Prediction of Future Surface PGA in the States of Indo-Gangetic Basin Considering Site Specific Studies

P. Anbazhagan, Mohammad Rafiq Joo, Meer Mehran Rashid, and Ketan Bajaj

Abstract Indo-Gangetic Basin (IGB) is the major geographical region of India extending from Punjab to Bihar including Uttar Pradesh (UP) and Haryana. In this region, major earthquake damages have been reported in the past. Several attempts have been made for different site response studies and estimation of earthquake risk in the region. However, most of them consider only shallow soil information < 50 m and available ground motions. Present study attempts to analyze the spatial variation of peak ground acceleration (PGA) at surface for possible future scenario earthquakes in and around IGB. The earthquakes were identified based on past seismic gaps and studies whose magnitudes ranged from Mw 7.5 to Mw 9.0. The earthquakes were simulated for 270 sites with available shear wave velocity data throughout the IGB. Using proper input parameters of soil column profiles, shear wave velocity, depth of input motion, suitable shear modulus reduction and damping curves; the detailed analyses were carried out using DEEPSOIL. This paper arrives at spatial variation of PGA at surface due to individual earthquakes. The response (bedrock as well as surface PGA) of different states toward each earthquake has been tabulated. Sites in Bihar reflect average and maximum surface PGA 0.15 g and 0.68 g, Uttar Pradesh 0.10 g and 1.18 g, Punjab and Haryana 0.12 g and 0.62 g respectively. These values are indicative of the sensitiveness toward earthquake damages. Maps representing surface PGA for each scenario earthquake were plotted giving detailed information about the surface seismic hazard of the area associated with each earthquake.

Keywords PGA · Indo-Gangetic Basin · IGB · Site response · Bed rock

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1 Introduction and Study Area

Indo-Gangetic Basin, consisting of thick alluvial deposits, lies between longitude 77 E and 88 E and latitude 24 N and 30 N. It covers an area of around 2,50,000 km^2 and encompasses densely populated Indian states viz. Bihar, Punjab, Haryana and Uttar Pradesh as shown in Fig. 1. Its closeness to Himalayan boundary, presence of thick sedimentary deposits and higher amplification of seismic waves makes the area seismically vulnerable.

Several researchers in India reported high seismic risk in the region. Ambraseys [1] reviewed the seismicity of North India during the early instrumentation period 1892–1915 and summarized evidences for 50 events. Khattri [2] also studied three seismic gaps in the Himalayan Plate boundary which can lead to potential future earthquakes.

In the recent past, researchers have made several advances in site response studies. Anbazhagan et al. [3] used borehole data and synthetic ground motions to study limited sites for 1999 Chamoli earthquake. Researchers [4–8] considered limited locally recorded ground motions for site response studies and Kumar et al. [9] used worldwide recorded ground motion for the site-response study irrespective of seismic background of IGB.

Literature survey reveals that site response studies are mostly limited to 30 m soil column depth using limited recorded motions. For the first time, our study has attempted to carry out site response studies for different possible futuristic earthquakes with suitable input soil parameters. In the present work, 16 possible earthquakes with varying parameters were identified and subsequently used to generate

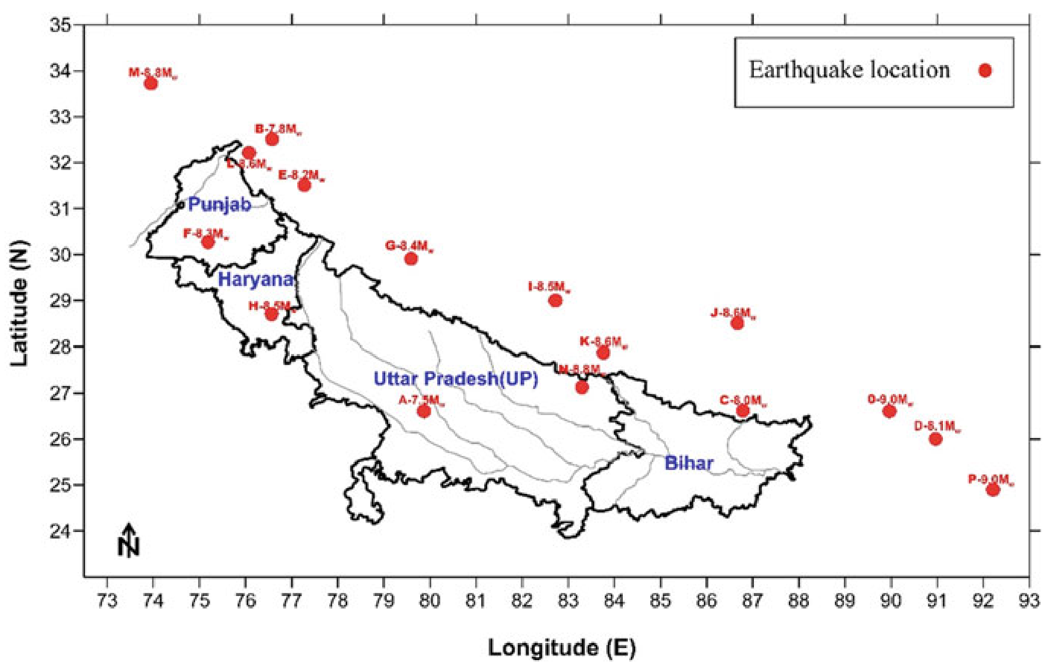

Fig. 1 Study area and earthquakes considered

synthetic ground motions for analysis. Contour maps illustrating variation of estimated surface PGA for each individual earthquake were developed. Wide range of PGA was observed corresponding to different earthquakes. Further each site exhibited different behavior toward different earthquakes. Sites in Bihar reflect average and maximum surface PGA 0.15 g and 0.68 g, Uttar Pradesh 0.10 g and 1.18 g, Punjab and Haryana 0.12 g and 0.62 g respectively. On an average, the percentage of sites hit by earthquakes in Bihar, Punjab and Haryana and UP are 38%, 35% and 37% respectively.

2 Simulation of Input Motions and Bedrock PGA

Synthetic ground motions are widely used for ground response studies, development of attenuation relationships, mapping of seismic hazards and amplification studies. To analyze 270 sites for identified seismic sources, ground motions at every site corresponding to each scenario earthquake were considered. This was done using EXSIM [10] taking into account seismotectonic parameters of the study area. The magnitudes of the identified earthquakes range between Mw 7.5 to 9.0, originating in and around IGB as depicted in Fig. 1. The detailed parameters of the earthquakes can be found from Ref. [11] and their locations and magnitudes can also be referred from Fig. 1. The ground motions used for analysis have varying parameters viz. frequency content, acceleration and duration. The bedrock PGA ranged between 0.0005 and 0.2996 g in Bihar, 0.0001 and 0.5771 in UP, 0.0003 and 0.6509 g in Punjab and Haryana. In whole IGB bedrock PGA varied from 0.0001 to 0.6509 g.

3 Input Soil Parameters

To analyze the sites with varying characteristics over IGB, different soil parameters viz nature of soil, density, shear wave velocity profiles and depth of input motion have been used as per provisions suggested by researchers. Shear wave velocity (Vs) as described by [12] while considering representative density from Vs of each layer [13], reliable depth level of input motion [14] and selected shear modulus reduction and damping curves as suggested by [15, 16]. The representative curves suggested have been therefore used to present site response studies of deep sites of IGB. In case of rock or hard layer, EPRI curve [17] and Zhang curve [18] have been used depending on whether $Vs \geq 800$ m/s or $Vs < 800$ m/s respectively for deposits of Quaternary type. For gravel sites with known particle size, Menq curve [19] has been used otherwise Zhang et al. [18] for deep gravel profiles. Zhang Curve [18] has also been used for deep sand deposits. For deep clay and silt sites, Darendeli curve [20] has been used.

4 Site Response Analysis and Surface PGA

For a given motion, PGA is the highest value of horizontal acceleration obtained from the accelerogram. Generally, horizontal accelerations describe ground motions because of their natural connection to inertial forces. It has been observed that ground motions with high peak accelerations are usually more damaging in nature. Site response analysis establishes the impact on ground surface motion due to the soils above the bedrock. Site response analysis finds its use in predicting ground surface motions for development of design response spectra, estimating liquefaction hazards and to measure earthquake induced forces. It requires the information of different field parameters like type, thickness and density of soil layers, shear wave velocity profiles, location of water table, depth of bedrock, shear modulus reduction and damping ratios. While designing any structure, it becomes important to know about the behavior of the soil column toward the incoming ground motions. The response influences the level of shaking which in turn governs the damage caused to the infrastructure in the area. To assess the site response, we simulated 16 earthquakes for 58 sites of Bihar, 136 sites of UP and 76 sites for Punjab and Haryana. Only those input motions which surpassed bedrock PGA 0.005 g were utilized in the study as the input motions and with PGA below 0.005 g were found ineffective in causing any significant damage to the infrastructure. 1D (one dimensional) nonlinear site response studies were carried out using DEEPSOIL V7 [21] and the results obtained are discussed in the subsequent section.

5 Results and Discussions

Seismic waves undergo amplification on traveling from bedrock to ground surface. Hence, parameters viz. peak ground acceleration, peak spectral acceleration, duration and frequency content associated with ground motions at surface differ from that at bedrock level or any hard layer. These modifications in seismic motions are site dependent and vary considerably from site to site. In present study, spatial variation of surface PGA corresponding to each earthquake has been shown. Surface PGA values due to each earthquake for UP, Bihar, Haryana and Punjab are summarized. These states showed varied levels of PGA and this behavior can be correlated to the magnitude, depth of fault, hypocentral distance, directivity, nature of soil deposits. Also, the PGA varied within the states giving rise to different hazard levels. The state wise analysis for future probable scenario earthquakes is briefly discussed below.

In Bihar, out of sixteen earthquakes considered, only nine have potential to generate bedrock PGA > 0.005 g and have therefore been used in site response analysis of 58 sites. The other seven earthquakes may be regarded having no or very little effect in the state. The highest bedrock PGA observed is 0.30 g in the state. The bedrock PGA is significantly amplified and goes as high as 0.68 g at surface. The PGA distribution for individual earthquakes is mapped in Figs. 2, 3, 4, 5, 6, 7,

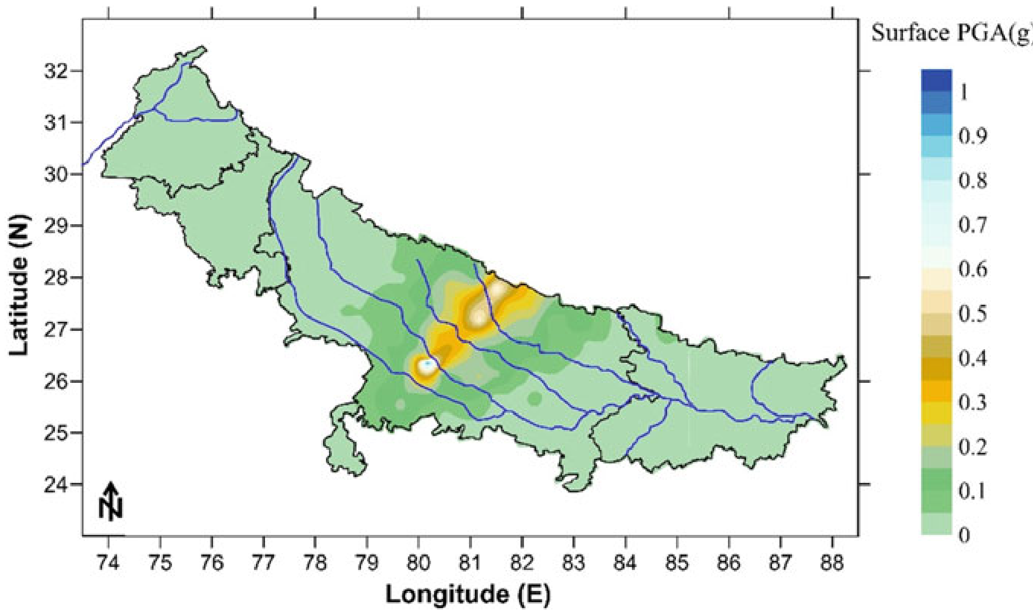

Fig. 2 Spatial variation of surface PGA for earthquake A

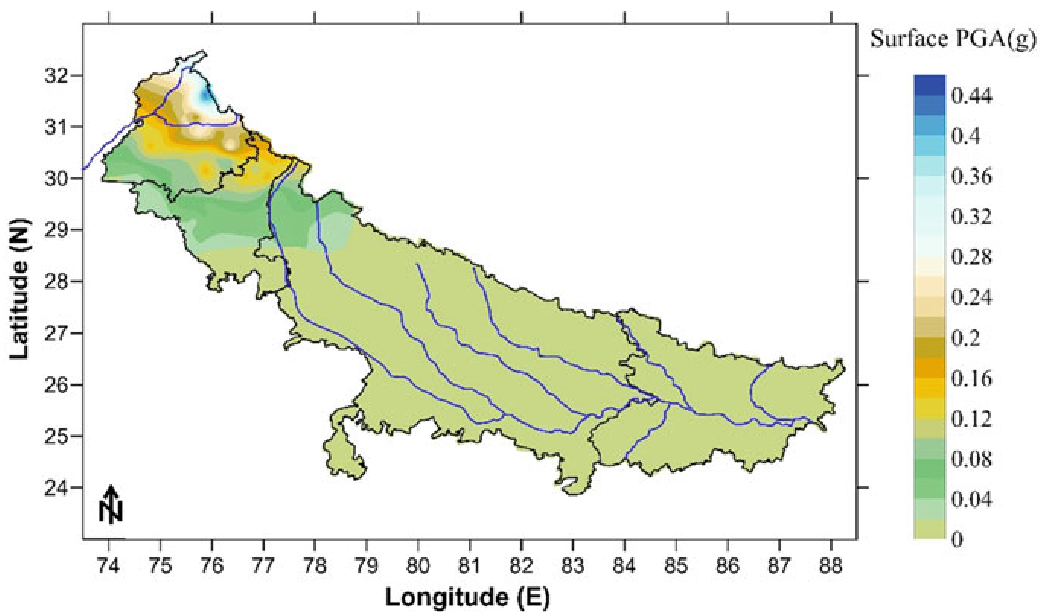

Fig. 3 Spatial variation of surface PGA for earthquake B

8, 9, 10, 11, 12, 13, 14, 15, 16 and 17. The surface PGA ranges from 0.007 to 0.68 g. Average surface PGA corresponding to each of 9 earthquakes are 0.03, 0.27, 0.1, 0.04, 0.17, 0.06, 0.30, 0.06 and 0.03 g. Earthquakes labeled as C and N affect 100% of the sites in Bihar and have a potential to generate surface PGA > 0.5 g at certain sites. Around 77% of analyzed sites in Bihar show average surface PGA > 0.1 g. The detailed information may be referred from Table 1.

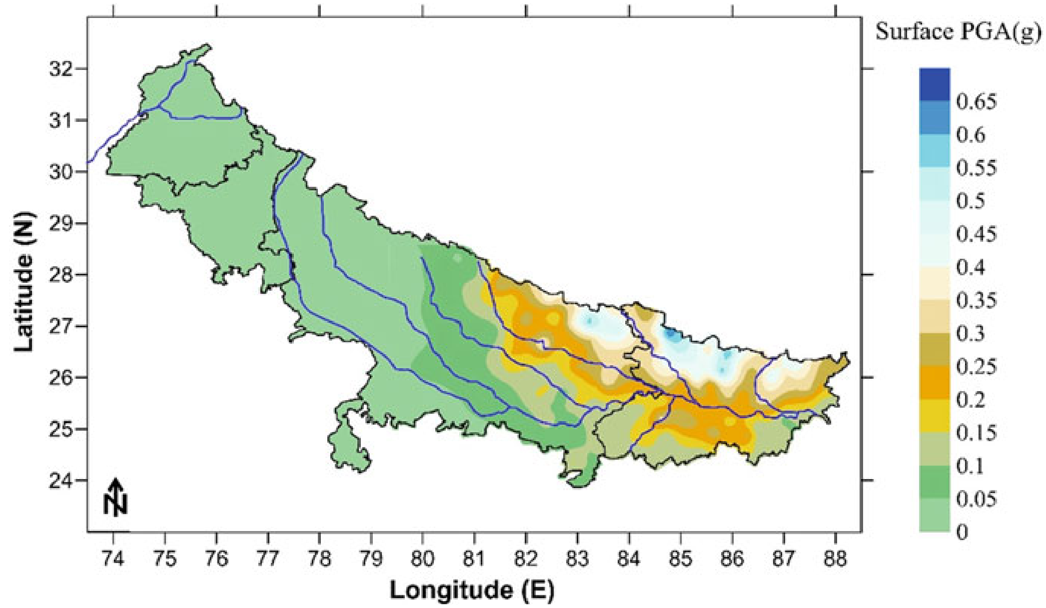

Fig. 4 Spatial variation of surface PGA for earthquake C

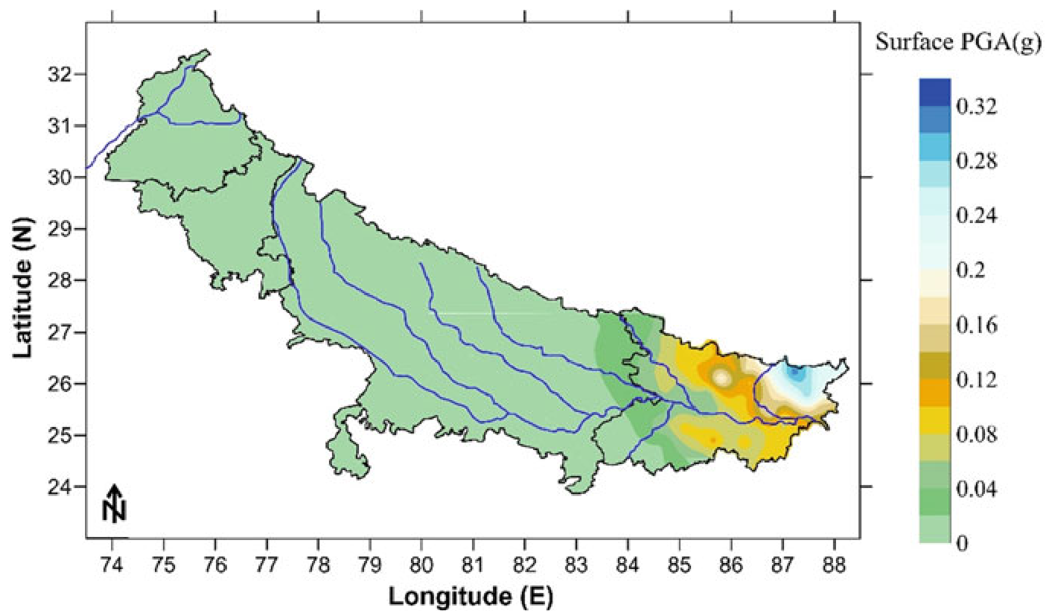

Fig. 5 Spatial variation of surface PGA for earthquake D

For Punjab and Haryana, eight earthquakes as listed in Table 2 were found to produce bedrock PGA > 0.005 g. The bedrock PGA varies between 0.0003 g and 0.6509 g. Ground motions (with PGA > 0.005 g) were inputted at sites in Punjab and Haryana to study site effects and arrive at distribution of surface PGA. Spatial variation due to 8 individual earthquakes can be referred from Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17. Surface PGA also varies significantly for different

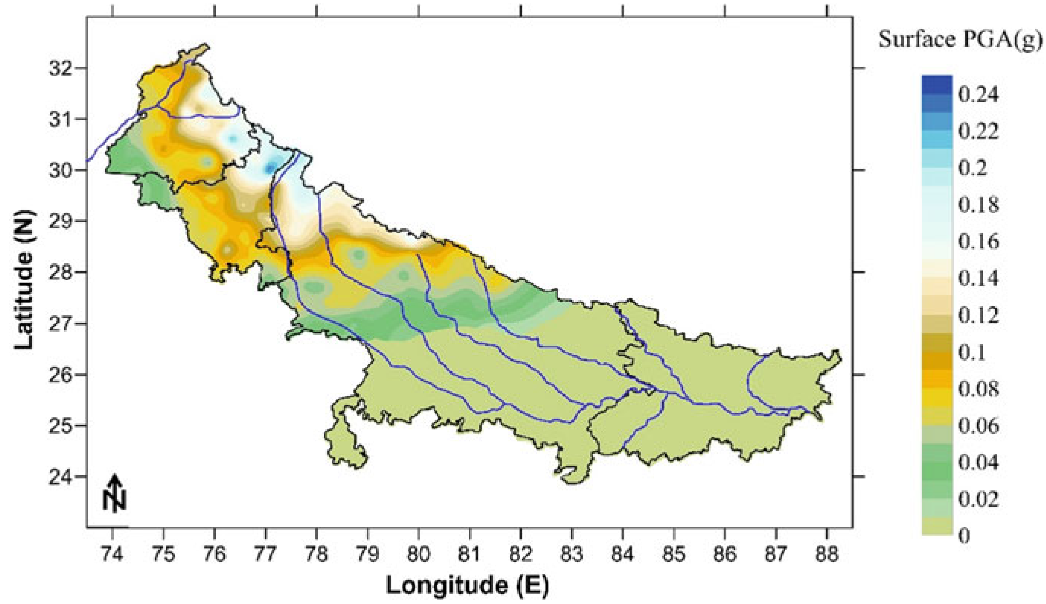

Fig. 6 Spatial variation of surface PGA for earthquake E

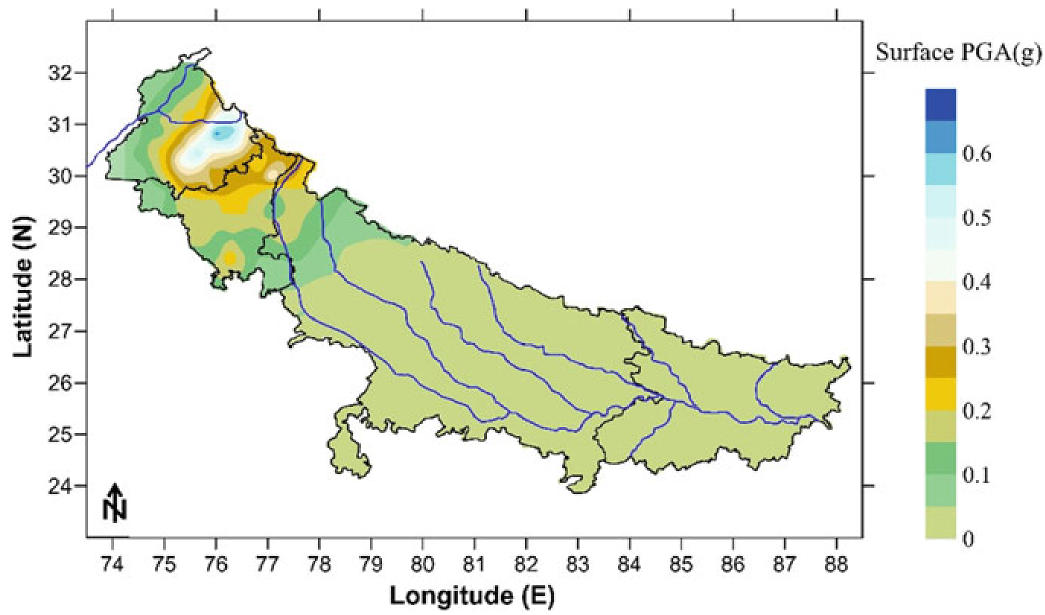

Fig. 7 Spatial variation of surface PGA for earthquake F

earthquakes and ranged in between 0.0011 g and 0.6238 g of surface PGA. The average values of surface PGA in the states due to selected earthquakes are 0.1285, 0.1030, 0.2174, 0.0319, 0.1254, 0.0018, 0.0769 and 0.0983 g. Earthquakes labeled as E, F and H respectively hit 97, 99 and 100% of sites in these states. Average PGA due to sources E, F and G are 0.1030, 0.2174 and 0.1254 g respectively. Structures in the area need specific provisions with respect to these seismic sources. About 65%

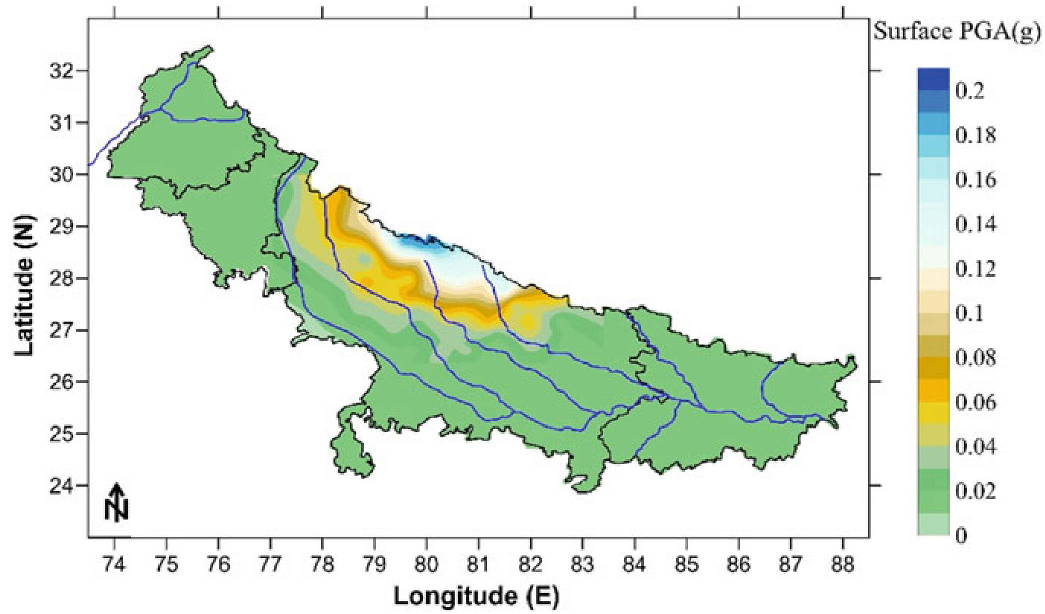

Fig. 8 Spatial variation of surface PGA for earthquake G

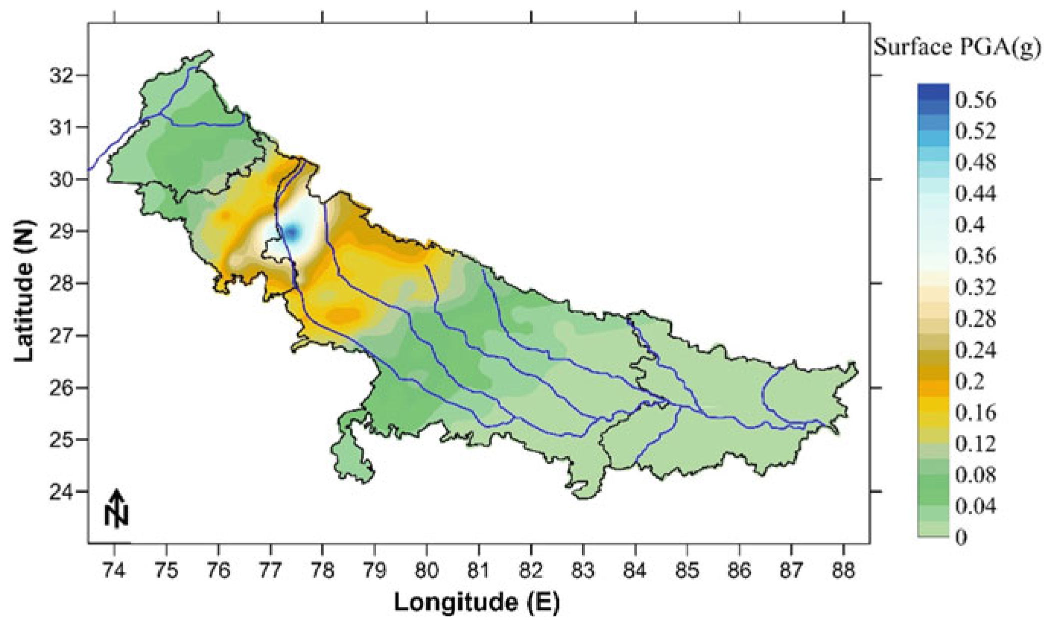

Fig. 9 Spatial variation of surface PGA for earthquake H

of sites analyzed in the region have average surface PGA > 0.1 g. Table 2 shows summary of results for Punjab and Haryana region.

Based on the same criteria, sites in Uttar Pradesh have been analyzed for thirteen seismic sources and surface PGA due to each considered earthquake has been evaluated. From the data obtained from DEEPSOIL program, spatial variation of surface PGA for each earthquake has been presented in Figs. 2, 3, 4, 5, 6, 7, 8,

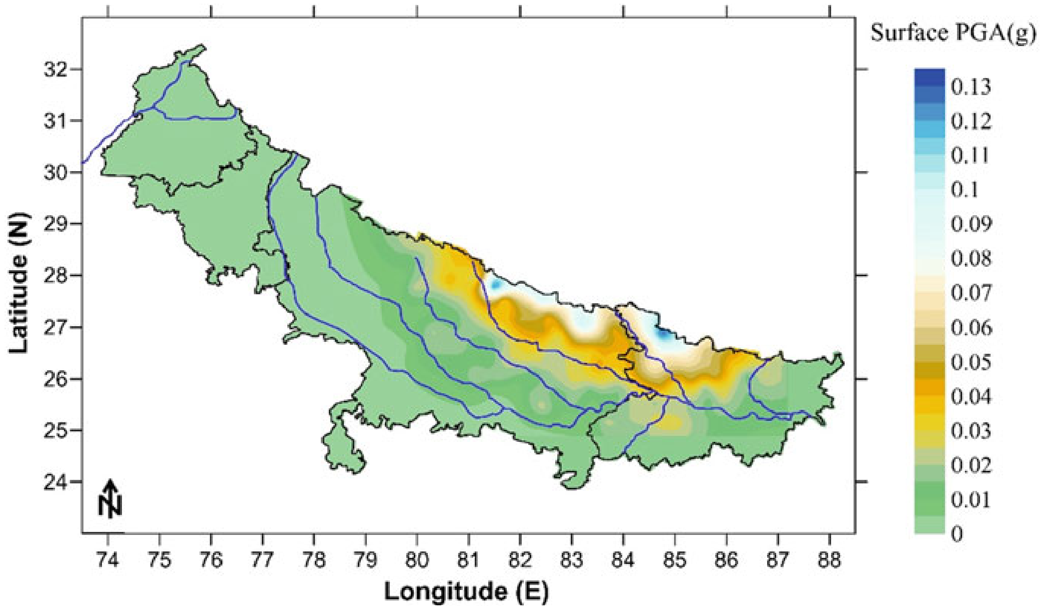

Fig. 10 Spatial variation of surface PGA for earthquake I

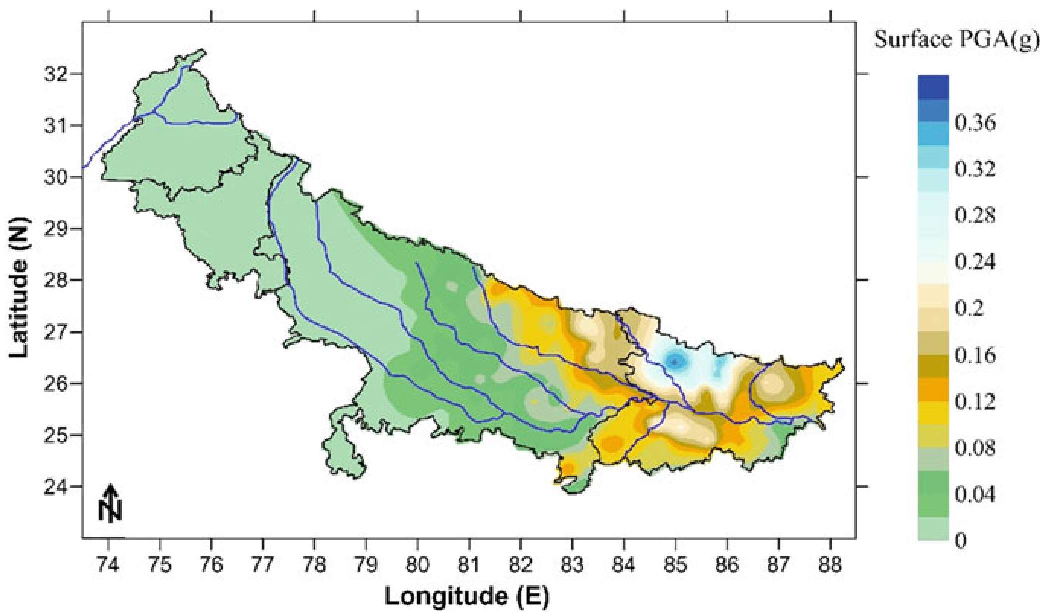

Fig. 11 Spatial variation of surface PGA for earthquake J

9, 10, 11, 12, 13, 14, 15, 16 and 17. A wide range of bedrock PGA is observed varying from 0.0001 g to 0.5771 g. Overall surface PGA for the state varies from 0.0018 g to 1.1827 g. The average values for each earthquake are 0.1096, 0.0420, 0.1504, 0.0205, 0.0669, 0.0556, 0.0578, 0.0924, 0.0260, 0.0724, 0.0208, 0.1912 and 0.1836 g as listed in Table 3. The sites in Uttar Pradesh show average PGA values lesser compared to Bihar, Punjab and Haryana and thus might be less prone to the

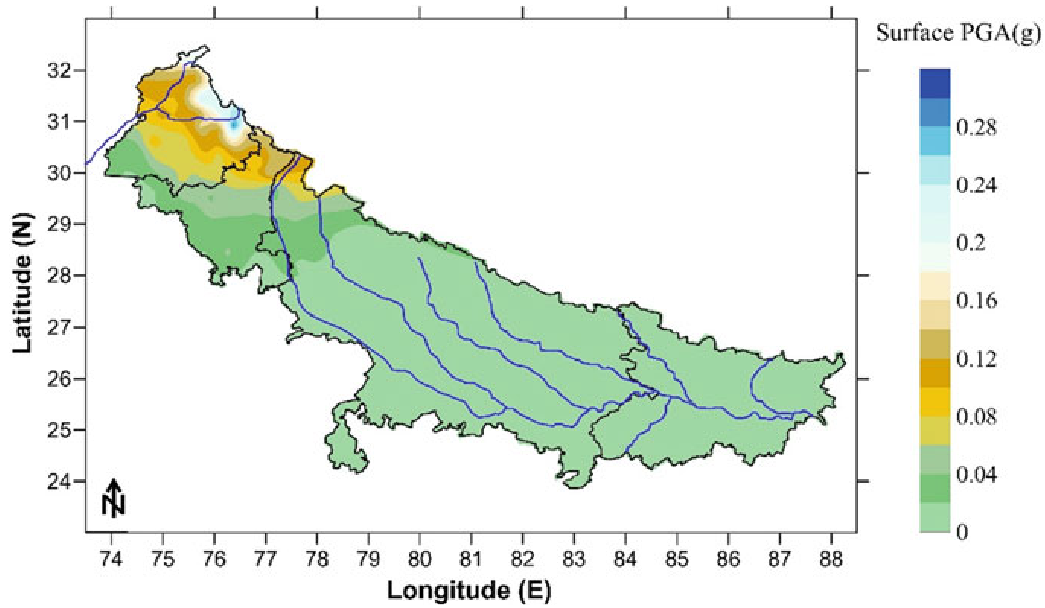

Fig. 12 Spatial variation of surface PGA for earthquake K

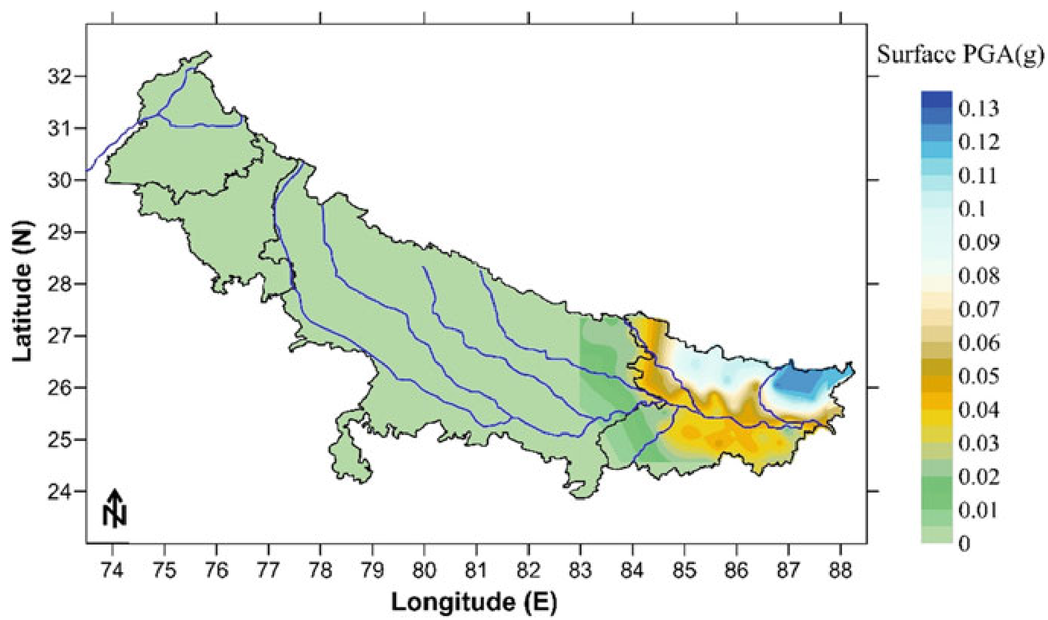

Fig. 13 Spatial variation of surface PGA for earthquake L

earthquake sources considered in this study. It is worth mentioning that surface PGA as high as > 1.0 g is observed for earthquakes 1 and 14 for few sites. Overall, 37% of analyzed sites show average surface values > 0.1 g.

Average surface PGA observed here is less as compared to PGA with respect to individual earthquakes. Overall average of 0.12 g is observed for the whole IGB which is quite different from state wise analysis. Average value of surface PGA

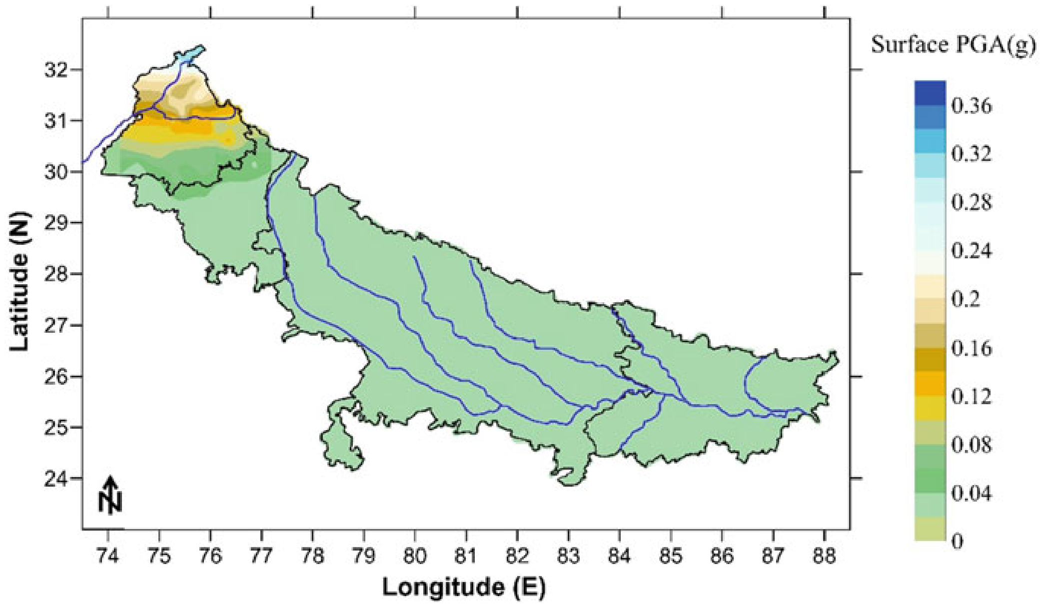

Fig. 14 Spatial variation of surface PGA for earthquake M

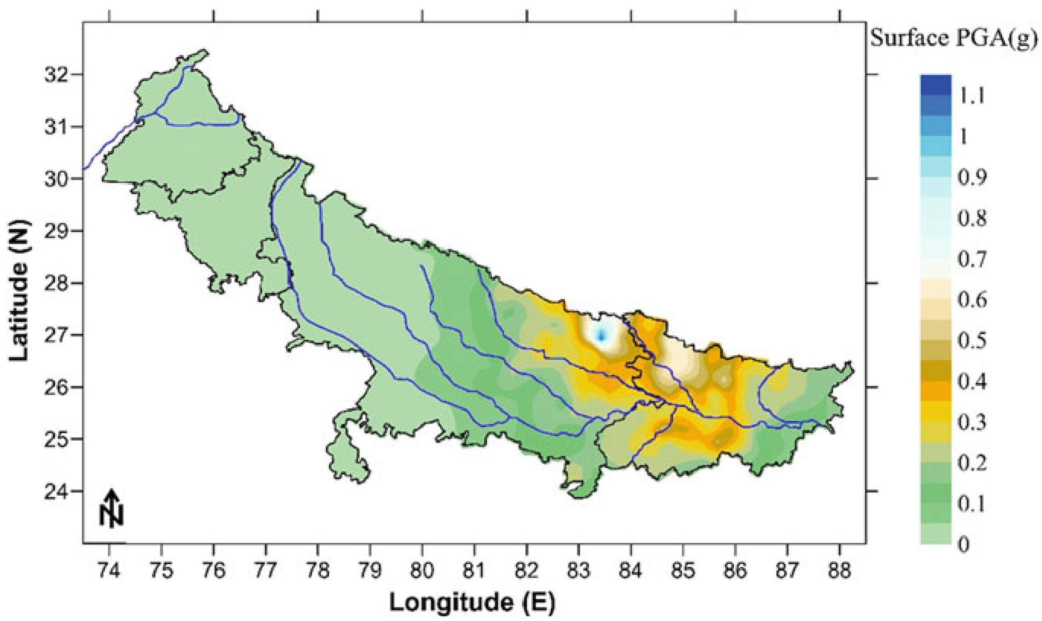

Fig. 15 Spatial variation of surface PGA for earthquake N

observed is as low as 0.014 g and as high as 0.32 g. An average value > 0.15 g is observed at a number of sites in IGB and therefore requires certain consideration in design of structures. The spatial variation may be referred from Fig. 18. Maximum surface PGA observed for IGB at any site is as high as 1.18 g and its spatial variation is shown in Fig. 19. A very smaller number of sites show maximum PGA > 0.7 g.

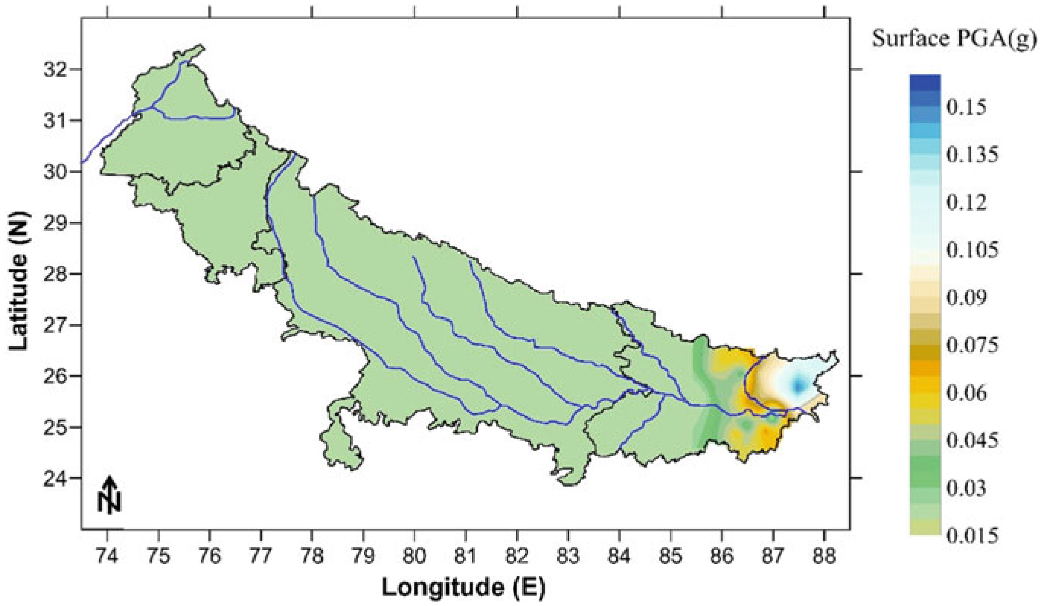

Fig. 16 Spatial variation of surface PGA for earthquake O

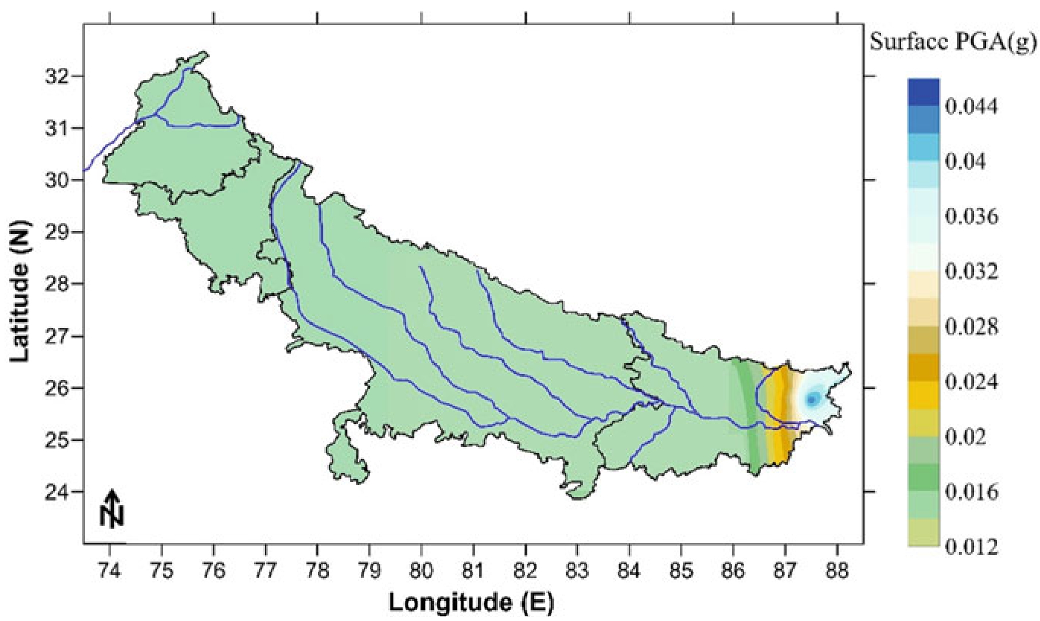

Fig. 17 Spatial variation of surface PGA for earthquake P

Majority of the sites show maximum PGA around 0.25 g. These maximum values may be referred for design of highly important structures, subjected to public use or national importance.

Table 1 Analysis of bedrock and surface PGA for Bihar

Earthquake	Bedrock PGA(g) range	Surface PGA(g) range	Average surface PGA(g)	Proportion (%) of sites
A	0.0005–0.0184	0.0093–0.0626	0.0316	21
C	0.0225–0.2996	0.0837–0.6546	0.2739	100
D	0.0021–0.1022	0.0215–0.3112	0.1005	89
I	0.0019–0.0468	0.0126–0.1310	0.0389	58
J	0.0267–0.1910	0.0311–0.3783	0.1671	98
L	0.0023–0.0463	0.0166–0.1266	0.0589	84
N	0.0289–0.3415	0.0599–0.6804	0.2985	100
O	0.0012–0.0428	0.0182–0.1518	0.0553	46
P	0.0008–0.0086	0.0122–0.0440	0.0280	12

Table 2 Analysis of bedrock and surface PGA for Punjab and Haryana

Earthquake	Bedrock PGA(g) range	Surface PGA(g) range	Average Surface PGA(g)	Proportion (%) of sites
B	0.0026–0.1383	0.0300–0.4319	0.1285	85
E	0.0102–0.0574	0.0297–0.2481	0.1030	97
F	0.0140–0.6509	0.0655–0.6238	0.2174	99
G	0.0004–0.0076	0.0229–0.0441	0.0319	8
H	0.0066–0.3302	0.0269–0.5875	0.1254	100
J	0.0003–0.0020	0.0011–0.0035	0.0018	5
K	0.0056–0.1040	0.0156–0.3087	0.0769	92
M	0.0012–0.1232	0.0208–0.3584	0.0983	67

6 Conclusion

1D nonlinear site response analyses for futuristic scenario earthquakes have been carried out at 270 sites covering UP, Punjab, Haryana and Bihar. Variation of estimated surface PGA for individual earthquakes has been deliberated using contour maps. Following are the main remarks concluded from the study:

- Wide range of bedrock PGA ranging from 0.0003 to 0.6509 g for Punjab and Haryana, 0.0005 to 0.2996 g for Bihar and 0.0001 to 0.5771 g for UP has been analyzed.
- Sites in Bihar reflect average and maximum surface PGA 0.15 and 0.68 g, Uttar Pradesh 0.10 and 1.18 g, Punjab and Haryana 0.12 and 0.62 g respectively.
- All the earthquakes hit varied proportion of sites in each state. On an average, the percentage of sites hit by earthquakes in Bihar, Punjab and Haryana and UP are 38, 35 and 37 respectively.

Table 3 Analysis of bedrock and surface PGA for Uttar Pradesh

Earthquake	Bedrock PGA(g) range	Surface PGA(g) range	Average surface PGA(g)	Proportion (%) of sites
A	0.0017–0.5771	0.0069–1.1593	0.1096	94
B	0.0001–0.0156	0.0266–0.0789	0.0420	4
C	0.0006–0.2534	0.0178–0.5983	0.1504	74
D	0.0001–0.0067	0.0029–0.0291	0.0205	3
E	0.0005–0.0522	0.0100–0.1919	0.0669	38
F	0.0002–0.0744	0.0148–0.1791	0.0556	19
G	0.0004–0.0466	0.0139–0.1846	0.0578	49
H	0.0010–0.3438	0.0093–0.4008	0.0924	67
I	0.0005–0.0561	0.0018–0.1319	0.0260	68
J	0.0013–0.1373	0.0116–0.2274	0.0724	78
K	0.0002–0.0322	0.0038–0.0684	0.0208	9
L	0.0002–0.0103	0.0137–0.0250	0.0192	8
N	0.0008–0.5105	0.0187–1.1827	0.1836	76

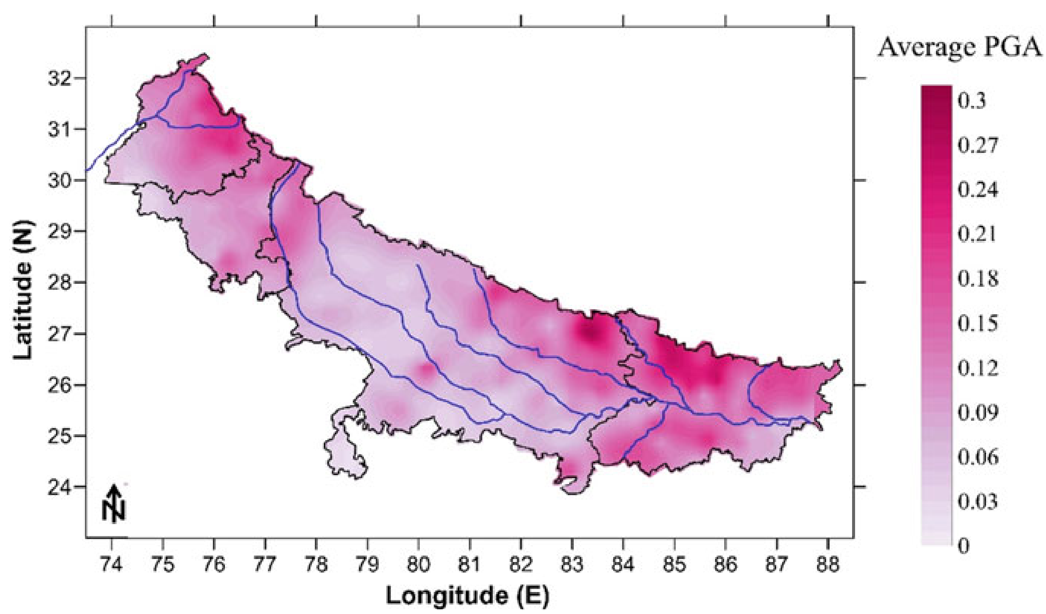

Fig. 18 Spatial variation of average surface PGA

- Earthquakes labeled as C, J and N have relatively higher impact on Bihar as they hit more than 90% of the sites, Punjab and Haryana show this response for earthquakes E, F, H and K while UP for A.
- Some of the earthquakes under consideration hit very little area (<10% of sites) viz. G and J for Punjab and Haryana, B, D, K and L for UP.

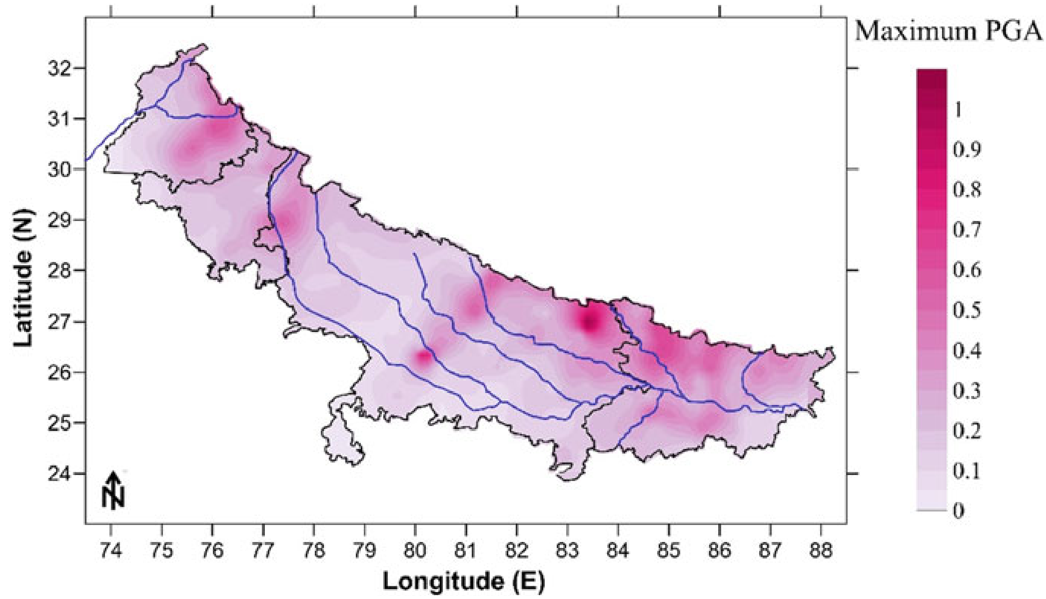

Fig. 19 Spatial variation of maximum surface PGA

- Higher surface PGA was observed for nearby seismic sources and have therefore higher expected damage level. These should be given due considerations while designing new structures in the area.
- PGA obtained from the study for futuristic earthquakes is much more than current seismic code of IS1893 [22].

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