Journal of Rock Mechanics and Tunnelling Technology (JRMTT)
27 (2) 2021 pp 85-102

Available online at www.isrmtt.com

Probabilistic Seismic Hazard in Uttarakhand Himalaya

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ABSTRACT

Seismic hazard analysis involves the quantitative estimation of ground shaking at a particular site for a specific region. Study on Probabilistic Seismic Hazard Analysis (PSHA) has been carried out for Uttarakhand Himalaya. This is the most seismically active Indian Himalayan area, where seismically acive faults, MCT, MBT and MFT are passing through it and making the region hazardous due to earthquake occurrences. The contributions of smaller local faults cannot be ignored because the Yamuna fault near Haridwar and Alaknanda fault near Rudraprayag make the region more seismic potential. The CRISIS 2015 has been used for seismic hazard computation. For PSHA study, area has been divided into grid size of 0.2° x 0.2°. The seismicity parameters and attenuation models have been used as input parameters to computed seismic hazard in terms of PGA for 20%, 10% and 2% probability of exceedance in 50 years which are equivalent to return periods of 225, 475 and 2475 years respectively. The maximum magnitude of earthquake may not exceed 6.9M in Uttarakhand state.

Keywords: Probabilistic Seismic Hazard Analysis (PSHA); Probability of exceedance; Attenuation models; Uniform Hazard Spectra (UHS); Peak Ground Acceleration (PGA); Return period

1. INTRODUCTION

Uttarakhand is one of the northern state of India located in the foot hill of Himalayan region which is seismically most active because of the earthquake occurrence associated with major as well as minor faults. This state is consisting of thirteen districts, most of which occupies a part of Himalaya stretching about 320 km between Himachal Pradesh in the west and Kali River in the east, forming the Indo-Nepal border. The seismic activities of the region are attributed due to continuous thrusting of the Indian plate under Eurasian plate since cretaceous time. A major portion of the region falls in Zones IV and V of the seismic zoning map of India (IS-1893:2016 Part 1). The Uttarakhand Himalaya exhibits a variety of geomorphic features, which give distinctive characteristics to each geological unit, namely Higher Himalaya, Lesser Himalaya and Outer (sub) Himalaya. The boundary between the Sub-Himalaya and Lesser Himalaya is marked by MBT, whereas the Lesser Himalaya is separated from the Higher Himalaya by MCT. The MCT is the predominant factor responsible for major tectonic activity in the region. However, the boundary between the Sub-Himalaya and Siwalik form Main Frontal Thrust (MFT). Mittal and Chakraverty (2005) considered MBT and MFT as main active features in the considered region.

The area is characterized by a high-amplitude topography and great denudational slope due to complex geomorphological conditions.

Geological investigations advocate that Great Himalaya is made up of high-grade metamorphic rocks closely associated with mylonitized porphyritic granites and augen gneisses. A massive part of these rocks rides over the sedimentary and low-grade metamorphic rock congregations of the Lesser Himalaya created the populated terrain of Uttarakhand. Valdiya (1988) stated that the southward thrusting of these rock masses along a variety of thrusts is comprising of the Main Central Thrust (MCT). The thrust is always associated with smaller faults or/and parallel, sub-parallel thrusts branching off from the main thrust, but never occur alone (Fig. 1).

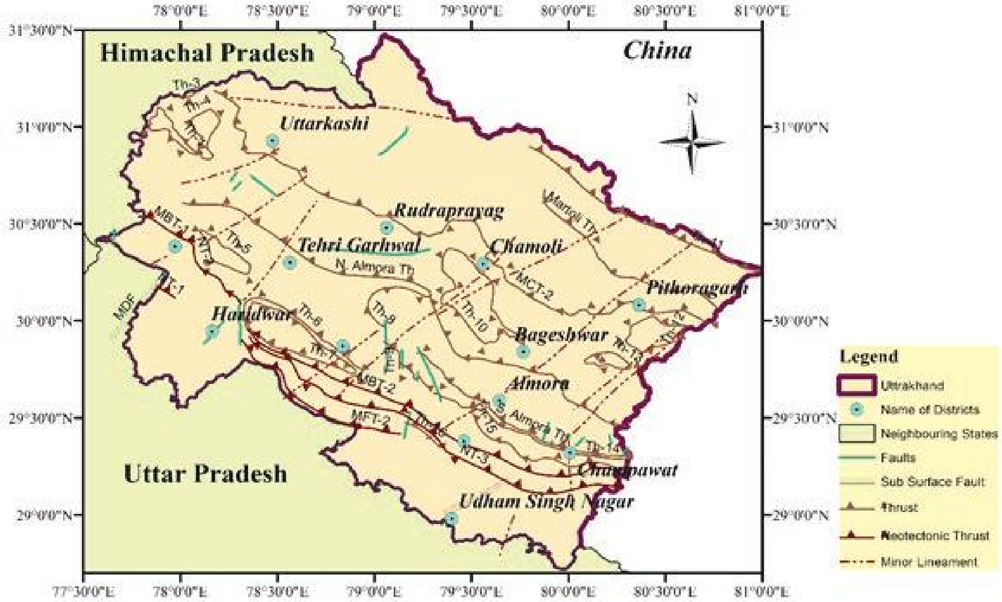


Figure 1 - Tectonic map of Uttarakhand with major Thrust and Faults (Soni et al., 2019)

Consequently, smaller Yamuna fault near Haridwar and Alaknanda fault near Rudraprayag make the region more seismic potential(Dasgupta et al., 2000). The MCT zone is seismically prominent active belt of Uttarakhand, where maximum strain build-up occurs. However, occurrence of the following three earthquakes of October 19, 1991, Pilang-Bhatwari, Uttarakashi (Mw=6.8); January 5, 1997, Dharchula area, Pithoragarh (Mw=5.6) and March 28, 1999, Pipalkoti area, Chamoli (Mw = 6.4) prove the geological reality of the geodynamical complexity of the region. Shanker et al. (2018) investigated the combined region (Himachal Pradesh and Uttarakhand) considering source and site approach, for deterministic seismic hazard assessment (DSHA) by identifying eighty-nine potential seismic line sources delineated based on the major tectonic features mapped and observed seismicity patterns.In this study they estimated that larger peak ground accelerations are where there is a higher density of larger faults and vice-versa. Soni et al. (2019) reported some preliminary seismic hazard results for Uttarakhand region in term of yearly expected number, return period and probability of occurrence using Gumbel's type-I extreme value theory and estimated the most probable earthquake that may occur after aninterval of 50 years to be 6.6. Shanker and Shubham (2020) investigated seismic hazard in terms of peak ground acceleration (PGA) for state of Uttarakhand, based on deterministic seismic hazard analysis (DSHA).

In the present article, Uttarakhand region has been the goal for peak ground acceleration (PGA) estimation using probabilistic seismic hazard analysis (PSHA) methodology. Since, in Deterministic approaches, only one seismic event (e.g. the maximum historical event from a pertinent seismogenic source, or the maximum earthquake compatible with the known tectonic framework) is considered. While, in the PSHA process, the level of ground motion is assessed through integrating all possible earthquake scenarios in the considered region in respect of magnitude, distance, and the variability of the ground motion (Gupta, 2005).

2. SEPARATION OF SEISMOGENIC SOURCE ZONES

For the purpose of PSHA, Uttrakhand, region has been divided into four seismotectonic source zones as shown in Fig. 2. The earthquakes data (1974 - 2018) taken from the catalogue of USGS and ISC and its epicentre distribution are also shown in this map. Seismotectonic sources zones are manifeston the basis of utilising information on tectonics and seismicity patters of the region, as well as geology of the area (Khattri et al., 1984). In certain area where the tectonic configuration/geological structure is not adequate, seismicity pattern is normally considered to demarcate the source zones. To achieve this ARCGIS 10 software is used for source zone demarcation (*UK-I, UK-II, UK-III and UK-IV*) which are characterized in the following sections.

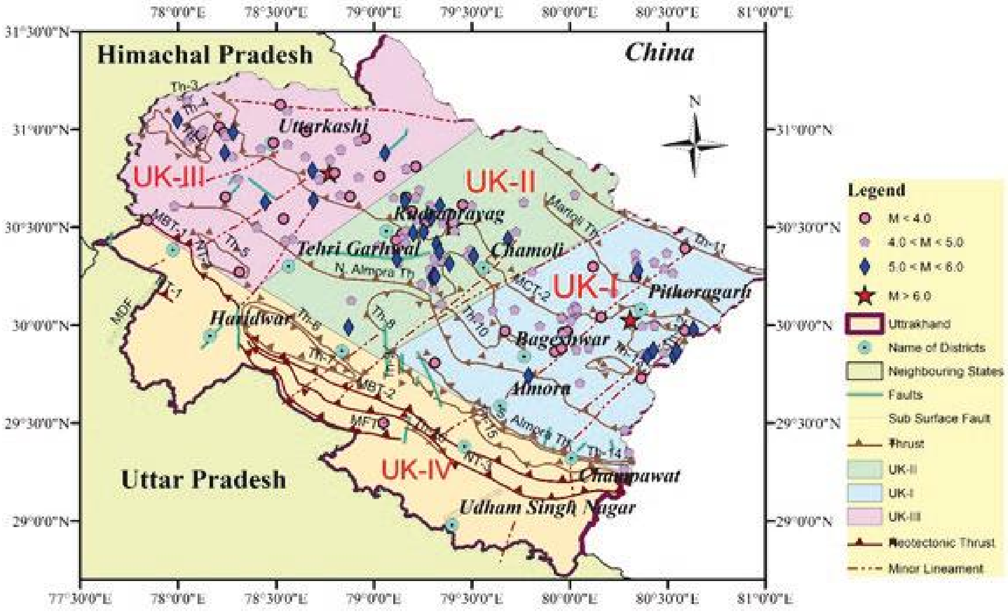


Figure 2 - Seismicity map of the region. Demarcated source zone (*UK-I, UK-II, UK-III and UK-IV*) are also shown

2.1 Seismotectonic Source Zone UK-I

Seismotectonic source zone UK-I is most active source zone and falls in Kumaon region and lie in Zone-V of seismic zoning map of India, IS-1893 (2016).It comprisesof earthquake of magnitude Mw=6.1 on 20 May 1979 near Pithoragarh district with depth of 22km. This covers area of 13183.767km^2 including Almora, Bageshwar, Champawat and Pithoragarh districts. The main tectonic features are MBT, MCT with some local thrust viz. Martoli thrust and south Almora thrust, Ramgarh fault are associated with this zone. This zone includes a part of western Himalaya.

2.2 Seismotectonic Source UK-II

This zone falls in centre of Uttarakhand and covers an area of about 11682.674km^{2}with Chamoli, Rudraprayag, Pauri Garhwal, and Tehri districts. Most prominent features of the Himalaya viz. MCT and southward dipping North Almora thrust, and the Alaknanda fault are passing through the area. This is highly seismically active and landslide prone area. Chamoli district has a history of repeated natural disasters due to its geological, structural and climatic conditions. The Chamoli earthquake of magnitude of Mw= 6.6, on 29 March 1999 is one of them which affected this region.

2.3 Seismotectonic Source Zone UK-III

This zone is located in eastern most side of Uttarakhand and covers an area of about 13262.387km^{2}with Uttrarkashi and Dehradun of Garhwal Himalaya. This lies in seismiczone IV of IS-1893 (2016). Most tectonic features of the Himalaya (MBT, MCT and southward dipping North Almora Thrust, Neotectonic Thrust) make the area seismically active and landslide prone. The Uttrarkashi earthquake of 19 October 1991 having magnitude Mw= 6.8, caused devastation in this region.

2.4 Seismotectonic source zone UK-IV

This zone falls in southern Uttarakhand and shares boundary with Indian state (Uttar Pradesh) and country Nepal. This zone includes Nainital, Udham Singh Nagar, and Haridwar districts.Main frontal thrust (MFT), and neotectonic thrust lineaments are most active features of this zone. Although, there are density of neotectonic thrust and other tectonic features but they could not generate much number of earthquakes till date except one of very low magnitude (<4.0). So due to scarcity of seismicity data, in this source zone, UK-IV has been excluded from the analysis.

3. ESTIMATION OF SEISMIC HAZARD PARAMETERS

The seismic hazard parameters of the Gutenberg-Richter relation such as a, b and magnitude of completeness m_c are very important in the PSHA of the region (Richter, 1958). Shanker and Shubham, (2018), interpreted the parameter 'a' represents the seismicity of the region (productivity) whereas 'b' gives the relative proportion of the large to small earthquakes and $m_c$is the magnitude of completeness or threshold magnitude. For present study, the entire magnitude range method (EMR) modified by Woessner and Wiemer (2005) and maximum curvature method is adopted to estimate the magnitude of completeness (m_c) as this method is stable under most conditions and provides a comprehensive seismicity model. In seimotectonic zone UK-II the EMR is not workable due to less earthquake events, that’s why Maximum Curvature method is used. Though, it slightly underestimates the magnitude of completeness while for zones UK-I and UK-III EMR method is used. The maximum magnitude is one of the important variables in the seismic hazard analysis (SHA) as it denotes the maximum potential of accumulated strain released in larger earthquakes. The instrumental and historical earthquake catalog is often short to reflect the full potential of long seismogenic fault. The maximum regional magnitude, M_{max} is the upper limit of magnitude for a given region or it is the magnitude of largest possible earthquake (Kijko, 2004). No earthquakes are to be expected with a magnitude exceeding $M_{max.}$ For the present study, M_{max} has been computed by the equation given by Kijko and Sellevoll (1992) given as:

$$M_{max} = M_{max}^{obs} + \frac{E_1(n_2) - E_1(n_1)}{\beta \exp{(-n_2)}} + M_{min} \exp{(-n)} \qquad (1)$$

where n denotes all earthquakes greater than M_{min}

$$n_1 = n/\{1 - \exp{[-\beta(M_{max} - M_{\min})]}\} \qquad (2)$$

$$n_2 = n_1 \exp{[-\beta(M_{max} - M_{\min})]} \qquad (3)$$

$E_1(z)$ can be conveniently approximated as

$$E_1(z) = \frac{z^2 + a_1 z + a_2}{2(z^2 + b_1 z + b_2)} \exp{(-z)} \qquad (4)$$

Where a_1=2.334733, a_2=0.250621, b_1=3.330657, b_2=1.681534 (Abramowitz and Stegun, 1970).

The seismic hazard parameters for different zones are calculated for instrumental seismicity (1974- 2018). The results obtained are Shown in Table 1.

Table 1 - Seismic hazard parameters considering entire earthquake data-set from 1974 to 2018

Source zone	Area (sq. km)	m_c	m_{max}	a	b	±b	α	β	λm	Return period ($1/\lambda m$)	Return period for m=6.0 (year)
UK-I	13183.767	4.4	**6.2**	4.52	1.05	0.00	10.41	2.42	0.794	1.259	60.256
UK-II	11682.674	4.6	**6.7**	4.64	1.08	0.19	10.68	2.49	0.470	2.128	69.183
UK-III	13262.387	4.2	**6.9**	3.30	0.84	0.00	7.60	1.93	0.592	1.689	59.954

Predicted earthquakes are likely to be the shallow earthquakes. High-rise buildings are safe during big earthquakes due to reduced chances of resonance.

4. PROBABILISTIC SEISMIC HAZARD ANALYSIS

The ultimate goal of PSHA is to estimate ground motion at the particular site of interest. Seismic hazard results using the ground motion prediction equation (GMPE) can be analysed by developing seismic hazard curves, which means the annual probability of exceedance of different values of any selected ground motion parameter in a specified period of time. Such curves can be estimated for an individual zone and thereby aggregated for a particular site. "The probability of exceeding a particular value, y* of a ground motion parameter, Y, is estimated for one possible earthquake at one possible source location and then multiplied by the probability that a particular magnitude earthquake would occur at that particular location" (Reiter, 1990). The process is iterated in all possible magnitudes and for all locations in consideration, with the probabilities of each summed and is given by equation (Kramer, 2003).

$$P[Y > y^*] = \iint P[Y > y^*|m,r] f_M(m) f_R(r) dmdr \qquad (5)$$

Where (m) and (r) are the probability density functions for magnitude and distance, respectively. If the study region is surrounded by potential seismogenic zones, and each has an average rate of threshold magnitude exceedance, $v_i = \exp\,(\alpha_i - \beta_i m_0)$ then the total average rate of exceedance for region will be given the by equation.

$$\lambda_{y^*} = \sum_{i=1}^{N_s} v_i \iint P[Y > y^*|m,r] f_{M_i}(m) f_{R_i}(r) dmdr \qquad (6)$$

The parameters appearing in the above equations are complicated and integrals cannot be evaluated analytically for estimation of realistic PSHA's. To simplify, the magnitude is divided into ranges and distance into a number of different segments to analyze separately. At present several software are available for probabilistic seismic hazard assessment like CRISIS2015, SEISRISK III, EQRM, FRISK88M, Open SHA etc. Most of the programs are based on probabilistic methodology developed by Cornell (1968). In the present study PSHA has been computed using CRISIS 2015 software.

4.1 Ground Motion Attenuation Model

An important aspect in the analysis of probabilistic seismic hazard is the selection of proper ground motion attenuation relationship. The ground motion produced by earthquakes is a complex phenomenon and it depends on the type of source and medium characteristics. The accuracy of these relationships is based on the data, function taken and methodology used to derive it. As it directly influences the estimation of strong ground motion, hence it plays a vital role in hazard estimation. Generally, region-specific attenuation relationships are favoured for estimation of ground motion, in the absence of these global relations can be used with similar conditions. Mainly ground motion attenuation model can be classified into three categories based on seismic environments: shallow crustal earthquake in the active tectonic region, the shallow crustal earthquake in stable continental regions and a subduction zone. Various attenuation models are proposed for the estimation of ground motion for specific regions and for the general area. Several attenuation relationships have been developed considering a worldwide database for the shallow crustal earthquakes. The various NGA (2014) models and their description which are used in this study are given in Table 2.

Table 2 -NGA attenuation models used in the study

NGA West2 model by Boore et al. (2014)	
Original units	g
Dimension	acceleration
Spectral period range	0-10 s
Valid distance range	0-300 km
Valid magnitude range	3-8.5
Type of distance metric	JyB
Residuals distribution	Log normal
Tectonic region	Active_Shallow_Crustal

NGA West2 model by Abrahamson, Silva and Kamai (2014)	
Original units	g
Dimension	acceleration
Spectral period range	0-10 s
Valid distance range	0-300 km
Valid magnitude range	3-8.5
Type of distance metric	Rrup
Residuals distribution	Log normal
Tectonic region	Active_Shallow_Crustal

5. RESULTS AND DISCUSSION

Probabilistic seismic hazard assessment (PSHA) for the state of Uttarakhand has been carried out using CRISIS 2015, for which the study area has been divided into grid size of 0.2° x 0.2°. The input parameters are seismicity parameters (Table 1) and attenuation models (Table 2). Seismic hazard is computed in terms of PGA for 20%, 10% and 2% probability of exceedance in 50 years which are equivalent to return periods of 225, 475 and 2475 years respectively. Contour maps have been produced for mean PGA for 2%, 10% and 20% probability of exceedance in 50 years. Uniform hazard spectra (UHS) at various sites for return periods of 225, 475 and 2475 years have been plotted. Probabilistic seismic hazard result is presented in terms of PGA for various return periods for each district of Uttarakhand considering two 2014 NGA attenuation models given in Table 3.

Table 3 **-** Computed PGA value for 225,475 and 2475 years return periods for each district of Uttarakhand

Cities	Abrahamson, Silva, and Kamai (2014) Attenuation Model (PGA)			Boore et al. (2014) NGA West2 Attenuation Model (PGA)		
	225	475	2475	225	475	2475
Almora	0.13	0.16	0.27	0.13	0.20	0.41
Bageshwar	0.15	0.19	0.31	0.16	0.23	0.45
Chamoli	0.19	0.25	0.40	0.23	0.32	0.61
Champawat	0.10	0.13	0.23	0.10	0.15	0.31
Dehradun	0.14	0.19	0.34	0.11	0.17	0.35
Haridwar	0.09	0.13	0.22	0.05	0.07	0.13
Nainital	0.09	0.13	0.19	0.06	0.08	0.14
Pauri Garhwal	0.14	0.19	0.32	0.13	0.20	0.42
Pithoragarh	0.14	0.18	0.30	0.16	0.23	0.45
Rudraprayag	0.21	0.27	0.43	0.23	0.33	0.61
Tehri Garhwal	0.19	0.27	0.41	0.21	0.30	0.57
Udham Singh Nagar	0.04	0.06	0.09	0.02	0.03	0.05
Uttarkashi	0.19	0.25	0.43	0.19	0.28	0.56

Mean PGA contour maps for 225, 475 and 2475 years return periods have been generated using Surfer software. Figure 3- a, b, c and Figure 4-a, b, c show mean PGA contour map for 225, 475 and 2475 years return periods, for Abrahamson, Silva and Kamai (2014) attenuation model and Boore et al. (2014) NGA West2 attenuation model.

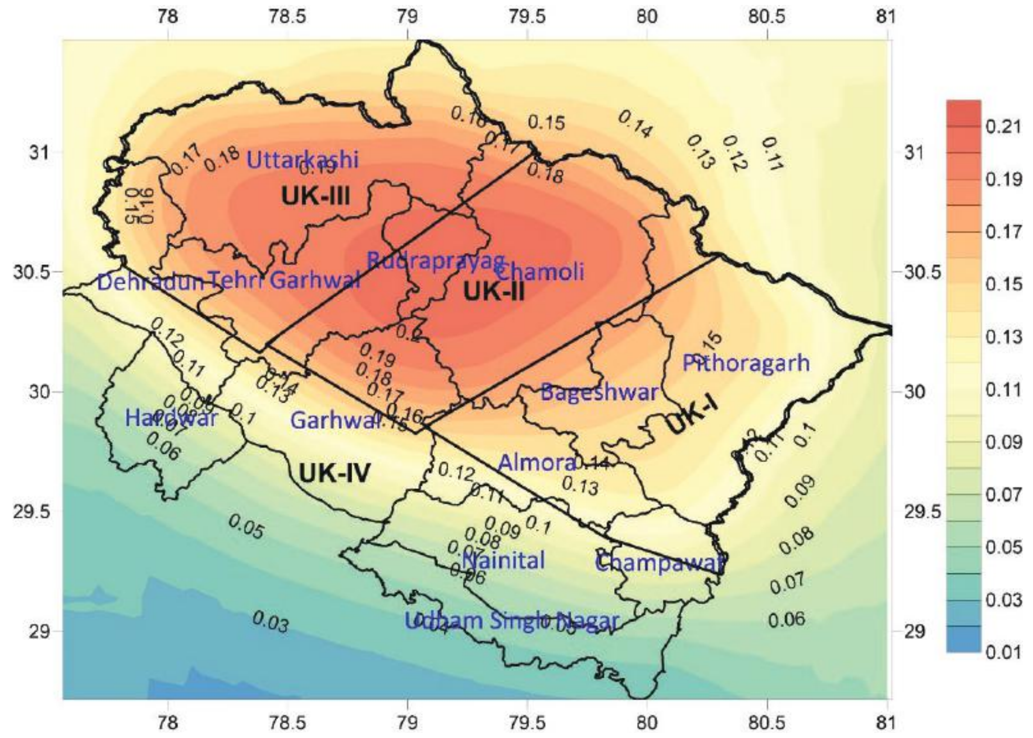


Figure 3(a) - Mean PGA contour map for 225 years return periods using Abrahamson, Silva and Kamai (2014) attenuation model

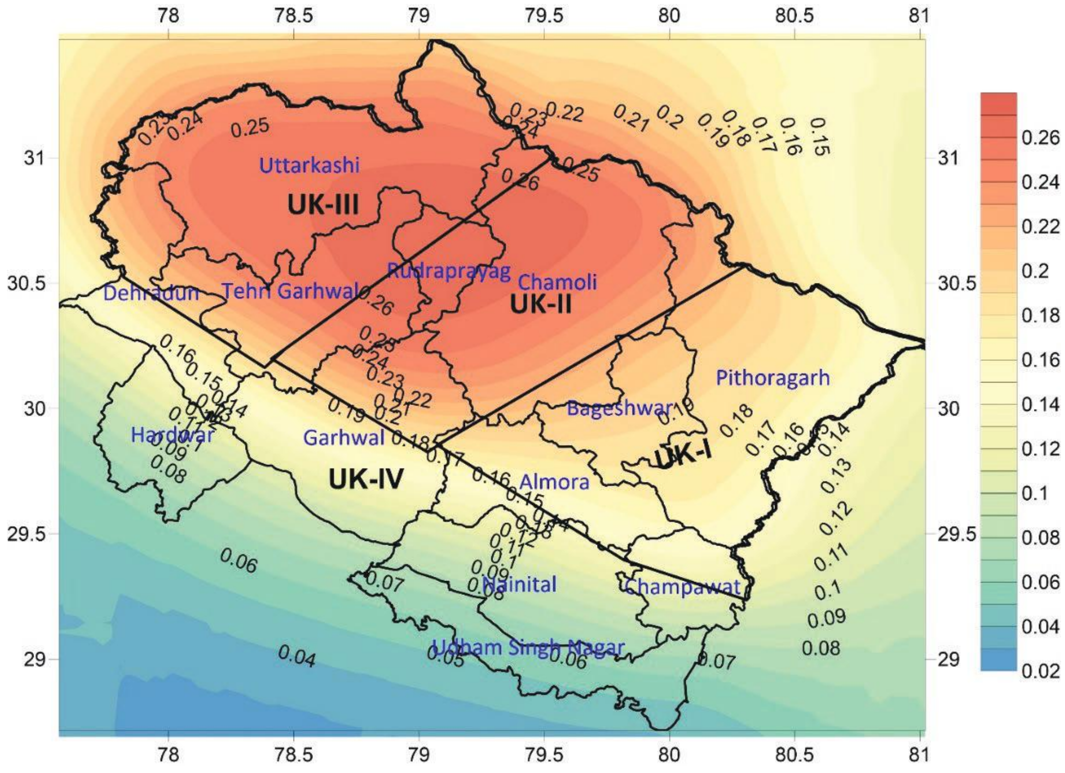


Figure 3(b) - Mean PGA contour map for 475 years return periods using Abrahamson, Silva and Kamai (2014) attenuation model

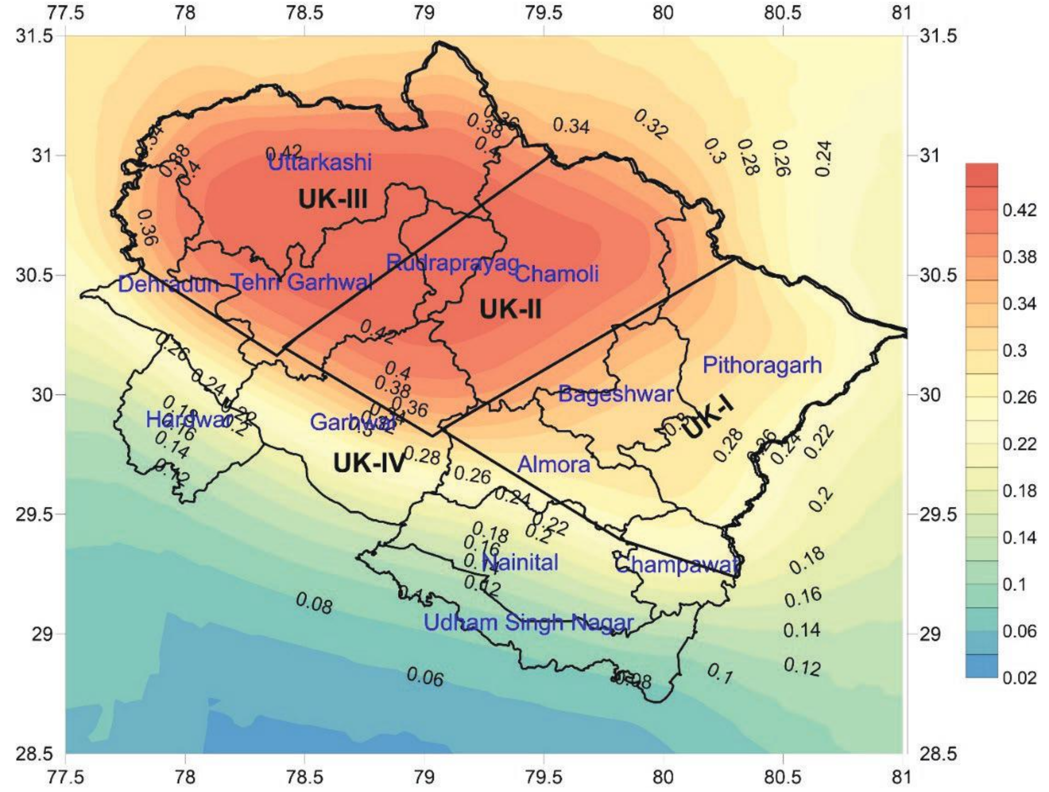


Figure 3(c) - Mean PGA contour map for 2475 years return periods using Abrahamson, Silva and Kamai (2014) attenuation model

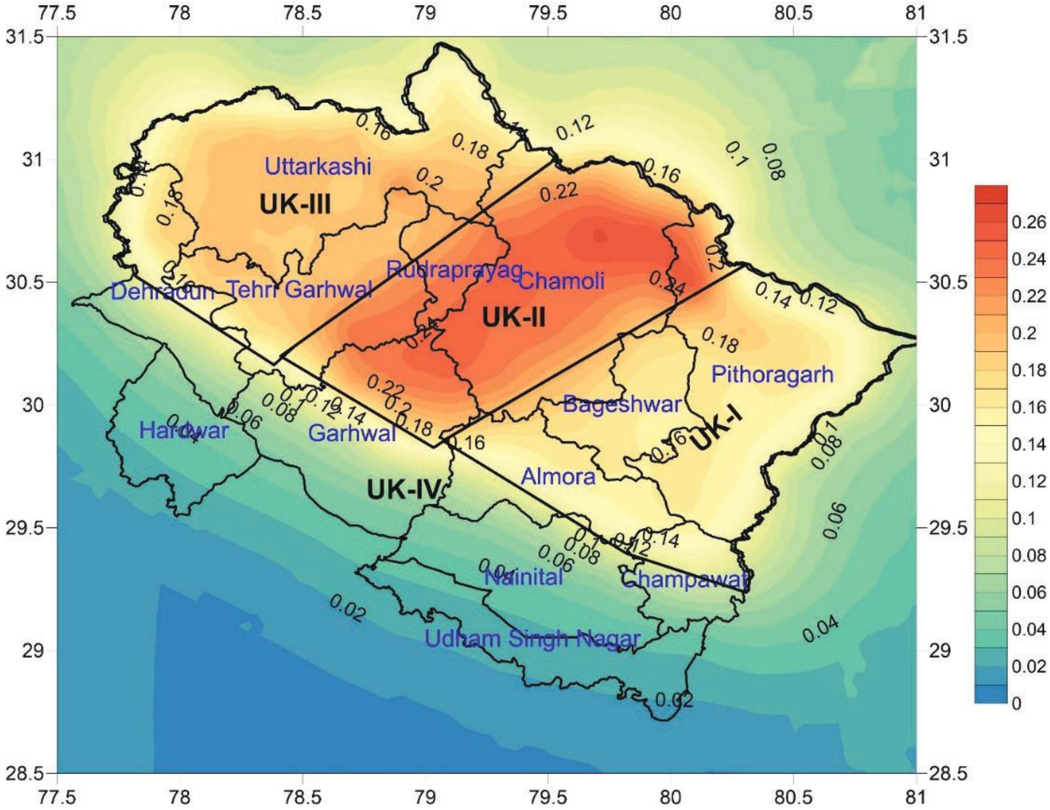


Figure 4(a) - Mean PGA contour map for 225 years return periods using Boore et al. (2014) attenuation model

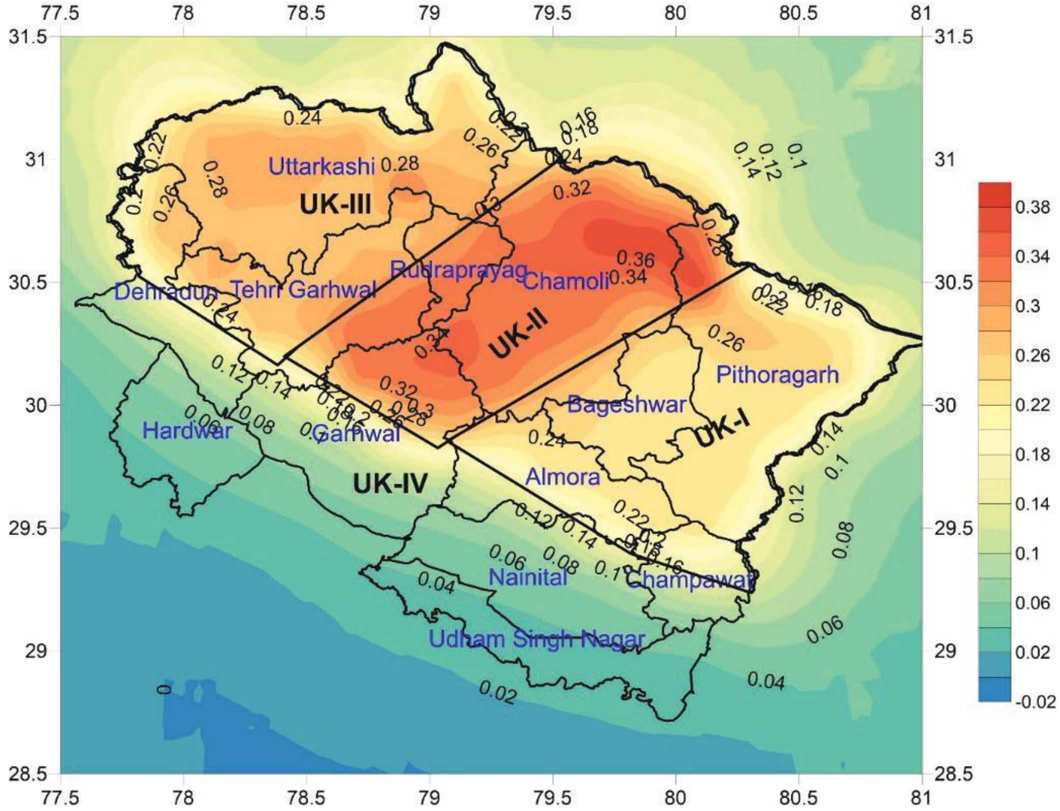


Figure 4(b) - Mean PGA contour map for 475 years return periods using Boore et al.(2014) attenuation model

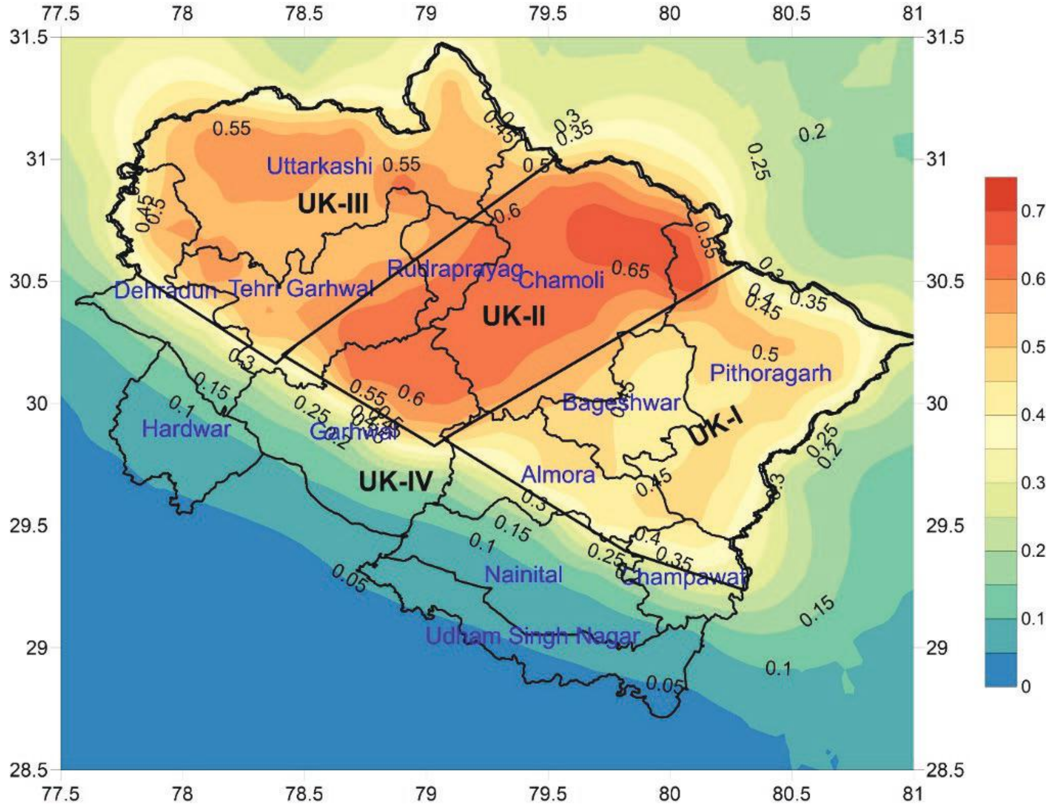
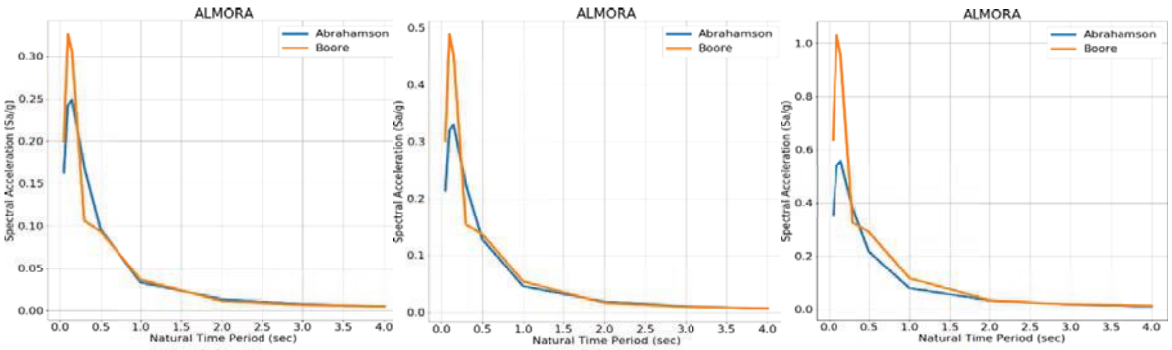


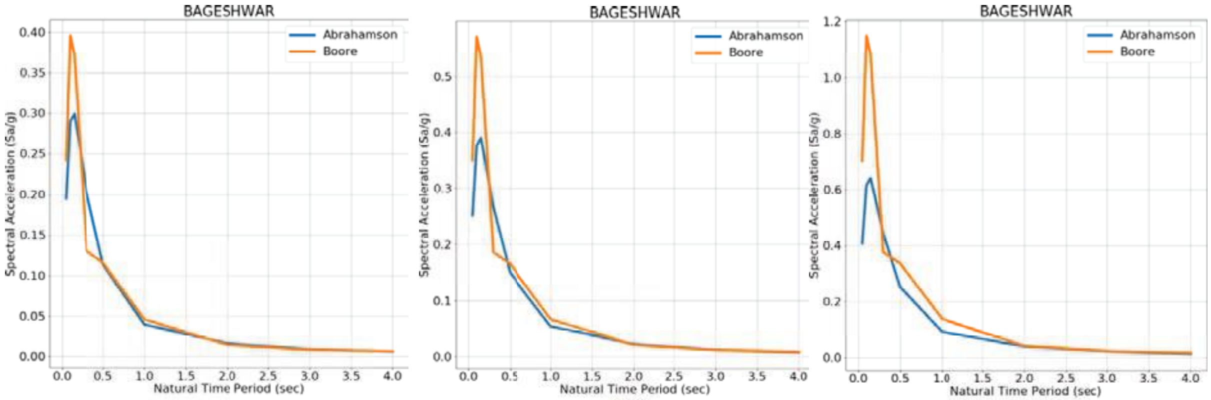
Figure 4(c) - Mean PGA contour map for 2475 years return periods using Boore et al.(2014) attenuation model

Uniform hazard spectra (UHS) at various sites for return periods of 225, 475 and 2475 years have been plotted for each district of Uttarakhand, using Abrahamson, Silva and Kamai (2014) attenuation model and Boore et al. (2014) Attenuation Model. Figures 5 to 19 show uniform hazard spectra (UHS) at various sites for return periods of 225, 475 and 2475 years respectively.



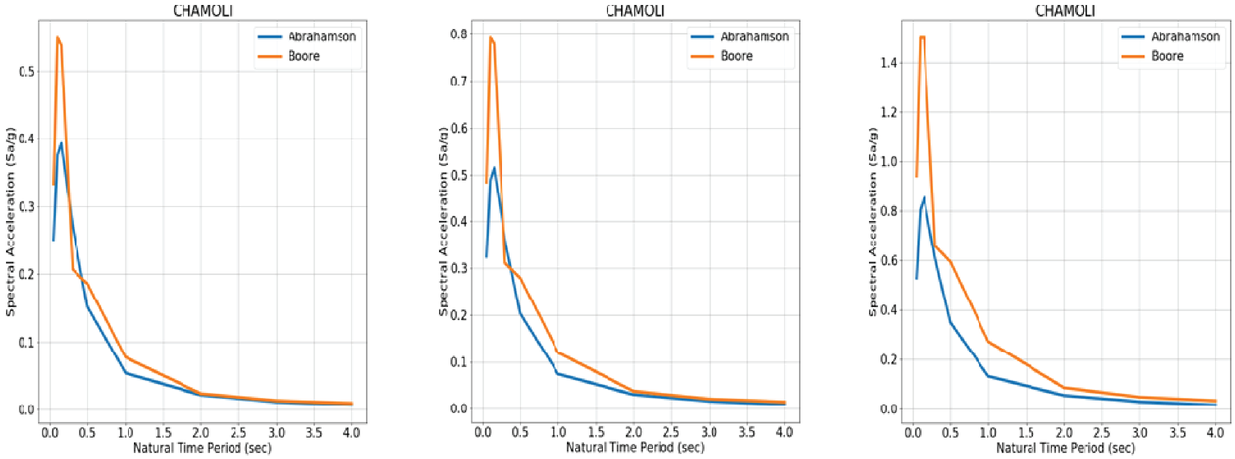
(a) (b) (c)

Figure 5(a), (b) and (c) -Uniform hazard spectra (UHS) at Almora for return periods of 225, 475 and 2475 years respectively



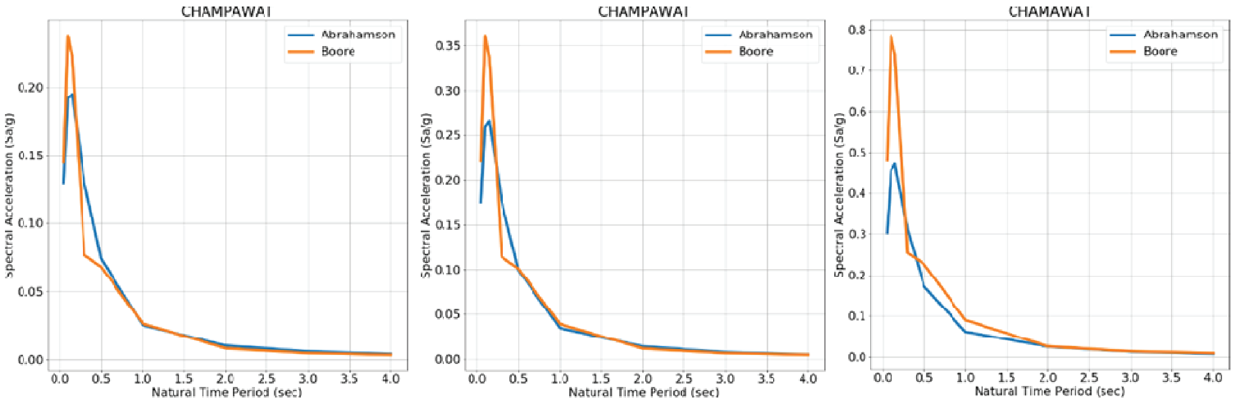
(a) (b) (c)

Figure 6(a), (b) and (c) - Uniform hazard spectra (UHS) at Bageshwar for return periods of 225, 475 and 2475 years respectively



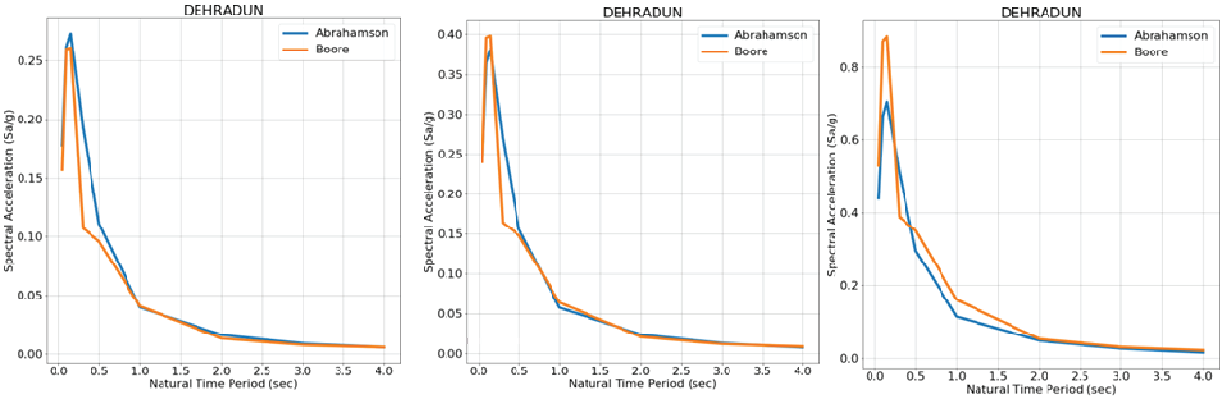
(a) (b) (c)

Figure 7(a), (b) and (c) - Uniform hazard spectra (UHS) at Chamoli for return periods of 225, 475 and 2475 years respectively



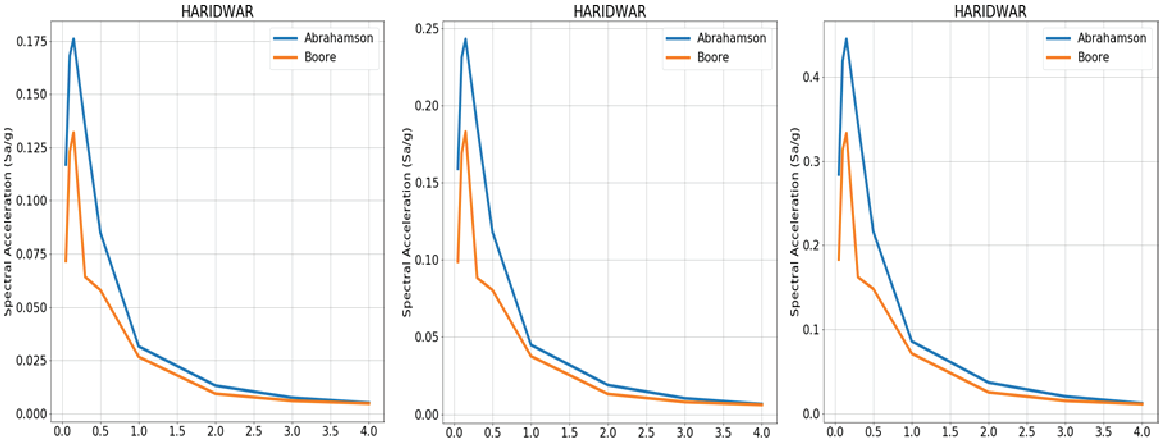
(a) (b) (c)

Figure 8 (a), (b) and (c) - Uniform hazard spectra (UHS) at Champawat for return periods of 225, 475 and 2475 years respectively



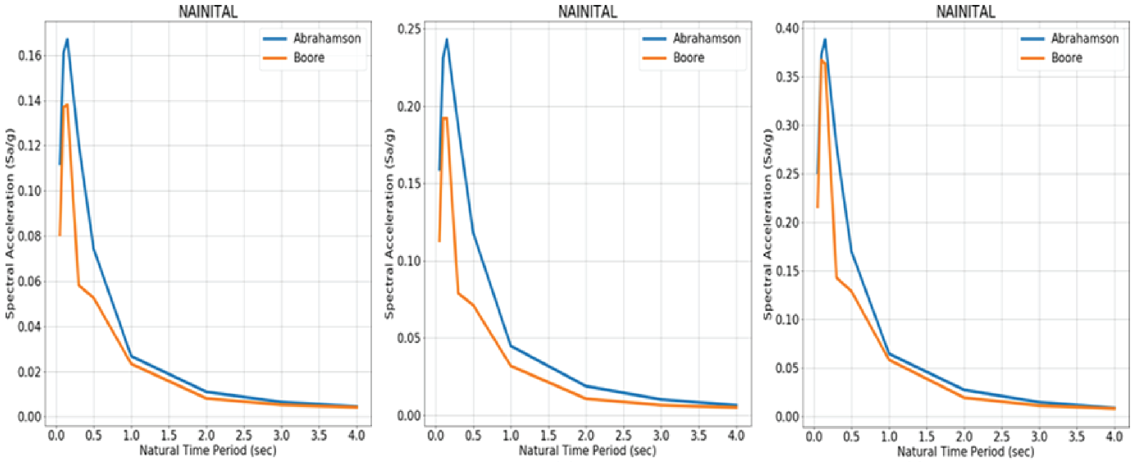
(a) (b) (c)

Figure 9 (a), (b) and (c) - Uniform hazard spectra (UHS) at Dehradun for return periods of 225, 475 and 2475 years respectively



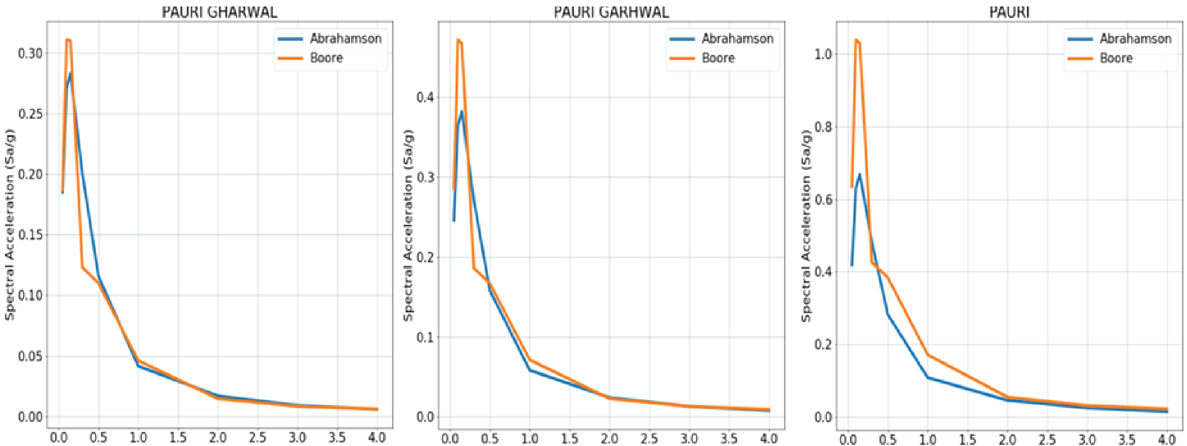
(a) (b) (c)

Figure 10 (a), (b) and (c) - Uniform hazard spectra (UHS) at Haridwar for return periods of 225, 475 and 2475 years respectively



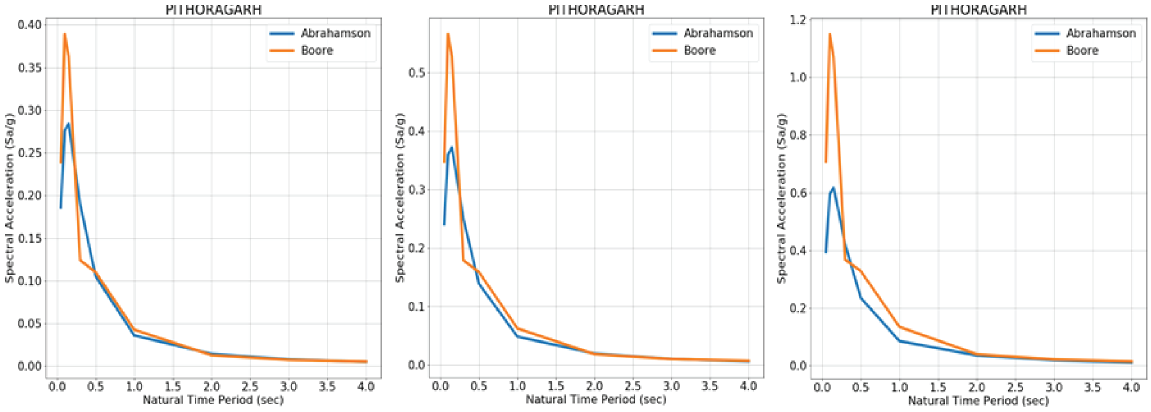
(a) (b) (c)

Figure 11 (a), (b) and (c) - Uniform hazard spectra (UHS) at Nainital for return periods of 225, 475 and 2475 years respectively



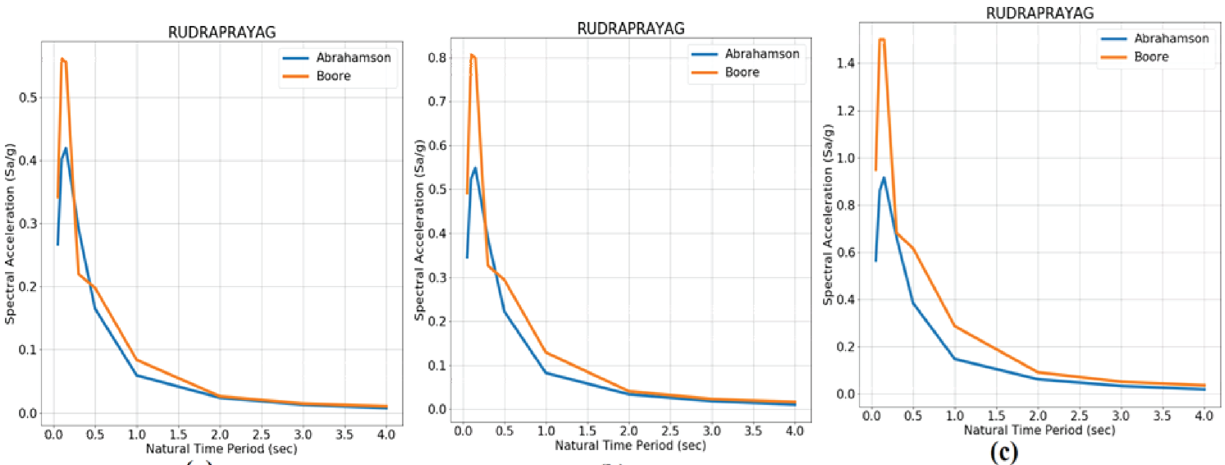
(a) (b) (c)

Figure 12 (a), (b) and (c) - Uniform hazard spectra (UHS) at Pauri Gharwal for return periods of 225, 475 and 2475 years respectively



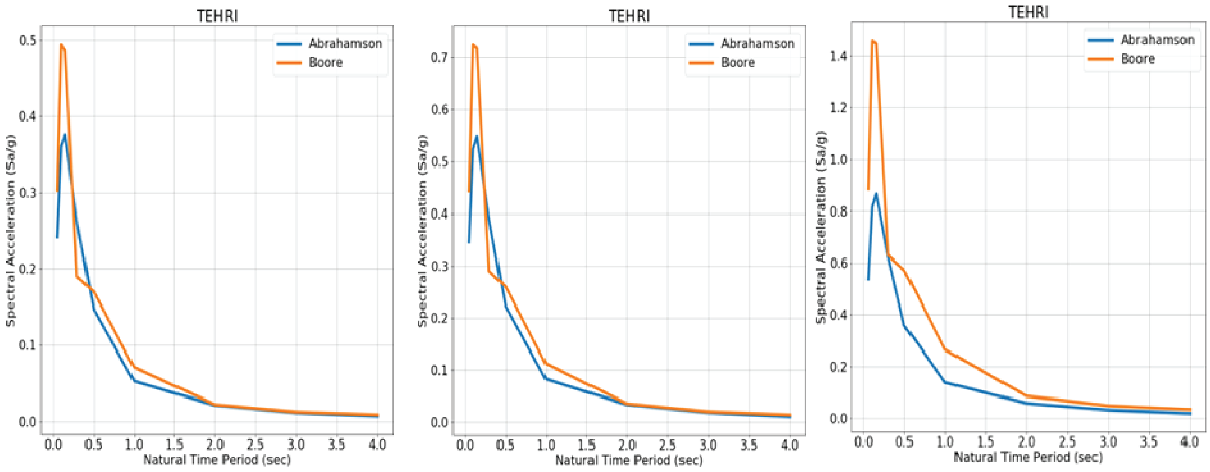
(a) (b) (c)

Figure 13(a), (b) and (c) - Uniform hazard spectra (UHS) at Pithoragarhfor return periods of 225, 475 and 2475 yearsrespectively



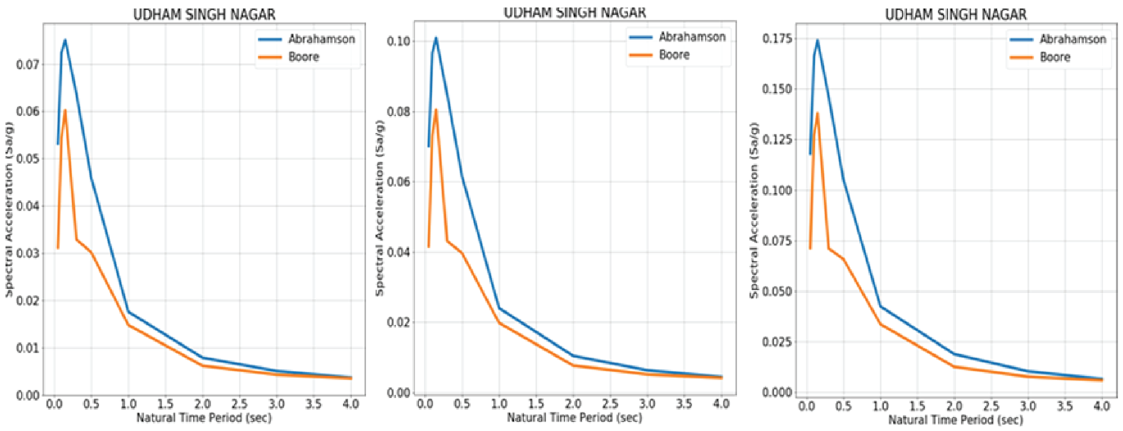
(a) **(b)** **(c)**

Figure 14 (a), (b) and (c) - Uniform hazard spectra (UHS) at Rudraprayag for return periods of 225, 475 and 2475 years respectively



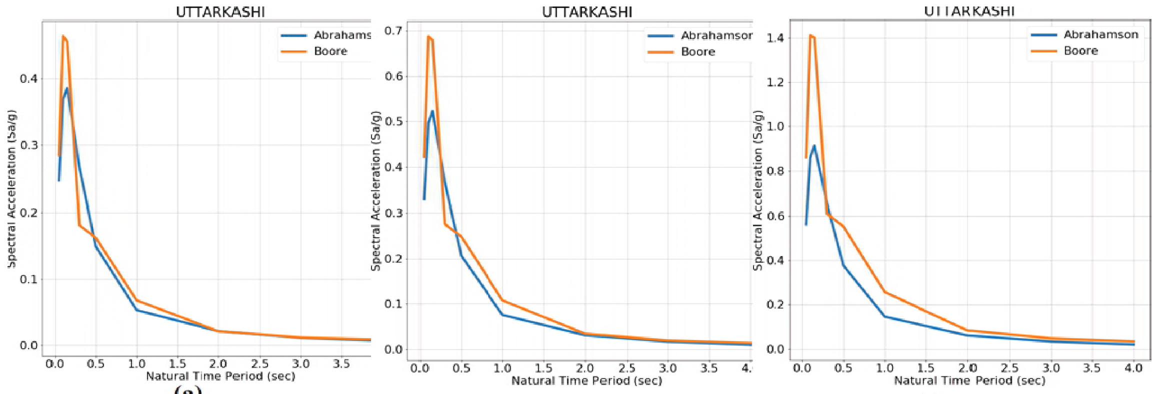
(a) **(b)** **(c)**

Figure 15 (a), (b) and (c) - Uniform hazard spectra (UHS) at Tehri for return periods of 225, 475 and 2475 years respectively



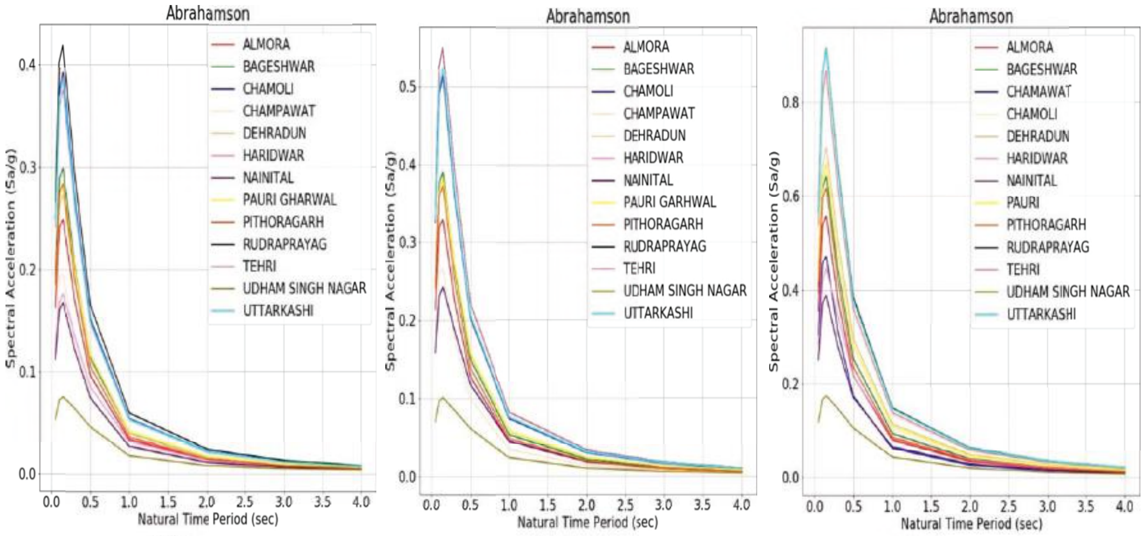
(a) **(b)** **(c)**

Figure 16(a), (b) and (c) - Uniform hazard spectra (UHS) at Udham Singh Nagar for return periods of 225, 475 and 2475 years respectively



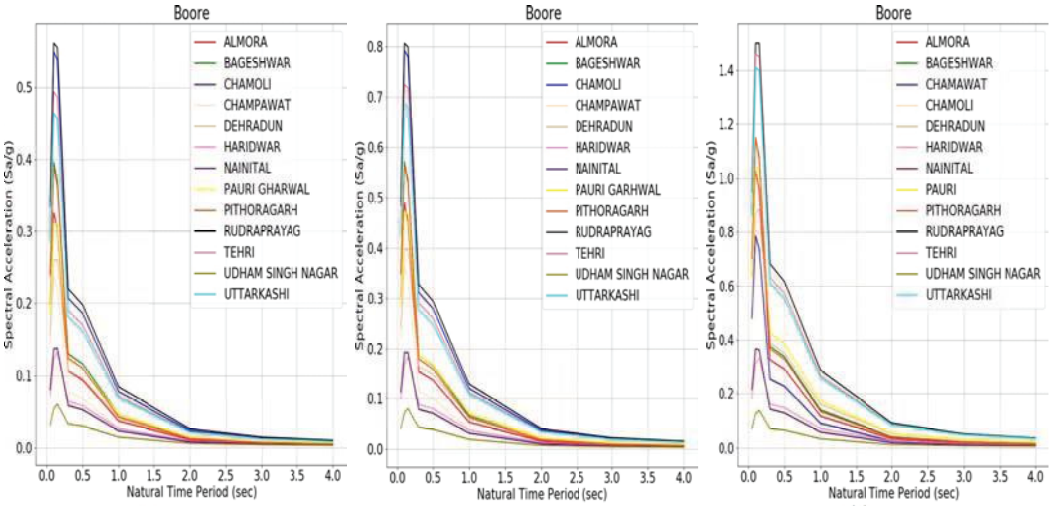
(a) (b) (c)

Figure 17(a), (b) and (c) - Uniform hazard spectra (UHS) at Uttarkashi for return periods of 225, 475 and 2475 years respectively



(a) (b) (c)

Figure 18(a), (b) and (c) -Comparison of uniform hazard spectra (UHS) at different districts of Uttarakhand for return periods of 225, 475 and 2475 years respectively using Abrahamson, Silva and Kamai (2014) attenuation model



(a) (b) (c)

Figure 19 (a), (b) and (c) -Comparison of uniform hazard spectra (UHS) at different districts of Uttarakhand for return periods of 225, 475 and 2475 years respectively using Boore et al. (2014) attenuation model

6. DISCUSSION AND CONCLUDING REMARKS

Uttarakhand is a Himalayan state of India. This mountainous state contains, in its northern section, some of the highest mountain peaks in the world which are prone to erosion and landslides and unstable because of high seismic activity. The probabilistic seismic hazard assessment (PSHA) is investigated because it involves the production of contour maps that represent the levels of ground and structural shaking expected to be experienced over a particular return period (in years). PSHA incorporates all types of uncertainties associated with the earthquake location, occurrence, magnitude etc. and is considered economical and less conservative model. PSHA results are widely used for designing any type of structures to reduce the probability of hazard level. Generally, the shaking is represented in terms of peak ground acceleration (PGA) that is generated by the effects of the rupture of a geological fault and the propagation and attenuation of seismic waves reaching the bedrock. But, actual research frontiers for state of the art in PSHA suggest to test the hazard curves against recorded strong motions and Mercalli intensity observations. The PSHA is generally performed at rock site conditions and a flat topography. However, the final response spectrum which is the further study scope must take into account the site effects through the amplification of ground motion due to the presence of sediments above the bedrock; however, the topographic effects might also influence the final motion for design at highland sites. On the basis of above study following conclusions may be drawn:

- Seismicity parameters have been estimated for various source zones, the results show that rate of occurrence of earthquakes is high in source zone UK- I as compared to other zones and low in source zone UK-II.
- Seismic hazard has been estimated in terms of PGA for various return periods for 225, 475 and 2475 years in different districts of Uttarakhand considering two NGA 2014 attenuation models. Results show that Rudraprayag district has maximum PGA value and Udham Singh Nagar has minimum value.
- Table 1 shows that the maximum magnitude of earthquake may not exceed 6.9M in Uttarakhand.

Results presented in the study could be useful for earthquake community in a wide spectrum of applications, ranging from research, national seismic hazard maps, seismic design codes, earthquake financial loss modelling, and site-specific seismic hazard evaluations for important facilities (e.g., power plants, dams, tall buildings, etc.).

Acknowledgements

Authors are grateful to Department of Earthquake Engineering, Indian Institute of Technology Roorkee, Roorkee for excellent computational facilities. Financial support provided by MHRD stipend is gratefully acknowledged by author (Shubham). Views expressed in this paper are that of authors only, and may not necessarily be of the institute.

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