcoming load on it resulting in tremendous settlements, failures of foundation of buildings and bridge bridges, slope failures etc. The terminology of liquefaction came into existence after the occurrence of Good Friday earthquake of 1964 with Mw of 9.2 in Alaska followed by Nigata earthquake with Mw of 7.5 in Japan. These two earthquakes caused failure of slopes, sinking of bridge piers, tilting of houses, embankments, foundations, pavements and exposure of the buried structures. After 1964, the numerous examples are available where liquefaction had caused massive destruction. These may include 1971 San Fernando earthquake (Mw-6.6), 1977 Argetina earthquake (Ms-7.4), 1989 Loma Prieta earthquake (Mw-6.9), 1995 Great Hanshin earthquake (Mw-6.8), 1999 Chi-Chi earthquake (Mw- 7.6), 2001 Bhuj earthquake (Mw-7.6), 2004 Niigata-ken Chuetsu earthquake (Mw-6.8) and 2011 Sendia earthquake (Mw-8.9), 2011 Sikkim earthquake (Mw-6.8) and many more. In India, damage due to liquefaction on large scale has been noticed 26 January 2001 Bhuj earthquake (Mw-7.6). Sand blows was evident during 1819 Bhuj earthquake and sand dykes at Beltaghat site during 1897 Shillong earthquake (Rajendran and Rajendran, 2001). Paleo-liquefaction studies in Assam also confirm liquefaction failures during Assam earthquake (Sukhija *et al*., 1999) The above case studies are the examples where the sites undergone liquefaction damages are far from the epicentre. Considering the seismic hazard of Lucknow from local sources as well as the ongoing seismicity of the Himalayas, liquefaction of Lucknow is very much desired.

Subsoil properties obtained from the borehole indicates the presence of low plasticity silts with high fine contents and sand with N-SPT of 15 up to a depth of 20 m. At further deep, N-SPT is further reduced to values of 10 or 12. Variation in the bulk density for this borehole has been found in the range of 1.86g/cc at the ground surface to 2.06g/cc at 30 m depth. Recorded N-SPT till 12 m depth suggested the presence of soft soil and thus there are chances of possible Liquefaction at this location. However, detailed analyses are needed to confirm these explanations.

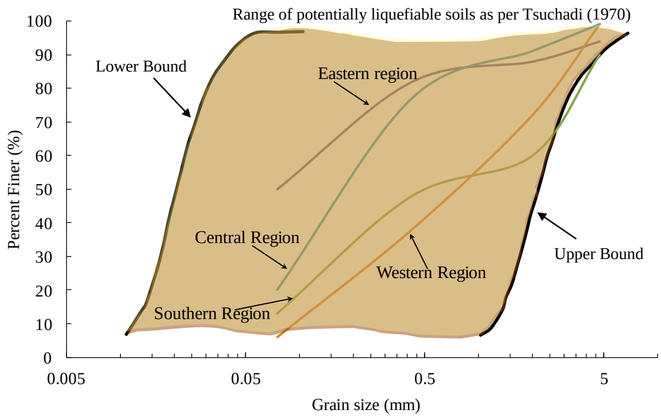

Fig 17 Comparison of grain size distribution curve of soils taken from different regions of Lucknow soil with the range of potentially liquefiable soils by Tsuchida (1970)

Also, the alignment of River Gomati shows the presence of sandy soil at shallow depths in many locations which highlights idea condition for the liquefaction. In another attempt, typical grain size distribution curves obtained from different parts of Lucknow are compared with the possible range of grain size distribution curves for possibly liquefiable soils as per Tsuchida (1970) as shown in Figure 17. It can be seen from Figure 17 that all the particle distribution curves for Lucknow soil fall within the upper and lower range. This observation confirms that the soils available at Lucknow are liquefiable.

In order to estimate the Factor of Safety (FOS) against liquefaction, simplified approach of Seed and Idriss (1970) is used. Detailed discussion on the liquefaction for Lucknow soil can be found in Abhishek *et al.*, (2013) and has not been discussed here to control the length of the paper. All the measured N-SPT from the boreholes are corrected from different corrections such as overburden correction, boreholes diameter correction, liner correction, rod length correction , hammer energy correction and fine content correction. Corrected N-SPT for fine content correction $[(N_1)_{60CS}]$ are used in the estimation of Cyclic Resistance Ratio (CRR). Further, surface PGA obtained from site response analysis as given in Figure 14 and 15 are used to determine the Cyclic Stress Ratio (CSR). The value of magnitude scaling factor (MSF) to be used in estimating the factor of safety (FOS) against liquefaction is estimated using the magnitude value which is giving maximum amplification in site

Table 1 Values of Factor of Safety and severity Index of Liquefaction

Group	Factor of Safety	Severity Index
1	0.0-0.7	Very Critical
2	0.7-1.2	Critical
3	1.2-1.5	Low critical
4	>1.5	Non-liquefiable

response analysis. For this work, MSF is calculated for magnitude of 6.8. Two maps representing FOS based on average amplification and maximum amplification in accordance with Figure 14 and 15are presented in Figure 18 and 19. Further based on Table 1, the site can be classified from very critical to liquefaction occurrence to non-

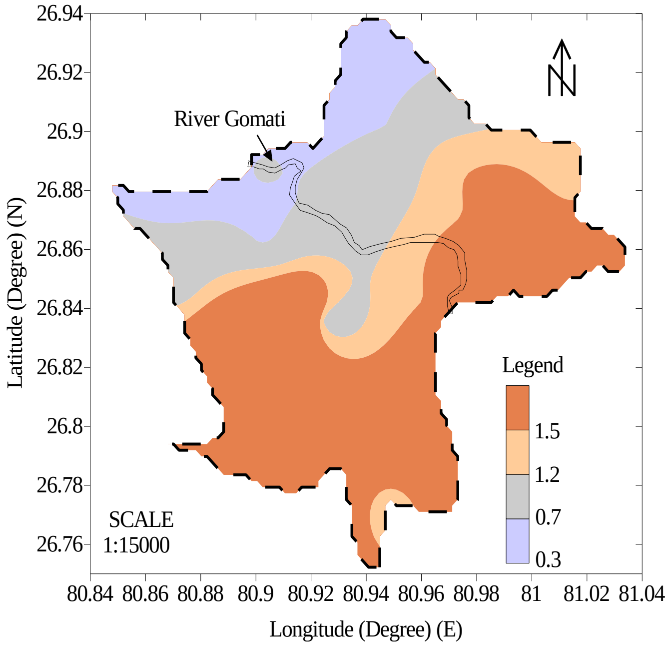

Fig 18 Map showing the FOS against Liquefaction for Lucknow based on average amplification

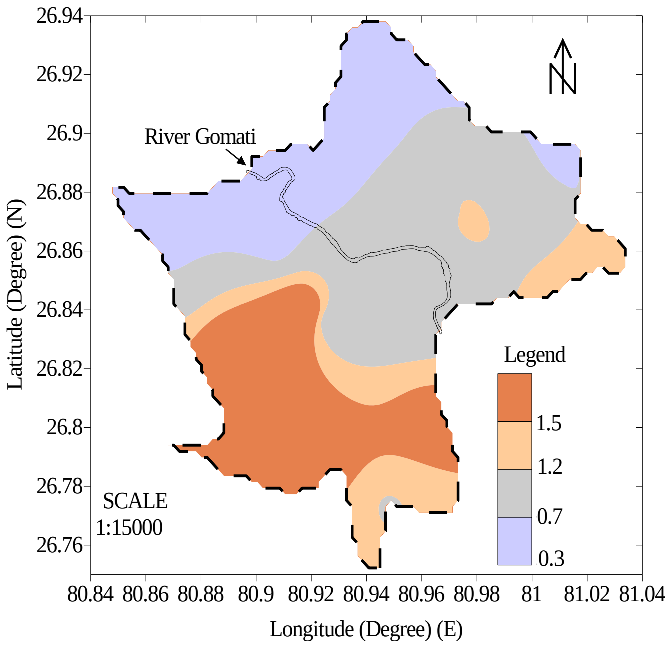

Fig 19 Map showing the FOS against Liquefaction for Lucknow based on maximum amplification

liquefiable. It can be seen from Figure 18 that the northern area of the city is having the minimum FOS ranging from 0.5 to 0.7 while the central and the western parts are showing the moderate FOS ranging from0.7 to 1.2. The southern and the eastern part of Lucknow come under high FOS above 1.5. It can be observed that the majority of Gomati comes under FOS < 1.2. A small approach of river Gomati near to Lohia path adjacent to Gomati barrage is showing the FOS > 1.5. Measured N-SPT values from this borehole show a variation from 9 to 20. These values show presence of soft to stiff soil at this location. Again, based on the maximum amplification, a map showing the distribution of FOS for Lucknow has been presented in Figure 19. As per the Figure 19, most of the city area is showing the FOS < 1.2. Observing the alignment of river Gomati similar to Figure 18 indicates that the whole Gomati River is having FOS from 0.3 to 1.2. Also, northern region of the city is showing FOS < 0.7 which indicates that the northern region of Lucknow is very critical to liquefaction.

Once, the quantification of seismic hazard, local site effects and induced effects, controlling parameters across Lucknow are available. These can be treated as various layers to develop the seismic microzonation map of Lucknow which is discussed in the next section.

DEVELOPMENT OF SEISMIC MICROZONATION MAPS FOR LUCKNOW CITY

Seismic microzonation is a broad term consisting of categorizing the whole study area into more and less hazard sites during earthquakes considering the geology, geomorphology, and seismological factors into account. Such studies are very valuable for city planning, identification of areas which are more prone to earthquake damages, vulnerability and risk assessment. It also provides useful information to locate important development infrastructure in a particular region with low seismic hazard. Seismic microzonation should show cumulative hazards of ground response analysis, slope instability and liquefaction potential. Earthquake hazards are governed by regional characteristics such as soil thickness, soil type, depositional geometry (valley or hill) etc. In addition to these attributes, a number of parameters which are related to earthquakes occurrence are also responsible for earthquake hazards. These are called as seismological parameters such as bedrock PGA, amplification factor, seismic site classification, predominant frequency, liquefaction, landslide and Tsunami. Weight given to any parameter is a function of region and depends upon the decision maker. Since, the area of Lucknow lies in thick overburden IGB, two different parameters which account for soil type and overburden thickness up to very dense layer have been considered in the form of 30 m average shear wave velocity (V_S^{30}) and average shear wave velocity up to a depth where the shear wave velocity is 760 ± 60m/s. The second parameter has been referenced as V_s^{760}. These parameters have been considered as the representation of geological attributes in the present study. Various seismological attributes considered are; i) Bedrock PGA based on DSHA and PSHA, ii) amplification factor, iii) VS30, iv) Vs760, v) FOS against liquefaction and vi) predominant frequency (PF). In total sex attributes are used in this work. Table 2 represents all the sex attributes and weights assigned to each of them based on their relative importance. Higher weights are given to attribute which is contributing maximum to the earthquake hazard and so on. Analytical Hierarchy Process (AHP) by Saaty

Table 2 Themes and weights assigned for geological and seismological attributes considered for final microzonation

Index	Themes	Weights
PGA	Rock level PGA using DSHA-DPGA	6
	Rock level PGA using PSHA 2%-PPGA2%	6
	Rock level PGA using PSHA 10%-PPGA10%	6
AF	Amplification factor	5
V_s^{30}	Equivalent Shear wave velocity for 30 depth	4
Vs^{760}	Average shear wave velocity till a depth where shear wave velocity if reaching 760±60 m/s	3
FS	Factor of safety against liquefaction	2
PF	Predominant period / frequency	1

(1980) is estimating the normalized weights and ranks for each of the above discussed attributed. Once, the normalized weights and ranks are determined, values of hazard index are estimated.

These hazard index are used to develop the seismic microzonation maps of Lucknow. Since, three bedrock maps are generated from seismic hazard, three microzonation maps are generated for Lucknow from this work.

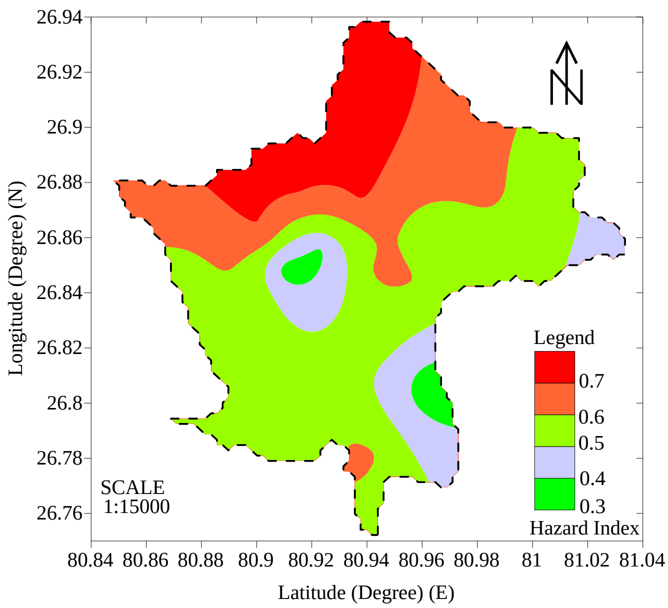

Fig 20 Deterministic seismic hazard analysis based seismic microzonation map of Lucknow

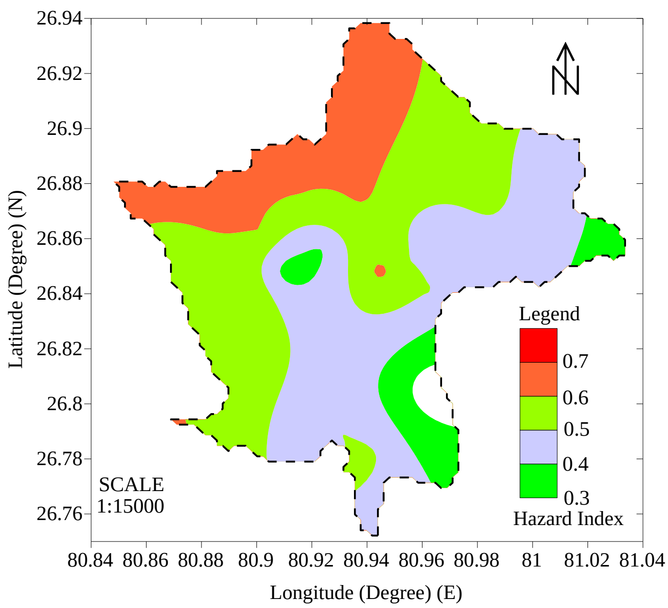

Fig 21 Seismic microzonation map of Lucknow based on 10 % probability of exceedence in 50 years

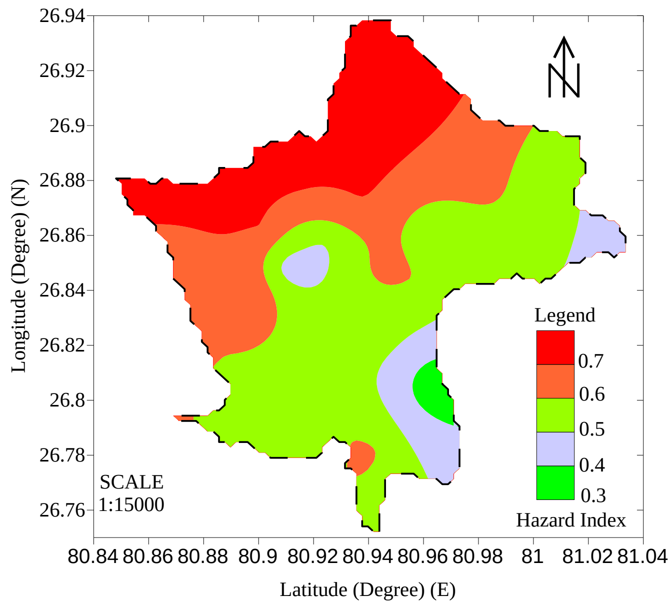

Fig 22 Seismic microzonation map of Lucknow based on 2 % probability of exceedence in 50 years

These represent DSHA based map, two maps based on PSHA fort 10 % probability of exceedence in 50 years and 2% probability of exceedence in 50 years. Figure 20, 21 and 22 represents all the three maps respectively. Based on Figure 20, it can be seen that the hazard index values vary from minimum value of 0.3 at some locations in southern part to a maximum value of 0.6 and above in the northern and western parts of Lucknow. Most part of the city falls in moderate hazard region with hazard index in the range of 0.5 to 0.6. Based on deterministic seismic microzonation map, eastern and central parts of Lucknow comes under low to moderate seismic hazard while the northern and western parts show high seismic hazard.
Further, observations from Figure 21 shows that the southern, eastern and the central parts of Lucknow shows hazard index in the range of 0.3 to 0.5 defining that these areas comes under low to moderate seismic hazard. However, northern and western parts show high seismic hazard with a hazard value of 0.6 and above. Based on this map also, the northern and western parts of Lucknow have been found with more hazard compared to other areas of Lucknow. Again, observing Figure 22, it can be said that areas which are located in the eastern parts and some portions of southern Lucknow come under low seismic hazard. However, a major portion is available in the central

and southern Lucknow where hazard index has reached in the range of 0.5 to 0.6 which denotes the area under moderate seismicity. Similar to Figure 20, northern and western parts of Lucknow comes under high hazard as observed from Figure 22.

Conclusion

In this paper detailed discussion of the present seismic scenario of Lucknow in the light of ongoing seismic activity of the central seismic gap in the Himalayan region and on Lucknow-Faizabad fault is presented. Limitations in the existing GMPEs for seismic hazard are highlighted. Based on existing database and simulation of new ground motions a new GMPE has been developed. Further, using three GMPEs including the new GMPE and other two highly ranked GMPEs detailed seismic hazard of Lucknow is attempted based on DSHA and PSHA. In order to explore local soil properties large number of field tests both geotechnical as well as geophysical are conducted at Lucknow. Based on the subsoil properties lithological cross-sections and seismic site classification for Lucknow soil are performed. Using the bedrock values of PGA from seismic hazard and the subsoil properties of Lucknow soil, a detailed site response analysis considering a wide range of ground motions are conducted based on which surface PGA maps and design response spectra for Lucknow is generated. Design response spectra are found comparative with codal provisions and other standards. Liquefaction assessment is attempted after highlighting the liquefaction potential of Lucknow soil. Based on simplified procedure, two maps showing FOS against liquefaction are developed showing major portion of Lucknow under liquefaction susceptibility along with entire alignment of river Gomati. In the end, considering six different attributes both geological and seismological, three microzonation maps are prepared for Lucknow highlighting that the northern and western parts of Lucknow are under high seismic hazard compared to other parts. This study is first of its kind where a new GMPE has been developed and used in the same analysis. Also, deep soil effects have been considered for the subsoil lithology. Deep soil response attempted is also first of its kind and can be used as a guideline for future works in IGB.

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