Electronic Supplement of

Site Characterization, Seismic Hazard in Kashmir Himalaya to Northeast India: 1D/2D/3D Modeling, Microzonation and Damage Studies

Geoinformatics & Geostatistics: An Overview

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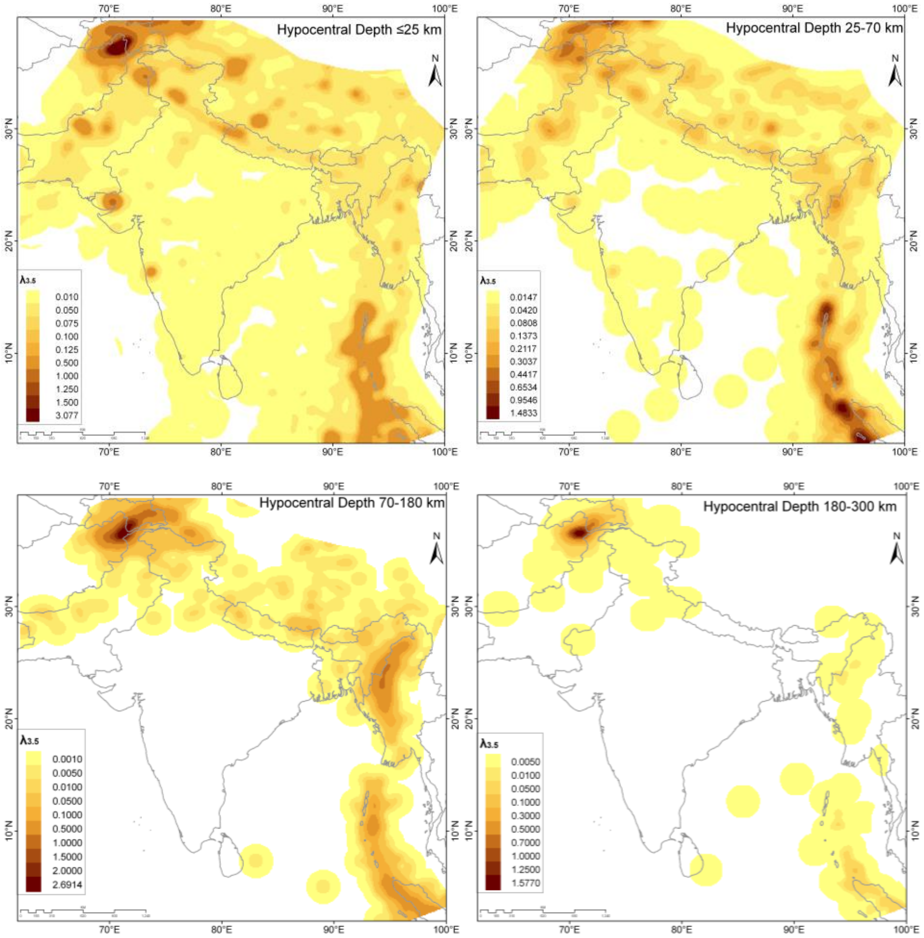


Figure S1: Representative smoothened gridded seismicity for the polygonal seismogenic sources of India and its surrounding region for the threshold magnitude of M_W 3.5 at the hypocentral depth range of (**a**) 0-25km, (**b**) 25-70km, (**c**) 70-180km and (**d**) 180-300km [1, 2].

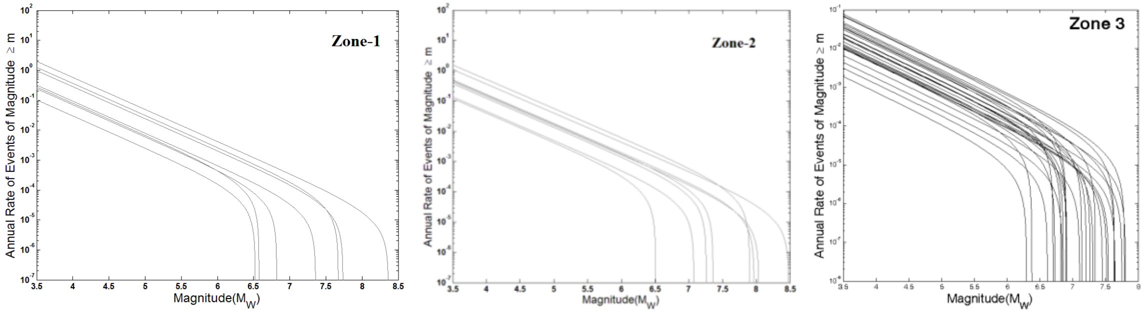
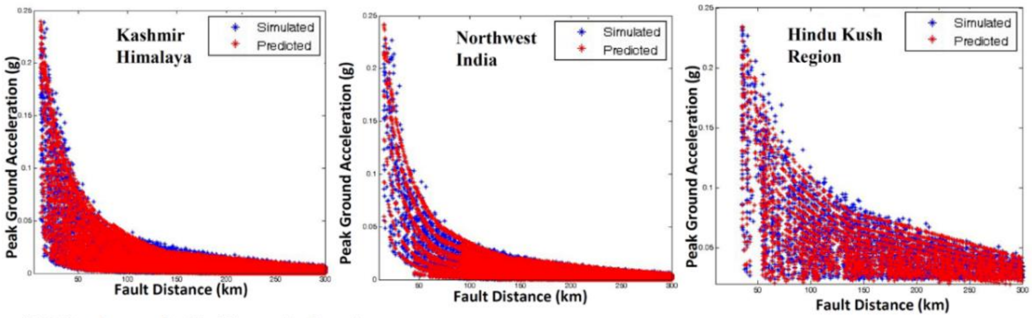


Figure S2: Representative annual activity rate versus magnitude for a group of active tectonic features inscribed in each polygonal areal seismogenic source at 0-25km focal depth range for threshold magnitude of M_W 3.5 [2].

Table S1: Selected Ground Motion Prediction Equations for PSHA of the Indian Peninsula comprising of eleven Seismogenic Tectonic Provinces shown in Figure 1 in the manuscript.

Seismogenic Tectonic Province	Seismogenic Sources	Global/Regional Ground Motion Prediction Equations (GMPEs)	Next Generation Attenuation (NGA) Models
Bengal Basin including Bangladesh	East-Central Himalaya	[3]; [4]; [5]	[2]; [6]; [7]
	Bengal Basin	[8]; [4]	[2]; [9]; [10]; [6]; [7]
	Northeast India	[11]; [5]; [12]	[2]; [13]; [12]; [6]; [7]
Indo-Gangetic Foredeep	Indo-Gangetic Foredeep	[14]; [15]; [16]	[2]; [17]; [6]; [7]
	Central Himalaya	[18]; [3]; [19]	[2]; [6]; [7]
	Central India	[8]; [4]; [14]	[2]; [6]; [7]
Koyna-Warna Region	Central India	[8]; [4]; [14]	[2]; [6]; [7]
	Kutch Region	[20]; [21]; [14]	[2]; [6]; [7]
	Koyna-Warna Region	[8]; [3]; [11]	[2]; [6]; [7]
Western Ghat Region	Western Ghat Region	[8]; [14]; [22]	[2]; [6]; [7]
	Eastern Ghat Region	[8]; [14]; [22]	[2]; [6]; [7]
	Koyna-Warna Region	[8]; [3]; [11]	[2]; [6]; [7]
Eastern Ghat Region	Western Ghat Region	[8]; [14]; [22]	[2]; [6]; [7]
	Eastern Ghat Region	[8]; [14]; [22]	[2]; [6]; [7]
	Koyna-Warna Region	[8]; [3]; [11]	[2]; [6]; [7]
Northwest India including Nepal Himalaya	Kashmir Himalaya	[18]; [16]; [23]	[2]; [6]; [7]
	Northwest India	[18]; [16]; [24]	[2]; [6]; [7]
	Hindu Kush Region	[18]; [14]; [11]	[2]; [6]; [7]
Darjeeling-Sikkim Himalaya	Normal Fault	[18]; [16]; [14]; [4]; [25]; [26]; [19]; [27]; [7]; [15]; [5]	[2]; [6]; [7]
	Reverse Fault	[18]; [16]; [14]; [4]; [25]; [26]; [19]; [27]; [7]; [15]; [5]; [3]; [12]	[2]; [28]; [6]; [7]
	Strike-slip Fault	[18]; [16]; [14]; [4]; [25]; [26]; [19]; [27]; [7]; [15]; [5]; [3]; [12]	[2]; [28]; [6]; [7]
Northeast India including Bhutan Himalaya	Eastern Himalayan Zone (EHZ)	[18]; [12]; [4]	[2]; [6]; [7]
	Mishmi Block Zone (MBZ)	[12]; [11]; [29]	[2]; [6]; [7]
	Eastern Boundary Zone (EBZ)	[30]; [29]; [11]	[2]; [6]; [7]
	Shillong Zone (SHZ)	[12]; [11]; [30]	[2]; [6]; [7]
Central India	Central India	[8]; [4]; [14]	[2]; [6]; [7]
	Kutch Region	[20]; [21]; [14]	[2]; [6]; [7]
	Koyna-Warna Region	[8]; [3]; [11]	[2]; [6]; [7]
Kutch Region	Central India	[8]; [4]; [14]	[2]; [6]; [7]
	Kutch Region	[20]; [21]; [14]	[2]; [6]; [7]
	Koyna-Warna Region	[8]; [3]; [11]	[2]; [6]; [7]
Kashmir Himalaya	Kashmir Himalaya	[18]; [16]; [23]	[2]; [6]; [7]
	Northwest India	[18]; [16]; [24]	[2]; [6]; [7]
	Hindu Kush Region	[18]; [16]; [11]	[2]; [6]; [7]

(a) Kashmir Himalaya Tectonic Province:



(b) Northwest India Tectonic Province:

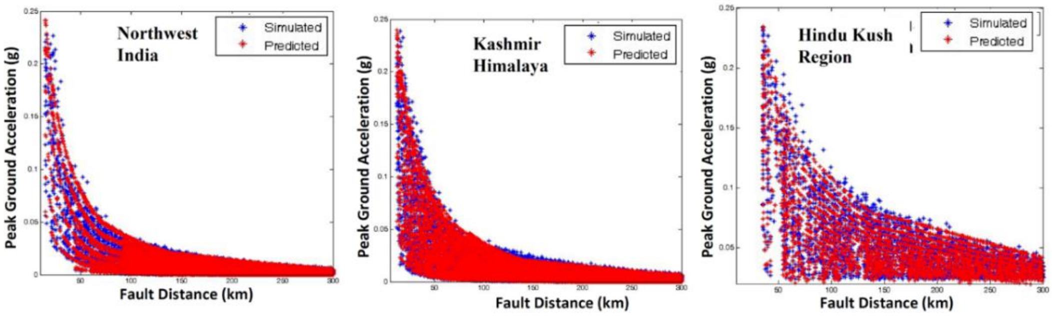
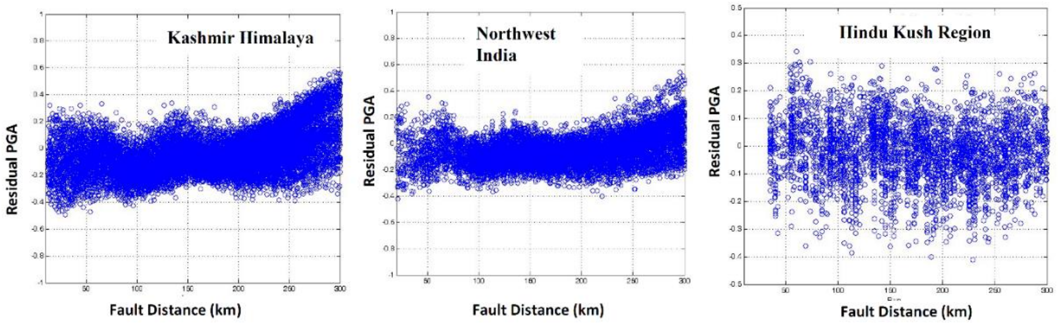


Figure S3: Peak Ground Acceleration (PGA) with respect to fault distance for corresponding seismogenic sources for the Tectonic Provinces of (**a**) Kashmir Himalaya, and (**b**) Northwest India including Nepal. The blue dots represent the simulated PGA; the red dots represent the estimated PGA from predicted NGA models of [7].

(a) Kashmir Himalaya Tectonic Province:



(b) Northwest India Tectonic Province:

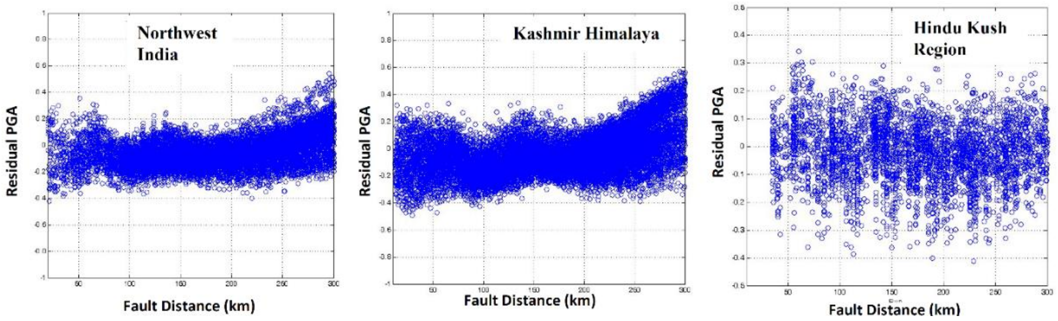


Figure S4: Residuals of PGA with respect to fault distance for corresponding seismogenic sources for the Tectonic Provinces of (**a**) Kashmir Himalaya, and (**b**) Northwest India considering NGA model of [7].

Table S2: The weights and ranks assigned to respective GMPEs based on the average LLH ranking in the three seismogenic source zones for Kashmir Himalaya Tectonic Province.

Kashmir Himalaya Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.1279	5	0.33
[7]; Present Study	2.1408	4	0.27
[23]	2.1505	3	0.20
[18]	2.2669	2	0.13
[16]	2.4501	1	0.07
Northwest India Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.1020	5	0.33
[7]; Present Study	2.1599	4	0.27
[24]	2.2276	3	0.20
[18]	2.2561	2	0.13
[16]	2.2733	1	0.07
Hindu Kush Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.2503	5	0.33
[7]; Present Study	2.2648	4	0.27
[18]	2.2791	3	0.20
[16]	2.4293	2	0.13
[11]	2.6283	1	0.07

Table S3: The weights and ranks assigned to respective GMPEs based on the average LLH ranking in the three seismogenic source zones for Northwest India Tectonic Province.

Kashmir Himalaya Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.1279	5	0.33
[7]; Present Study	2.1408	4	0.27
[23]	2.1505	3	0.20
[18]	2.2669	2	0.13
[16]	2.4501	1	0.07
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Model	LLH	Rank	Weight
[6]; Present Study	2.1020	5	0.33
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[24]	2.2276	3	0.20
[18]	2.2561	2	0.13
[16]	2.2733	1	0.07
Hindu Kush Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.2503	5	0.33
[7]; Present Study	2.2648	4	0.27
[18]	2.2791	3	0.20
[16]	2.4293	2	0.13
[11]	2.6283	1	0.07

Table S4: The weights and ranks assigned to respective GMPEs based on the average LLH ranking in the three seismogenic source zones for Indo-Gangetic Foredeep Tectonic Province.

Indo-Gangetic Foredeep Seismogenic Source			
Model	LLH	Rank	Weight
[6]; Present Study	2.144	5	0.33
[7]; Present Study	2.346	4	0.27
[14]	2.386	3	0.20
[15]	2.510	2	0.13
[16]	2.511	1	0.07

Central Himalaya Seismogenic Source			
Model	LLH	Rank	Weight
[6]; Present Study	2.482	5	0.33
[7]; Present Study	2.546	4	0.27
[3]	2.552	3	0.20
[18]	2.577	2	0.13
[19]	2.892	1	0.07
Central India Seismogenic Source			
Model	LLH	Rank	Weight
[6]; Present Study	2.201	5	0.33
[7]; Present Study	2.219	4	0.27
[4]	2.225	3	0.20
[14]	2.303	2	0.13
[8]	2.389	1	0.07

Table S5: The weights and ranks assigned to respective GMPEs based on the average LLH ranking in the three seismogenic source zones for Bengal Basin Tectonic Province.

Bengal Basin Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.169	4	0.4
[7]; Present Study	2.189	3	0.3
[8]	2.368	2	0.2
[4]	2.397	1	0.1
Northeast India Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.306	5	0.33
[7]; Present Study	2.331	4	0.27
[12]	2.370	3	0.20
[5]	2.545	2	0.13
[11]	2.670	1	0.07
East-Central Himalaya Seismogenic Source regime			
Model	LLH	Rank	Weight
[6]; Present Study	2.264	5	0.33
[7]; Present Study	2.296	4	0.27
[4]	2.371	3	0.20
[3]	2.412	2	0.13
[5]	2.712	1	0.07

Table S6: The weights and ranks assigned to respective GMPEs based on the average LLH ranking in the three seismogenic source zones for Darjeeling-Sikkim Himalaya Tectonic Province.

Strike-Slip Fault			
Model	LLH	Rank	Weight
[6]; Present Study	2.325	15	0.125
[7]; Present Study	2.357	14	0.117
[18]	2.363	13	0.108
[7]	2.401	12	0.100
[3]	2.421	11	0.092
[12]	2.436	10	0.083
[25]	2.434	9	0.075
[14]	2.441	8	0.067
[16]	2.476	7	0.058
[26]	2.483	6	0.050
[4]	2.552	5	0.042
[5]	2.592	4	0.033
[15]	2.652	3	0.025
[19]	2.742	2	0.017
[27]	2.987	1	0.008
Reverse Fault			

Model	LLH	Rank	Weight
[6]; Present Study	2.222	15	0.125
[7]; Present Study	2.285	14	0.117
[18]	2.345	13	0.108
[16]	2.389	12	0.100
[14]	2.405	11	0.092
[12]	2.495	10	0.083
[4]	2.496	9	0.075
[26]	2.497	8	0.067
[7]	2.504	7	0.058
[3]	2.536	6	0.050
[25]	2.636	5	0.042
[19]	2.657	4	0.033
[15]	2.822	3	0.025
[5]	2.977	2	0.017
[27]	3.078	1	0.008
Normal Fault			
Model	LLH	Rank	Weight
[6]; Present Study	2.037	13	0.143
[7]; Present Study	2.206	12	0.132
[18]	2.218	11	0.121
[16]	2.243	10	0.110
[14]	2.315	9	0.099
[4]	2.322	8	0.088
[25]	2.357	7	0.077
[26]	2.412	6	0.066
[19]	2.433	5	0.055
[27]	2.539	4	0.044
[7]	2.547	3	0.033
[15]	2.595	2	0.022
[5]	2.652	1	0.011

Table S7: The weights and ranks assigned to respective GMPEs based on the average LLH ranking in the four seismogenic zones for Northeast India Tectonic Province.

Eastern Himalayan Seismogenic Zone (EHZ)			
Model	LLH	Rank	Weight
[6]; Present Study	2.168	5	0.33
[7]; Present Study	2.236	4	0.27
[18]	2.268	3	0.20
[12]	2.438	2	0.13
[4]	2.656	1	0.07
Mishmi Block Seismogenic Zone (MBZ)			
Model	LLH	Rank	Weight
[6]; Present Study	2.243	5	0.33
[7]; Present Study	2.333	4	0.27
[12]	2.570	3	0.20
[11]	2.573	2	0.13
[29]	2.760	1	0.07
Eastern Boundary Seismogenic Zone (EBZ)			
Model	LLH	Rank	Weight
[6]; Present Study	2.369	5	0.33
[7]; Present Study	2.370	4	0.27
[30]	2.635	3	0.20
[29]	2.712	2	0.13
[11]	2.786	1	0.07
Shillong Seismogenic Zone (SHZ)			
Model	LLH	Rank	Weight
[6]; Present Study	2.316	5	0.33

[7]; Present Study	2.323	4	0.27
[12]	2.425	3	0.20
[11]	2.705	2	0.13
[30]	2.748	1	0.07

Table S8: Pairwise comparison matrix and normalized weights assigned to the GMPEs used for Northwest India seismogenic source zone.

Model	[6]	[7]	[24]	[18]	[16]	Weight
[6]	1	5/4	5/3	5/2	5/1	0.33
[7]	4/5	1	4/3	4/2	4/1	0.27
[24]	3/5	3/4	1	3/2	3/1	0.20
[18]	2/5	2/4	2/3	1	2/1	0.13
[16]	1/5	1/4	1/3	1/2	1	0.07

Table S9: Comparison of Peak Ground Acceleration (PGA) for 10% probability of exceedance in 50 years from various literatures and the present study.

Sl. No.	**City Name**	**PGA(g) for 10% probability of exceedance in 50 years**				**Citation**
		[31] [zone]	**[1]**	**Present Study**	**Other Studies**	
1	Amritsar	0.12 [IV]	0.20-0.25	0.17-0.18	0.18 0.20-0.35 0.12	[32] [33] [34]
2	Bhubaneswar	0.08 [III]	0.04-0.08	0.07-0.08	0.05-0.08 0.04-0.06	[33] [35]
3	Chandigarh	0.12 [IV]	0.30-0.35	0.30-0.31	0.14-0.21 0.24 0.35-0.55	[36] [32] [33]
4	New Delhi	0.12 [IV]	0.20-0.25	0.19-0.20	0.27 0.00-0.37 0.2-0.35 0.18 0.07-0.33 0.10	[37] [38] [33] [39] [40] [41]
5	Guwahati	0.18 [V]	0.60-0.70	0.70-0.71	0.46 0.35-0.55 0.20-0.25 0.54-0.62	[42] [33] [43] [44]
6	Kolkata	0.08 [III]	0.12-0.16	0.13-0.14	0.13 0.08-0.20	[37] [33]
7	Lucknow	0.08 [III]	0.16-0.20	0.16-0.17	0.08-0.13 0.06	[33] [41]
8	Ranchi	0.05 [II]	0.12-0.16	0.05-0.15	0.04-0.06 0.13-0.20	[35] [33]
9	Patna	0.12 [IV]	0.20-0.25	0.14-0.15	0.11-0.15 0.08-0.13 0.04	[45] [33] [41]
10	Srinagar	0.18 [V]	0.08-0.12	0.36-0.37	0.22-0.27 0.39 0.06 0.35-0.55	[46] [34] [41] [33]
11	Varanasi	0.08 [III]	0.08-0.12	0.10-0.11	0.09-0.11 0.05-0.08	[18] [33]

12	Dhaka		0.20-0.25	0.23-0.24	0.14 0.29 0.13 0.15-0.20 0.27 0.13-0.20	[47] [48] [49] [50] [51] [33]
13	Chittagong		0.30-0.35	0.35-0.36	0.18 0.13 0.19 0.40-0.50 0.41	[47] [48] [49] [50] [51]
14	Jammu	0.12 [IV]	0.30-0.35	0.33-0.34	0.17-0.22 0.35-0.55	[46] [33]
15	Thimphu		0.25-0.30	0.35-0.37	0.55-0.60 0.20-0.35	[43] [33]
16	Kathmandu		0.45-0.5	0.50-0.51	0.51-0.55 0.75 0.35 0.52-0.57 0.08	[52] [53] [54] [55] [41]
17	Aizawl	0.18 [V]	0.50-0.55	0.54-0.56	0.35-0.55 0.15-0.20	[33] [43]
18	Imphal	0.18 [V]	0.60-0.70	0.68-0.69	0.20-0.25 0.55-0.90 0.90-1.50	[56] [33] [43]
19	Shillong	0.18 [V]	0.60-0.70	0.73-0.74	0.35-0.55 0.16 0.40-0.45	[33] [57] [43]
20	Gangtok	0.12 [IV]	0.30-0.35	0.36-0.38	0.43 0.35-0.55 0.55-0.60 0.08	[54] [33] [43] [41]
21	Agartala	0.18 [V]	0.25-0.30	0.28-0.29	0.20-0.35	[33]

Table S10: Comparison of Peak Ground Acceleration (PGA) for 2% probability of exceedance in 50 years from various literatures and the present study.

Sl. No.	**City Name**	**PGA(g) for 2% probability of exceedance in 50 years**			
		[1]	**Present Study**	**Other Studies**	**Citation**
1	Amritsar	0.25-0.40	0.40-0.42	0.25-0.3	[37]
2	Bhubaneswar	0.08-0.20	0.17-0.19	0.09-0.14 0.01	[35] [58]
3	Chandigarh	0.35-0.70	0.60-0.61	0.24-0.4	[36]
4	New Delhi	0.25-0.50	0.42-0.43	0.22 0.51 0.00-0.64 0.32 0.12-0.37 0.18	[59] [37] [38] [39] [40] [41]
5	Guwahati	0.70-1.30	0.85-0.87	0.78 0.83-0.93	[42] [44]
6	Kolkata	0.16-0.30	0.30-0.31	0.23	[37]
7	Lucknow	0.20-0.40	0.42-0.43	0.07-0.13 0.08	[60] [41]

8	Ranchi	0.30-0.40	0.28-0.30	0.09-0.14	[35]
9	Patna	0.25-0.40	0.31-0.33	0.05-0.44 0.3-0.38 0.08	[61] [45] [41]
10	Srinagar	0.30-0.40	0.58-0.60	0.69-0.70 0.37-0.47 0.08	[62] [46] [41]
11	Varanasi	0.30-0.40	0.25-0.27	0.03	[63]
12	Dhaka	0.50-0.60	0.39-0.40	0.30-0.40 0.55	[50] [51]
13	Chittagong	0.70-0.80	0.49-0.51	0.9-1.0 0.84	[50] [51]
14	Jammu	0.60-0.70	0.52-0.54	0.27-0.37	[46]
15	Kathmandu	0.90-1.00	0.76-0.78	1.00-1.07 0.66 0.81-0.90 1.00 0.18	[52] [53] [54] [55] [41]
16	Aizawl	1.00-1.10	0.72-0.73	0.13-0.20 0.22-0.32	[64] [44]
17	Imphal	1.30-1.40	0.97-0.99	0.3-1.1 0.14 0.32-0.42	[56] [65] [44]
18	Shillong	1.40-1.50	0.87-0.88	0.24 0.73-0.83	[57] [44]
19	Gangtok	0.60-0.70	0.69-0.70	0.62 0.18	[54] [41]
20	Agartala	0.50-0.60	0.45-0.46	0.20-0.27 0.42-0.52	[65] [44]

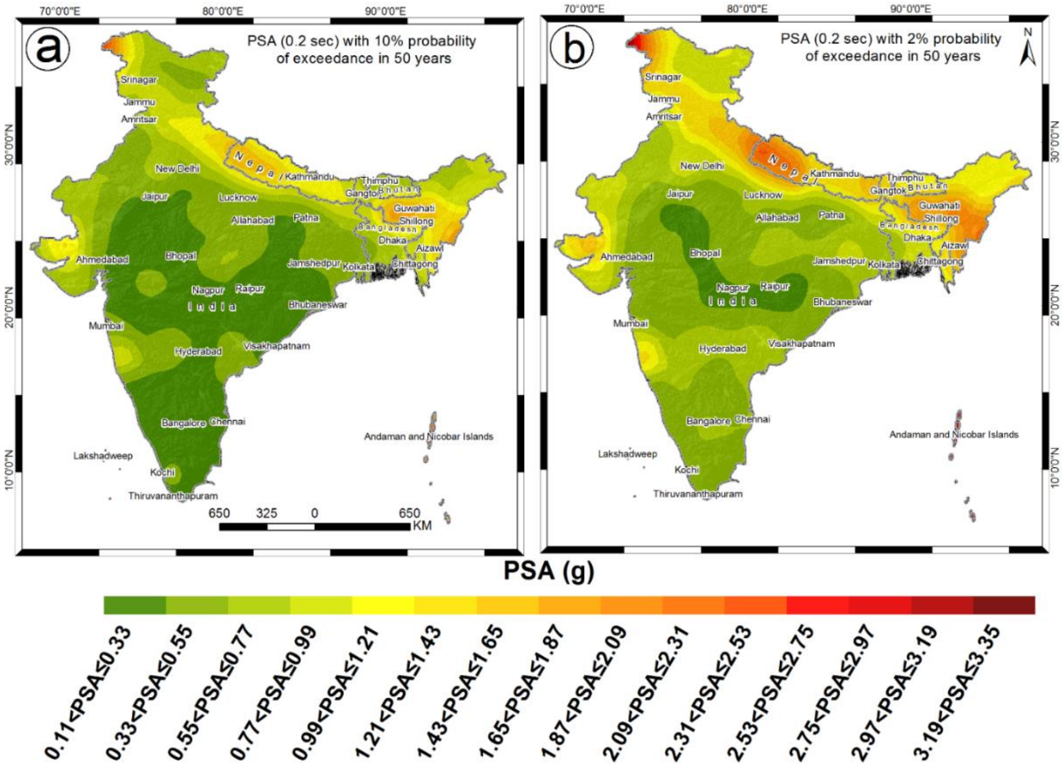


Figure S5: Probabilistic Seismic Hazard of India and its adjoining region in terms of PSA distribution for 0.2sec period for (**a**) 10% and (**b**) 2% probability of exceedance in 50 years at bedrock level.

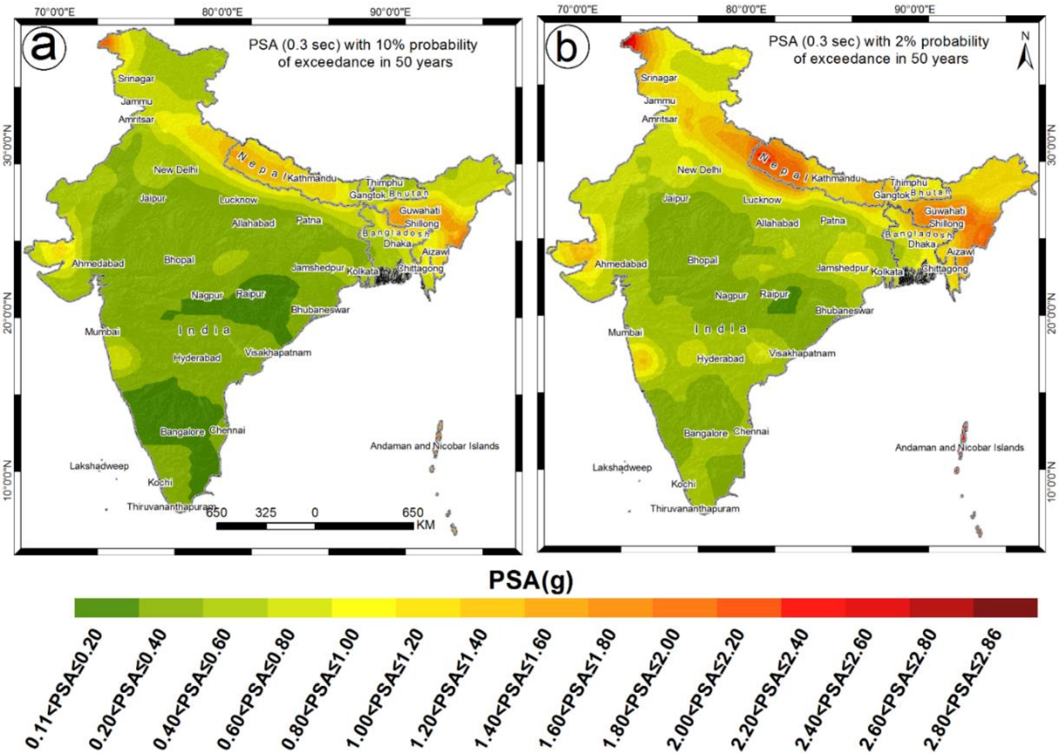


Figure S6: Probabilistic Seismic Hazard of India and its adjoining region in terms of PSA distribution for 0.3sec period for (**a**) 10% and (**b**) 2% probability of exceedance in 50 years at bedrock level.

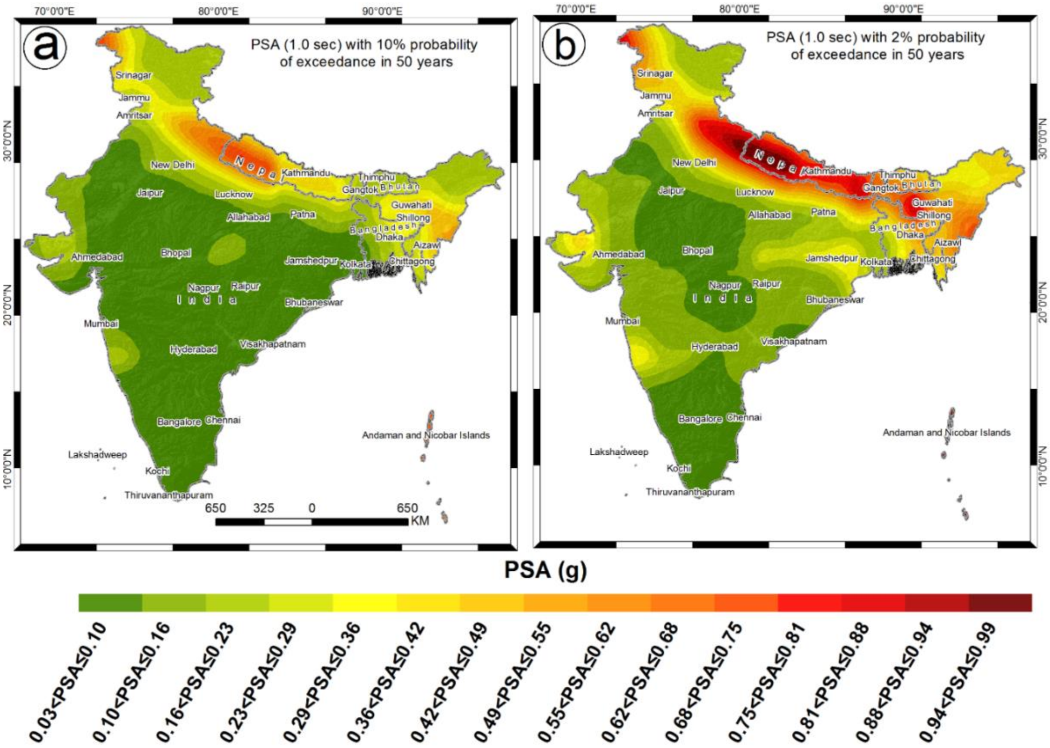
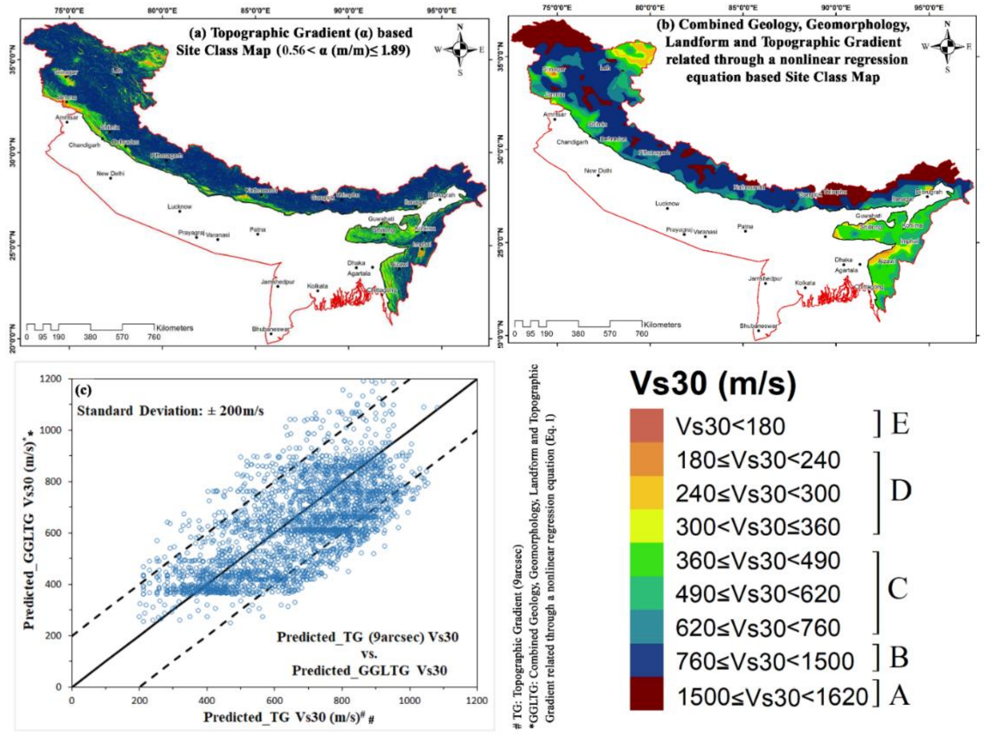


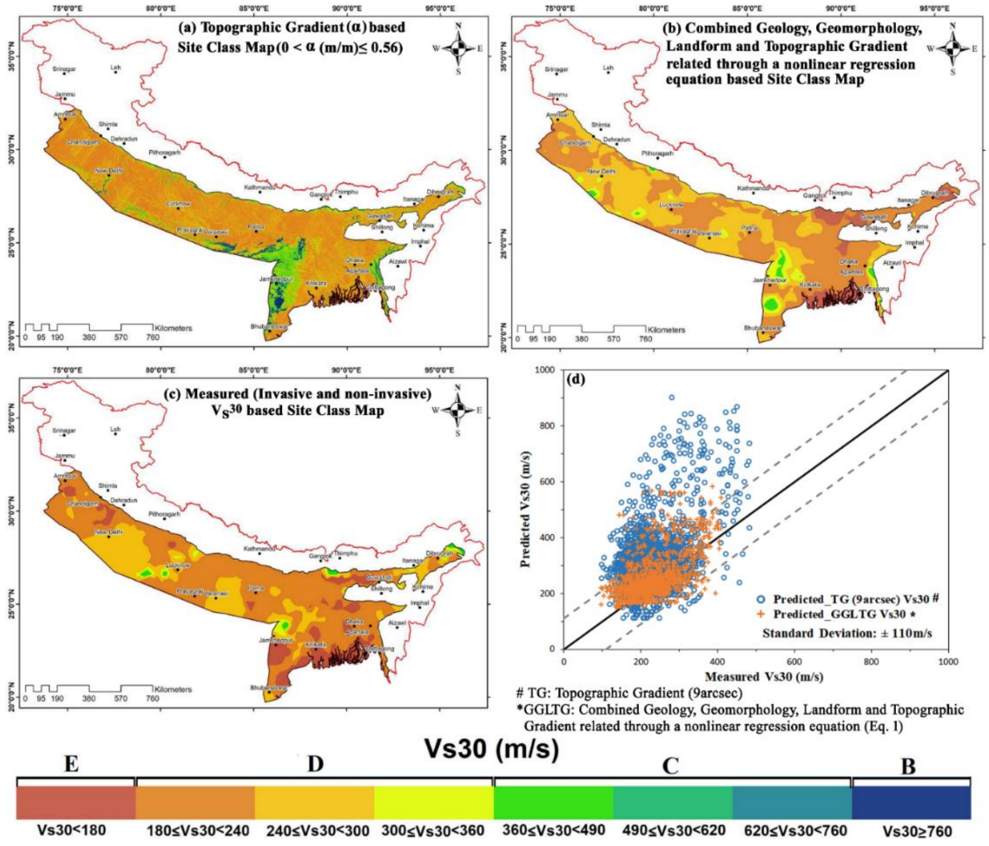
Figure S7: Probabilistic Seismic Hazard of India and its adjoining region in terms of PSA distribution for 1.0sec period for (**a**) 10% and (**b**) 2% probability of exceedance in 50 years at bedrock level.



TG: Topographic Gradient (9arcsec)

*GGLTG: Combined Geology, Geomorphology, Landform and Topographic Gradient related through a nonlinear regression equation (Eq. 1)

Figure S8: Site Classification maps of the high-altitude region from "Moderately Steep Slope" to "Escarpment/cliff" in the Tectonic Ensemble following NEHRP nomenclature based on (**a**) TG: Topographic-Gradient (α; 0.56< α(m/m) ≤ 1.89)-based V_S^{30} spatial distribution and (**b**) GGLTG: Geology, Geomorphology, Landform and Topographic Gradient regressed Polynomial relation-based site classification map together with the correlation plots in (**c**) between the Predicted_TG (9arcsec)-based V_S^{30} versus Predicted_GGLTG-based V_S^{30} demonstrating a good clustering along the 1:1 correspondence line with a standard deviation of ±200m/s.



TG: Topographic Gradient (9arcsec)

*GGLTG: Combined Geology, Geomorphology, Landform and Topographic Gradient related through a nonlinear regression equation (Eq. 1)

Figure S9: Site Classification maps of the low to mid-altitude regions in the Tectonic Ensemble following NEHRP nomenclature based on (**a**) Topographic-Gradient (TG) (α; $0< \alpha(m/m) \leq 0.56$), (**b**) Combined Geology, Geomorphology, Landform and Topographic Gradient GGLTG-based nonlinear regression proxy and (c) Measured (invasive and non-invasive) V_S^{30} along with the correlation plots amongst these three types of V_S^{30} i.e. (**d**) Predicted_TG-based (in blue circles) V_S^{30} and Predicted_GGLTG-based (in dark orange '+') V_S^{30} and measured V_S^{30}. A strong clustering has been exhibited between measured V_S^{30} and GGLTG-based V_S^{30} along the 1:1 correspondence line with a standard deviation of ±110m/s demarcated by dark orange points; in contrast as shown in the same diagram the Topographic Gradient TG-based V_S^{30} values show a large scattering with respect to the 1:1 correspondence line thus indicating an over-prediction of shear-wave velocity in comparison with the measured V_S^{30} designated by blue points in the same plot.

Table S11: Comparison of effective shear wave velocity (V_S^{30}) variation from various literatures and the present study.

Sl. No.	Location	V_S^{30} (m/s) Present study	V_S^{30} (m/s) Other studies	Reference
1	Amritsar	257-370	180-360	[66]
2	New Delhi	220-360	230-350 270-565	[67] [68]
3	Lucknow	204-391	230-470	[69]
4	Patna	198-356	180-270	[66]
5	Varanasi	191-356	180-360 221-692	[66] [70]
6	Kolkata	160-310	119-359	[10]
7	Dhaka	114-291	127-320	[71]
8	Chittagong	108-304	123-420	[72]
9	Jammu	250-470	340-390	[73]
10	Chandigarh	180-360	210-290	[74]
11	Kathmandu	112-368	366-490 148-298	[75] [76]
12	Guwahati	102-300	180-760	[77]
13	Aizawl	320-620	360-760 200-950	[78] [79]
14	Shillong	248-760	275-375	[80]
15	Agartala	120-240	180-360	[78]
16	Srinagar	140-380	<180-360 139-451	[81] [82]

Table S12: Comparison of Surface-consistent Probabilistic Peak Ground Acceleration (PGA) for 10% probability of exceedance in 50 years from various literatures and the present study.

Sl. No.	City Name	Surface-consistent PGA(g) for 10% probability of exceedance in 50 years		References
		Present Study	Other Studies	
1	Aizawl	0.51-0.72	0.60-0.70	[37]
2	Ambala	0.52-0.54	0.299 0.30-0.40	[83] [37]
3	Chandigarh	0.61-0.66	0.20-0.30 0.30-0.40	[36] [37]
4	Gangtok	0.41-0.45	0.70	[37]
5	Imphal	0.89-1.5	0.30-0.80 0.63	[84] [37]
6	Itanagar	0.54-0.61	0.60-0.70	[37]
7	Kohima	0.69-0.93	0.60-0.70	[37]
8	Kolkata	0.31-0.34	0.17-0.25 0.30-0.40 0.39	[9] [37] [10]
9	Lucknow	0.34-0.36	0.10-0.40 0.26-0.29 0.20-0.30	[37] [17] [37]

10	New Delhi	0.45-0.47	0.42 0.20	[37] [59]
11	Panipat	0.48-0.50	0.145 0.20-0.30	[83] [37]
12	Patna	0.31-0.34	0.22-0.24 0.20-0.30	[17] [37]
13	Srinagar	0.42-0.80	0.6-0.7	[37]
14	Varanasi	0.26-0.28	0.14-0.17 0.20-0.30	[17] [37]

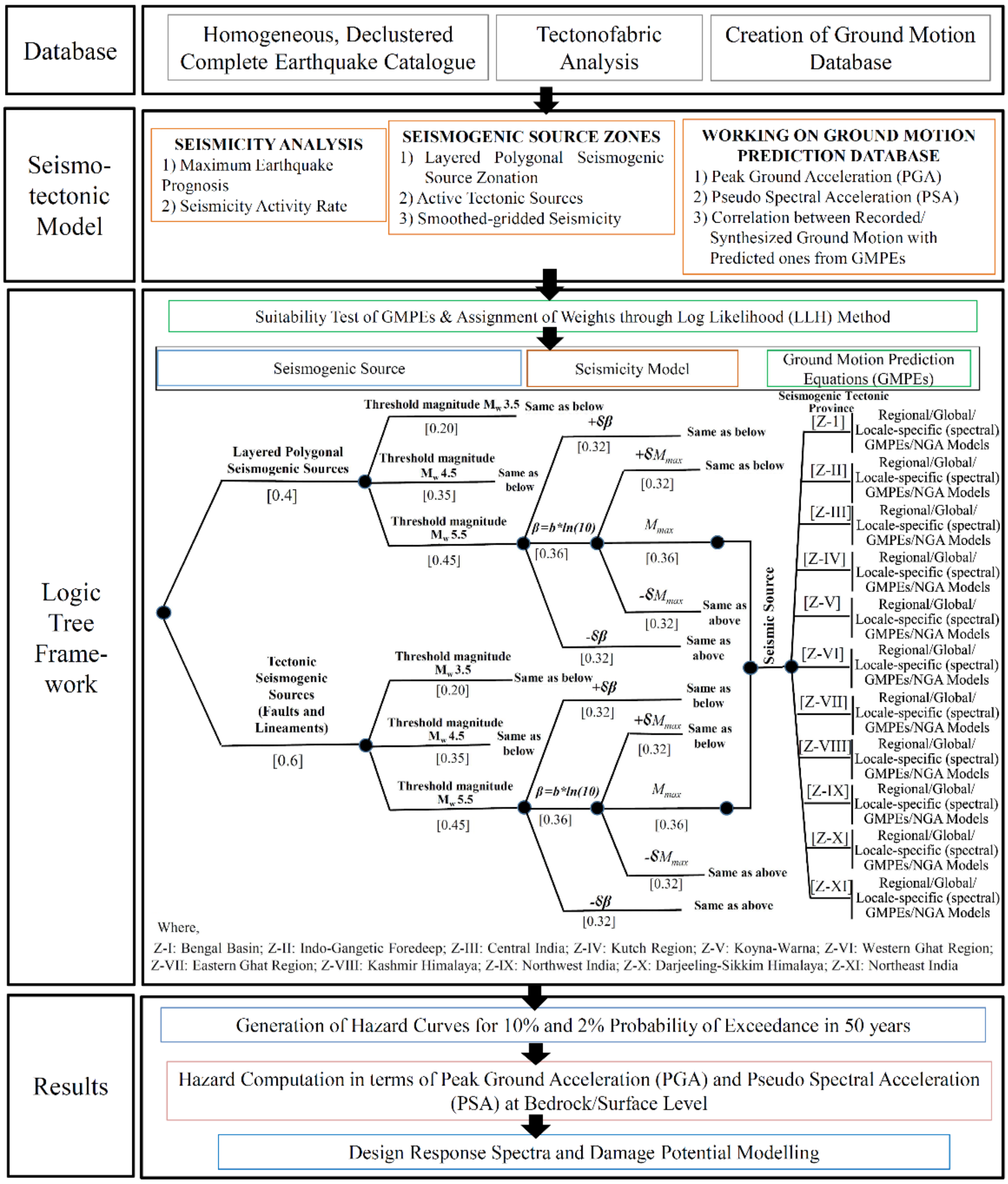
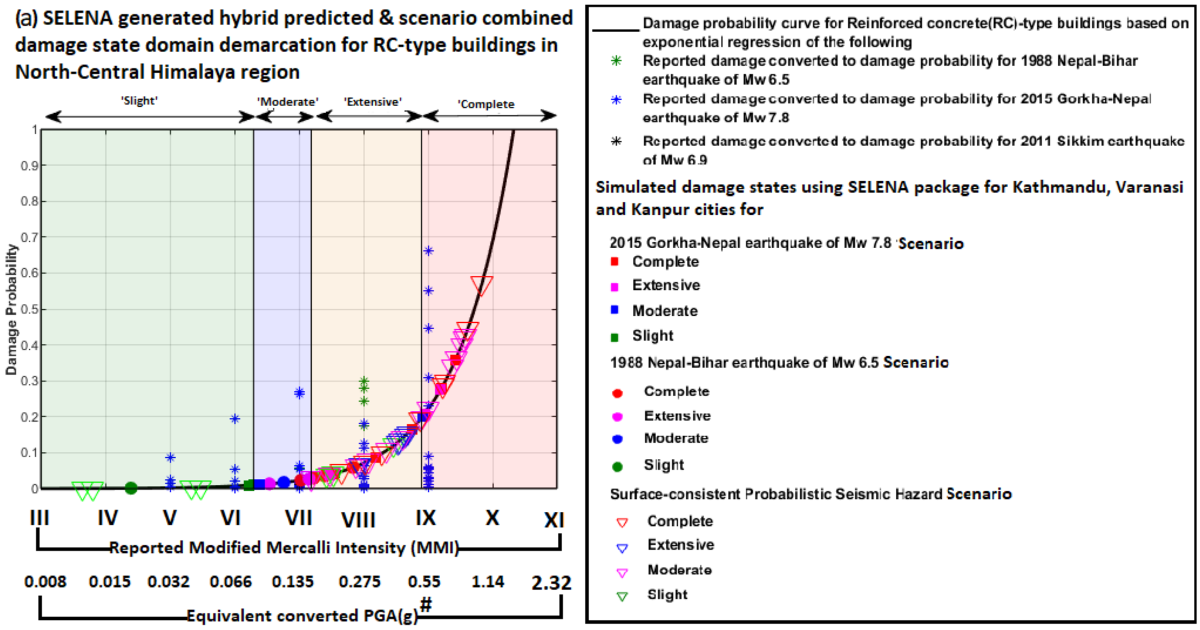


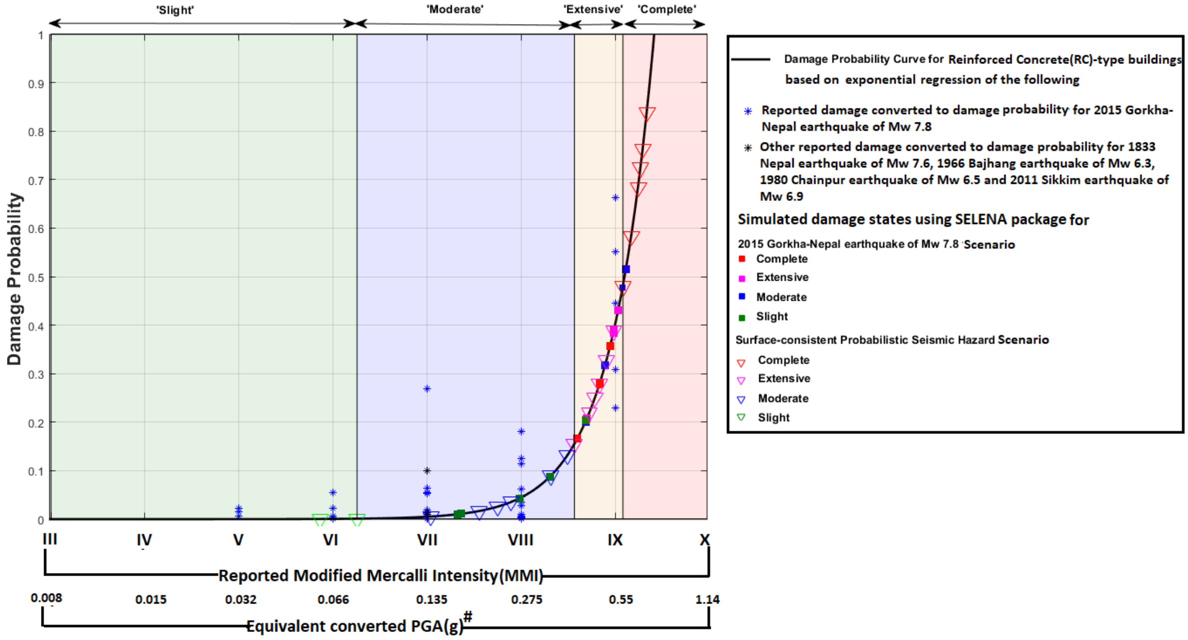
Figure S10: Computational Protocol used in the estimation of Probabilistic Seismic Hazard of India and the Tectonic Ensemble considered here.

(a) SELENA generated hybrid predicted & scenario combined damage state domain demarcation for RC-type buildings in North-Central Himalaya region



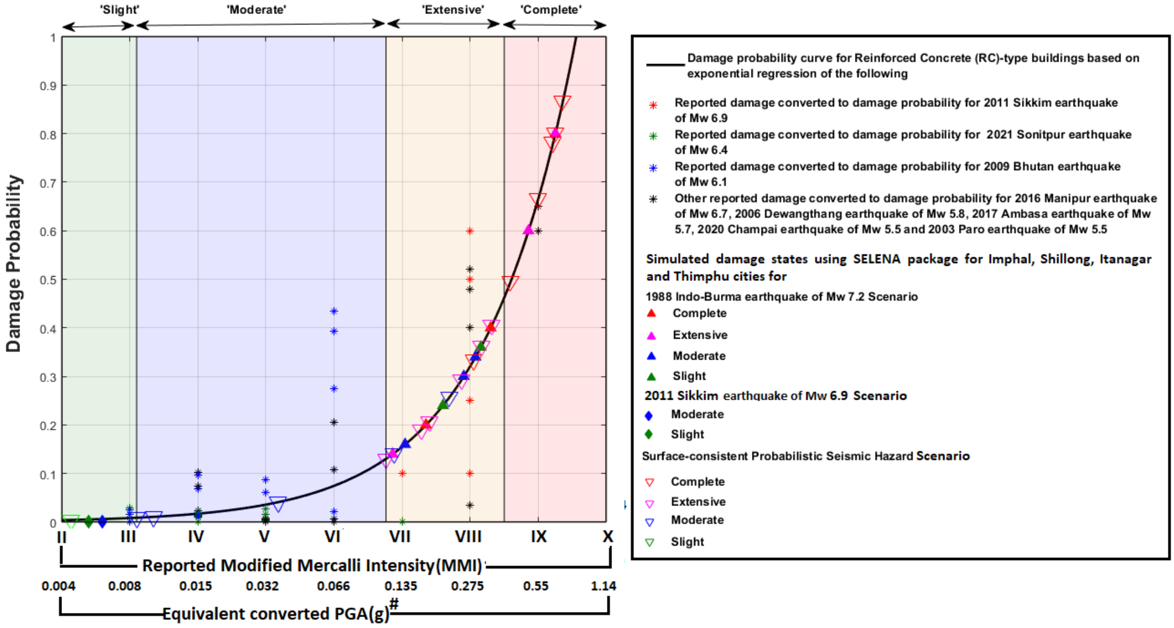
MMI to PGA conversion (Anbazhagan et al., 2016): MMI=0.1417+3.2335log(PGA)

(b) SELENA generated hybrid predicted & scenario combined damage state domain demarcation for RC-type buildings in Nepal



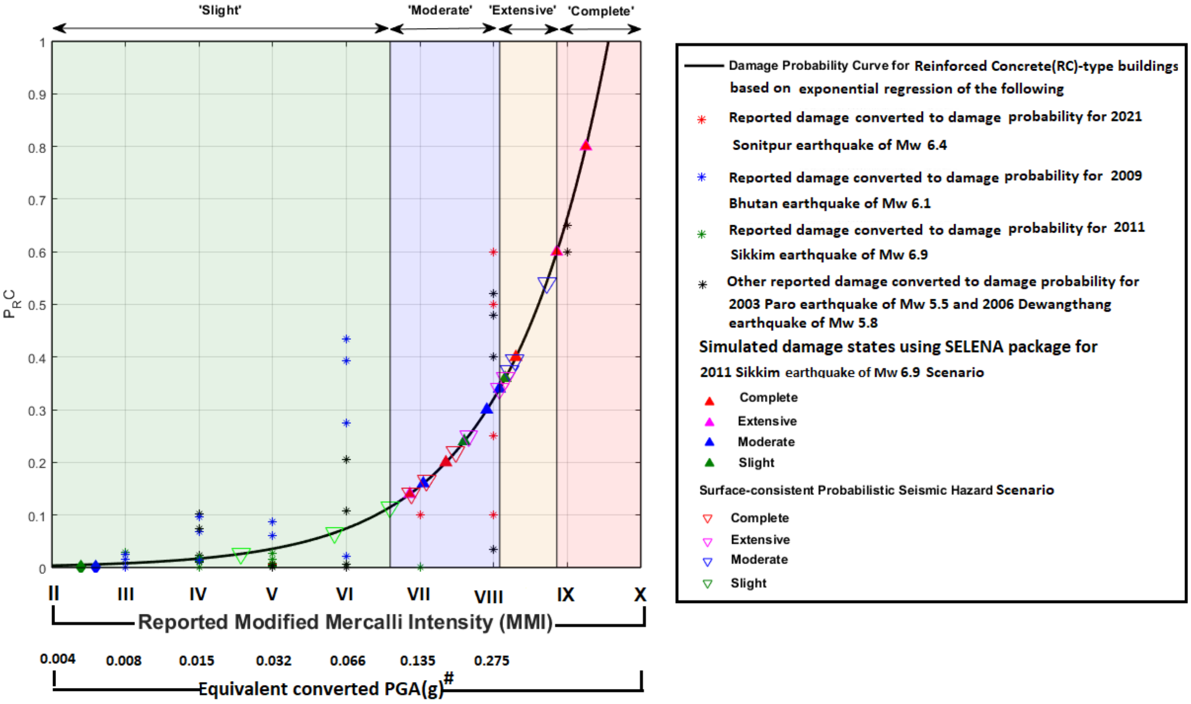
MMI to PGA conversion (Anbazhagan et al., 2016) : MMI=0.1417+3.2335log(PGA)

(c) SELENA generated hybrid predicted & scenario combined damage state domain demarcation for RC-type buildings in Northeast India region



MMI to PGA conversion (Anbazhagan et al., 2016): MMI=0.1417+3.2335log(PGA)

(d) SELENA generated hybrid predicted & scenario combined damage state domain demarcation for RC-type buildings in Bhutan region



MMI to PGA conversion (Anbazhagan et al., 2016): MMI=0.1417+3.2335log(PGA)

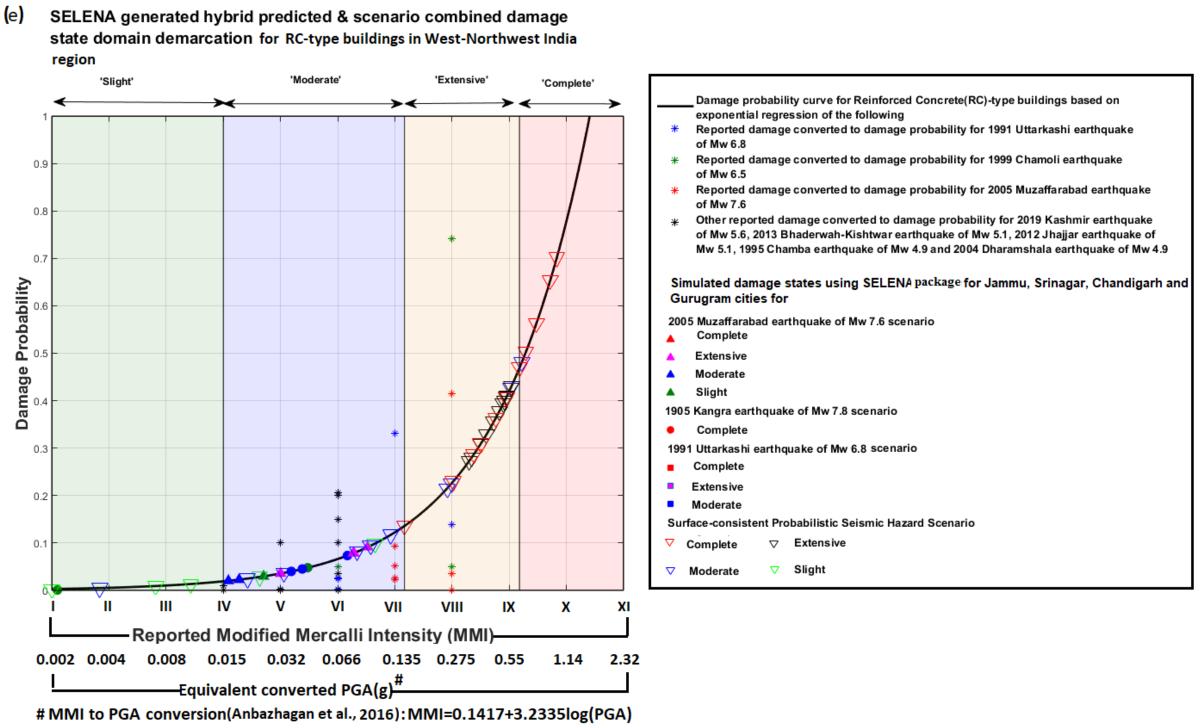


Figure S11: Damage probability calculation from reported damage through nonlinear exponential regression analysis across various scenario earthquakes for RC (Reinforced Concrete) type buildings in (**a**) North-Central Himalaya, (**b**) Nepal, (**c**) Northeast India, (**d**) Bhutan and (**e**) West-Northwest India regions. Furthermore, Damage states generated by SELENA for both scenario and probabilistic has been displayed based on damage outcomes simulated for the scenario earthquakes, along with the surface-consistent Probabilistic Seismic Hazard scenario.

Reference:

1. Nath SK, Thingbaijam KKS (2012) Probabilistic seismic hazard assessment of India. Seismological Research Letters 83(1):135-149. https://doi.org/10.1785/gssrl.83.1.135
2. Nath SK (2017) Probabilistic Seismic Hazard Atlas of 40 Cities in India. Ministry of Earth Sciences, Government of India, New Delhi, pp 457
3. Sharma ML, Douglas J, Bungum H, Kotadia J (2009) Ground-Motion Prediction Equations Based on Data from the Himalayan and Zagros Regions. Journal of Earthquake Engineering 13(8):1191-1210. https://doi.org/10.1080/13632460902859151
4. Toro GR (2002) Modification of the Toro et al. (1997) attenuation equations for large magnitudes and short distances. Risk Engineering Technical Report 10.
5. Campbell KW, Bozorgnia Y (2008) NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10s. Earthquake Spectra 24(1):139-171. https://doi.org/10.1193%2F1.2857546
6. Campbell KW, Bozorgnia Y (2003) Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. Bulletin of the Seismological Society of America 93(1):314-331. https://doi.org/10.1785/0120020029
7. Atkinson GM, Boore DM (2006) Earthquake ground-motion prediction equations for eastern North America. Bulletin of the Seismological Society of America 96(6):2181-2205. https://doi.org/10.1785/0120050245
8. Raghukanth STG, Iyengar RN (2007) Estimation of seismic spectral acceleration in peninsular India. Journal of Earth System Science 116(3):199-214. https://doi.org/10.1007/s12040-007-0020-8
9. Nath SK, Adhikari MD, Maiti SK, Devaraj N, Srivastava N, et al. (2014) Earthquake scenario in West Bengal with emphasis on seismic hazard microzonation of the city of Kolkata, India. Natural Hazards and Earth System Sciences 14:2549-2575. https://doi.org/10.5194/nhess-14-2549-2014
10. Maiti SK, Nath SK, Adhikari MD, Srivastava N, Sengupta P, et al. (2017) Probabilistic seismic hazard model of West Bengal, India. Journal of Earthquake Engineering 21(7):1113-1157. https://doi.org/10.1080/13632469.2016.1210054

11. Youngs RR, Chiou SJ, Silva WJ, Humphrey JR (1997) Strong ground motion attenuation relationships for subduction zone earthquakes. Seismological Research Letters 68(1):58-73. https://doi.org/10.1785/gssrl.68.1.58
12. Nath SK, Thingbaijam KKS, Maiti SK, Nayak A (2012) Ground-motion predictions in Shillong region, northeast India. Journal of Seismology 16(3):475-488. https://doi.org/10.1007/s10950-012-9285-8
13. Nath SK, Raj A, Thingbaijam KKS, Kumar A (2009) Ground Motion Synthesis and Seismic Scenario in Guwahati City—A Stochastic Approach. Seismological Research Letters 80(2):233-242. https://doi.org/10.1785/gssrl.80.2.233
14. NDMA (2010) Development of probabilistic seismic hazard map of India. Working committee of experts (WCE), NDMA, Technical Report Published by Govt. of India, New Delhi.
15. Abrahamson N, Silva W (2008) Summary of the Abrahamson & Silva NGA ground-motion relations. Earthquake Spectra 24(1):67-97. https://doi.org/10.1193%2F1.2924360
16. Raghukanth STG, Kavitha B (2014) Ground motion relations for active regions in India. Pure and Applied Geophysics 171(9):2241-2275. https://doi.org/10.1007/s00024-014-0807-x
17. Nath SK, Adhikari MD, Maiti SK, Ghatak C (2019) Earthquake hazard potential of Indo-Gangetic Foredeep: its seismotectonism, hazard, and damage modeling for the cities of Patna, Lucknow, and Varanasi. Journal of Seismology 23(4):725-769. https://doi.org/10.1007/s10950-019-09832-3
18. Anbazhagan P, Kumar A, Sitharam TG (2013a) Ground motion prediction equation considering combined dataset of recorded and simulated ground motions. Soil Dynamics and Earthquake Engineering 53:92-108. https://doi.org/10.1016/j.soildyn.2013.06.003
19. Chiou BJ, Youngs RR (2008) An NGA model for the average horizontal component of peak ground motion and response spectra. Earthquake Spectra 24(1):173-215. https://doi.org/10.1193%2F1.2894832
20. Boore DM, Atkinson GM (2008) Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01s and 10.0s. Earthquake Spectra 24(1):99-138. https://doi.org/10.1193%2F1.2830434
21. Sadigh K, Chang CY, Egan JA, Makdisi F, Youngs RR (1997) Attenuation relationships for shallow crustal earthquakes based on California strong motion data. Seismological Research Letters 68(1):180-189. https://doi.org/10.1785/gssrl.68.1.180
22. Hwang H, Huo JR (1997) Attenuation relations of ground motion for rock and soil sites in eastern United States. Soil Dynamics and Earthquake Engineering 16(6):363-372. https://doi.org/10.1016/S0267-7261(97)00016-X
23. Sharma ML, Harbindu A, Kamal (2012) Strong ground motion prediction equation for Northwest Himalayan region based on stochastic approach. In: Proceedings of 15th World Conference of Earthquake Engineering, Lisbon.
24. Harbindu A, Gupta S, Sharma ML (2014) Earthquake ground motion predictive equations for Garhwal Himalaya, India. Soil Dynamics and Earthquake Engineering 66:135-148. https://doi.org/10.1016/j.soildyn.2014.06.018
25. Akkar DS, Bommer JJ (2010) Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the Mediterranean region, and the Middle East. Seismological Research Letters 81 (2):195-206. https://doi.org/10.1785/gssrl.81.2.195
26. Lin PS, Lee CT (2008) Ground-motion attenuation relationships for subduction-zone earthquakes in northeastern Taiwan. Bulletin of the Seismological Society of America 98(1):220-240. https://doi.org/10.1785/0120060002
27. Zhao JX, Zhang J, Asano A, Ohno Y, Oouchi T, Takahashi T, Ogawa H, Irikura K, Thio HK, Somerville PG, Fukushima Y, Fukushima Y (2006) Attenuation relations of strong ground motion in Japan using site classification based on predominant period. Bulletin of the Seismological Society of America 96(3):898-913. https://doi.org/10.1785/0120050122
28. Adhikari MD, Nath SK (2016) Site-specific next generation ground motion prediction models for Darjeeling-Sikkim Himalaya using strong motion seismometry. Journal of Indian Geophysical Union 20(2):151-170.
29. Gupta ID (2010) Response spectral attenuation relations for in-slab earthquakes in Indo-Burmese subduction zone. Soil Dynamics and Earthquake Engineering 30(5):368-377. https://doi.org/10.1016/j.soildyn.2009.12.009
30. Singh NM, Rahman T, Wong IG (2016) A New Ground Motion Prediction Model for Northeastern India (NEI) Crustal Earthquakes. Bulletin of the Seismological Society of America 106(3):1282-1297. https://doi.org/10.1785/0120150180
31. BIS (2002) IS 1893–2002 (Part 1): Indian Standard Criteria for Earthquake Resistant Design of Structures, Part 1 – General Provisions and Buildings. Bureau of Indian Standards, New Delhi.
32. Bajaj K, Anbazhagan P (2019) Comprehensive amplification estimation of the Indo Gangetic Basin deep soil sites in the seismically active area. Soil Dynamics and Earthquake Engineering 127:105855. https://doi.org/10.1016/j.soildyn.2019.105855

33. Rao A, Dutta D, Kalita P, Ackerley N, Silva V, et al. (2020) Probabilistic seismic risk assessment of India. Earthquake Spectra 36(1_suppl):345–371. https://doi.org/10.1177/8755293020957374
34. Mir RR, Parvez IA (2020) Ground motion modelling in northwestern Himalaya using stochastic finite-fault method. Natural Hazards 103:1989–2007. https://doi.org/10.1007/s11069-020-04068-8
35. Scaria A, Gupta ID, Gupta VK (2021) An improved probabilistic seismic hazard mapping of peninsular shield region of India. Soil Dynamics and Earthquake Engineering 141:106417. https://doi.org/10.1016/j.soildyn.2020.106417
36. Puri N, Jain A (2018) Possible seismic hazards in Chandigarh city of north-western India due to its proximity to Himalayan frontal thrust. Journal of Indian Geophysical Union 22(5):485-506.
37. Sitharam TG, Kolathayar S, James N (2015) Probabilistic assessment of surface level seismic hazard in India using topographic gradient as a proxy for site condition. Geoscience Frontiers 6(6):847-859. https://doi.org/10.1016/j.gsf.2014.06.002
38. Sarkar S, Shanker D (2017) Estimation of seismic hazard using PSHA in and around National Capital Region (NCR) of India. Geosciences 7(4):109-116. https://doi.org/109-116, 10.5923/j.geo
39. Gupta A, Gupta ID, Gupta VK (2021a) Probabilistic seismic hazard mapping of National Capital Region of India using a modified gridded seismicity model. Soil Dynamics and Earthquake Engineering 144:106632. https://doi.org/10.1016/j.soildyn.2021.106632
40. Gupta L, Agrawal N, Dixit J (2021b) Spatial distribution of bedrock level peak ground acceleration in the National Capital Region of India using geographic information system. Geomatics, Natural Hazards and Risk 12(1):3287-3316. https://doi.org/10.1080/19475705.2021.2008022
41. Ramkrishnan R, Kolathayar S, Sitharam TG (2021) Probabilistic seismic hazard analysis of North and Central Himalayas using regional ground motion prediction equations. Bulletin of Engineering Geology and the Environment 80(10):8137-8157, https://doi.org/10.1007/s10064-021-02434-9
42. Bahuguna A, Sil A (2020) Comprehensive seismicity, seismic sources and seismic hazard assessment of Assam, North East India. Journal of Earthquake Engineering 24(2):254-297. https://doi.org/10.1080/13632469.2018.1453405
43. Ghione F, Poggi V, Lindholm C (2021) A hybrid probabilistic seismic hazard model for Northeast India and Bhutan combining distributed seismicity and finite faults. Physics and Chemistry of the Earth, Parts A/B/C 123:103029. https://doi.org/10.1016/j.pce.2021.103029
44. Agrawal N, Gupta L, Dixit J, Dash SK (2021) An integrated assessment of seismic hazard exposure and its societal impact in Seven Sister States of North Eastern Region of India for sustainable disaster mitigation planning. https://doi.org/10.21203/rs.3.rs-1003515/v1
45. Anbazhagan P, Bajaj K, Matharu K, Moustafa SSR, Al-Arifi NSN (2019a) Probabilistic seismic hazard analysis using the logic tree approach – Patna district (India). Natural Hazards and Earth System Sciences 19:2097–2115. https://doi.org/10.5194/nhess-19-2097-2019
46. Jaisal AK, Gupta ID, Gupta VK (2020) Probabilistic seismic hazard mapping of northwest India using area sources with non-uniform spatial distribution of seismicity. ISET Journal of Earthquake Technology, Paper No. 556 57(3):103-150.
47. Al-Hussaini TM, Al-Noman MN (2010) Probabilistic estimates of PGA and Spectral Acceleration in Bangladesh. In: Proc. 3rd international earthquake symposium, Bangladesh, Dhaka, pp 5-6.
48. Trianni SCT, Lai CG, Pasqualini E (2014) Probabilistic seismic hazard analysis at a strategic site in the Bay of Bengal. Natural Hazards 74(3):1683-1705 https://doi.org/10.1007/s11069-014-1268-3.
49. BNBC (2017) Bangladesh National Building Code. Bangladesh House Building Research Institute.
50. Rahman M, Siddiqua S, Kamal ASM (2020) Seismic source modeling and probabilistic seismic hazard analysis for Bangladesh. Natural Hazards 103(2):2489-2532. https://doi.org/10.1007/s11069-020-04094-6
51. Haque DME, Khan NW, Selim M, Kamal ASM, Chowdhury SH (2020) Towards improved probabilistic seismic hazard assessment for Bangladesh. Pure and Applied Geophysics 177(7):3089-3118 https://doi.org/10.1007/s00024-019-02393-z
52. Ram TD, Wang G (2013) Probabilistic seismic hazard analysis in Nepal. Earthquake Engineering and Engineering Vibration 12(4):577-586. https://doi.org/10.1007/s11803-013-0191-z
53. Chaulagain H, Rodrigues H, Silva V, Spacone E, Varum H (2015) Seismic risk assessment and hazard mapping in Nepal. Natural Hazards 78:583-602. https://doi.org/10.1007/s11069-015-1734-6
54. Rahman MM, Bai L, Khan NG, Li G (2018a) Probabilistic seismic hazard assessment for Himalayan–Tibetan region from historical and instrumental earthquake catalogs. Pure and Applied Geophysics 175(2):685-705. https://doi.org/10.1007/s00024-017-1659-y
55. Stevens VL, Shrestha SN, Maharjan DK (2018) Probabilistic seismic hazard assessment of Nepal. Bulletin of the Seismological Society of America 108(6):3488-3510. https://doi.org/10.1785/0120180022
56. Pallav K, Raghukanth STG, Singh KD (2012) Probabilistic seismic hazard estimation of Manipur, India. Journal of geophysics and engineering 9(5):516-533. https://doi.org/10.1088/1742-2132/9/5/516

57. Baro O, Kumar A, Ismail-Zadeh A (2020) Seismic hazard assessment of the Shillong Plateau using a probabilistic approach. Geomatics, Natural Hazards and Risk 11(1):2210-2238. https://doi.org/10.1080/19475705.2020.1833989
58. PM, Dash SR (2022) Probabilistic Seismic Hazard Assessment at Bedrock Level Using a Logic Tree Approach: A Case Study for Odisha, an Eastern State of India. Pure and Applied Geophysics 179:527-549. https://doi.org/10.1007/s00024-021-02929-2
59. Iyengar RN, Ghosh S (2004) Seismic hazard mapping of Delhi city. In: Proc. 13th world conference on earthquake engineering, Vancouver, BC, Canada, pp 180
60. Sitharam TG, Kumar A, Anbazhagan P (2013) Comprehensive seismic microzonation of Lucknow city with detailed geotechnical and deep site response studies. Proceedings of Indian geotechnical conference, Roorkee, India.
61. Anbazhagan P, Bajaj K, Patel S (2015) Seismic hazard maps and spectrum for Patna considering region-specific seismotectonic parameters. Natural Hazards 78:1163–1195. https://doi.org/10.1007/s11069-015-1764-0
62. Sana H (2019) A probabilistic approach to the seismic hazard in Kashmir basin, NW Himalaya. Geoscience Letters 6(5). https://doi.org/10.1186/s40562-019-0136-0
63. Raghucharan MC, Somala SN (2022) Seismic risk for vernacular building classes in the fertile Indus Ganga alluvial plains at the foothills of the Himalayas, India. In: Risk, Reliability and Sustainable Remediation in the Field of Civil and Environmental Engineering, pp 53-72. https://doi.org/10.1016/B978-0-323-85698-0.00025-3
64. Sil A, Sitharam TG, Kolathayar S (2013) Probabilistic seismic hazard analysis of Tripura and Mizoram states. Natural Hazards 68:1089–1108. https://doi.org/10.1007/s11069-013-0678-y
65. Das R, Sharma ML, Wason HR (2016) Probabilistic Seismic Hazard Assessment for Northeast India Region. Pure and Applied Geophysics 173:2653–2670. https://doi.org/10.1007/s00024-016-1333-9
66. Anbazhagan P, Srilakshmi KN, Bajaj K, Moustafa SS, Al-Arifi NS (2019b) Determination of seismic site classification of seismic recording stations in the Himalayan region using HVSR method. Soil Dynamics and Earthquake Engineering 116:304-316. https://doi.org/10.1016/j.soildyn.2018.10.023
67. Satyam DN, Rao KS (2010) Multi-channel analysis of surface wave (MASW) testing for dynamic site characterization of Delhi region. In: Fifth International Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics and Symposium in Honor of Professor IM Idriss, San Diego, California.
68. Pandey B, Jakka RS, Kumar A, Mittal H (2016) Site characterization of strong-motion recording stations of Delhi using joint inversion of phase velocity dispersion and H/V curve. Bulletin of the Seismological Society of America 106(3):1254-1266. https://doi.org/10.1785/0120150135
69. Anbazhagan P, Kumar A, Sitharam TG (2013b) Seismic Site Classification and Correlation between Standard Penetration Test N Value and Shear Wave Velocity for Lucknow City in Indo-Gangetic Basin. Pure and Applied Geophysics 170:299-318. https://doi.org/10.1007/s00024-012-0525-1
70. Singh M, Duggal SK, Singh VP (2021) A Study to Establish Regression Correlation Between Shear Wave Velocity and "N"-Value for Varanasi City, India. Proceedings of the National Academy of Sciences, India Section A: Physical Sciences 91:405-417. https://doi.org/10.1007/s40010-020-00686-w
71. Rahman MZ, Kamal AM, Siddiqua, S (2018b) Near-surface shear wave velocity estimation and Vs30 mapping for Dhaka City, Bangladesh. Natural Hazards 92(3):1687-1715. https://doi.org/10.1007/s11069-018-3266-3
72. Rahman MZ, Siddiqua S, Kamal AM (2016) Shear wave velocity estimation of the near-surface materials of Chittagong City, Bangladesh for seismic site characterization. Journal of Applied Geophysics 134, 210-225. https://doi.org/10.1016/j.jappgeo.2016.09.006
73. Mahajan AK, Mundepi AK, Chauhan N, Jasrotia AS, Rai N, Gachhayat TK (2012) Active seismic and passive microtremor HVSR for assessing site effects in Jammu city, NW Himalaya, India—A case study. Journal of Applied Geophysics 77:51-62. https://doi.org/10.1016/j.jappgeo.2011.11.005
74. Kandpal GC, John B, Joshi KC (2009) Geotechnical studies in relation to seismic microzonation of union territory of Chandigarh. Journal of Indian Geophysical Union 13(2):75-83.
75. Chen H, Xie Q, Li Z, Xue W, Liu K (2017) Seismic damage to structures in the 2015 Nepal earthquake sequences. Journal of Earthquake Engineering 21(4):551-578. https://doi.org/10.1080/13632469.2016.1185055
76. Gautam D, Chamlagain D (2016) Preliminary assessment of seismic site effects in the fluvio-lacustrine sediments of Kathmandu valley, Nepal. Natural Hazards 81(3):1745-1769. https://doi.org/10.1007/s11069-016-2154-y
77. Kumar P, Joshi A, Kumar S, Lal S (2018) Determination of site effect and anelastic attenuation at Kathmandu, Nepal Himalaya region and its use in estimation of source parameters of 25 April 2015 Nepal earthquake M_w= 7.8 and its aftershocks including the 12 May 2015 M_w= 7.3 event. Natural Hazards 91(3):1003-1023 https://doi.org/10.1007/s11069-018-3178-2

78. Sil A, Sitharam TG (2017) Detection of local site conditions in Tripura and Mizoram using the Topographic Gradient Extracted from Remote Sensing Data and GIS Techniques. Natural Hazards Review 18(2):04016009. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000228
79. Rao KS, Ramhmachhuani R (2017) Site specific seismic input for structures on hill slopes. Procedia engineering 173:1747-1754. https://doi.org/10.1016/j.proeng.2016.12.212
80. Biswas R, Baruah S, Bora N (2018) Assessing shear wave velocity profiles using multiple passive techniques of Shillong region of northeast India. Natural Hazards 94(3):1023-1041. https://doi.org/10.1007/s11069-018-3453-2
81. Sana H (2018) Seismic microzonation of Srinagar city, Jammu and Kashmir. Soil Dynamics and Earthquake Engineering 115:578-588, https://doi.org/10.1016/j.soildyn.2018.09.028
82. Zahoor F, Rao KS, Malla SA, Tariq B, Bhat WA (2021) Seismic Site Characterization using MASW of Sites along Srinagar Metro Rail Alignment, Jammu and Kashmir. In: Patel S, Solanki CH, Reddy KR, Shukla SK (eds) Proceedings of the Indian Geotechnical Conference 2019, Lecture Notes in Civil Engineering, Springer, Singapore, Vol. 138. https://doi.org/10.1007/978-981-33-6564-3_49
83. Puri N, Jain A (2021) Development of Surface Level Seismic Hazard Maps Considering Local Soil Conditions for the State of Haryana, India. Journal of the Geological Society of India 97(11):1365-1378. https://doi.org/10.1007/s12594-021-1875-z
84. Pallav K, Raghukanth STG, Singh KD (2015) Estimation of seismic site coefficient and seismic microzonation of Imphal City, India, using the probabilistic approach. Acta Geophysica 63(5):1339-1367. https://doi.org/10.1515/acgeo-2015-0045