

# Development of Surface Level Probabilistic Seismic Hazard Map of Himachal Pradesh

Muthuganeisan Prabhu and S.T.G. Raghukanth

**Abstract** Himachal Pradesh has experienced several major earthquakes in the past and this high seismicity can be attributed to the under-thrusting of the Indian tectonic plate against the Asian plate. Multi-channel Analysis of Surface Waves tests (MASW) were carried out at 73 test sites, located in 22 important cities, which indicated that the test sites were of C and D types. The ground motion prediction equations capable of predicting the surface level ground motion for these site conditions have been developed in line with the Probabilistic Seismic Hazard Analysis (PSHA) methodology of NDMA report (2011) by incorporating the evaluated site response functions. The probable seismic sources were identified from the Seismotectonic Atlas of India published by GSI (2000) and the recurrence parameters were established from the earthquake catalogue of Raghukanth (Bull Earthq Eng 9:1361–1386, 2011). The surface level peak ground acceleration (PGA) was estimated by PSHA approach for a return period of 2,475 year that corresponds to a 2 % probability of exceedance during a design life of 50 years. Also, the uniform hazard response spectrum plots for some important test cities are presented. The predictions of the developed GMPE agrees well with the seismic events recorded in this region.

**Keywords** Seismic hazard · Seismic zones · Site response · MASW · Himachal Pradesh

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# 1 Introduction

Himachal Pradesh lies in a seismically active region and has experienced several major earthquakes in the past such as the Kangras ( $M_w$ 7.8, 1905), Uttarkashi ( $M_w$ 7, 1991), Killari ( $M_w$ 6.2, 1993), Chamoli ( $M_w$ 6.8, 1999). The seismicity can be attributed to the presence of several major faults in this region such as the Main central thrust (MCT), Main boundary thrust (MBT), etc. Due to high topographic variation and the presence of several perennial rivers (see Fig. 1), this region has immense hydro-electric potential that has drawn a considerable investment on infrastructures such as Dams, Tunnels, etc. Additionally, the touristic appeal of this region combined with the rugged terrain has resulted in clustered and unplanned developments across this region. Hence, it becomes necessary to judiciously evaluate the seismic hazard of this region and the risk it poses to human life and infrastructure. Several works have presented the hazard map of this region such as, Khattri et al. [13], Bhatia et al. [1], Parvez et al. [19], Mahajan et al. [15], report by the National Disaster Management Authority of India (NDMA) [17], Patil et al. [20]. It should be noted that these values are presented for bedrock level with a shear wave velocity exceeding 1,300 m/s. However, most of the population centers (such as Kangra, Shimla, Mandi, Una, Solan, Sundernagar, etc.) are located on the

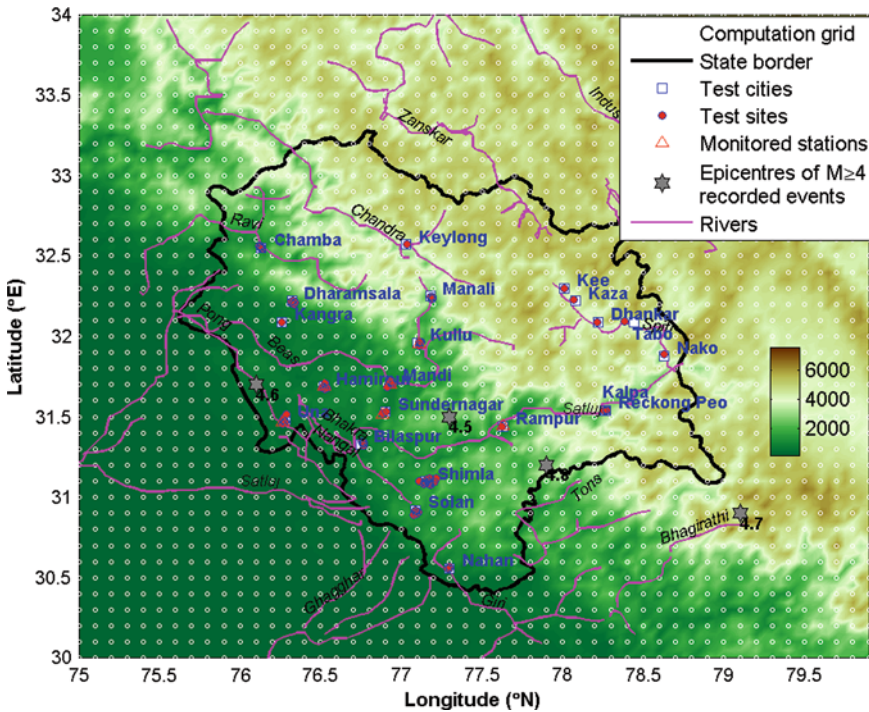


Fig. 1 Map of Himachal Pradesh: topography, location of the test sites, PSHA computation grid

lesser Himalayan region which are featured by thick Neogene Siwalik sediments with gravel and boulder beds [15] whose attenuation characteristics needs to be considered while estimating the hazard level. In such cases, the existing practice is to scale the design spectrum by a multiplying factor known as site coefficient. But, it has been well established that the local site conditions can significantly alter the ground motion by amplifying only certain frequencies depending on its dynamic characteristics. Instead, in this study, the site response function is incorporated in the procedure of PSHA to estimate the seismic hazard at surface level directly. However, this necessitates the characterisation of the site conditions at some of the important urban agglomerations in this study region.

As a result, Multi-channel Analysis of Surface Waves (MASW) tests were performed at 73 sites located in 22 important cities to characterise the dynamic properties of soil. Based on these tests, the site response functions have been evaluated using SHAKE91 [10] which were used to develop the surface level attenuation relation for the two geologic regions, viz., Himalayan and Indo-Gangetic region, observed within the test region. The developed attenuation relationships are integrated into the PSHA approach presented in NDMA report [17] to estimate the surface level hazard maps in terms of PGA values for MCE event with a return period of 2475 years that corresponds to a 2 % probability of exceedance in 50 years. The probable seismic sources have been identified from the Seismotectonic Atlas of India [8] whose seismogenic characteristics or recurrence parameters have been adopted from the NDMA report [17].

The methodology of developing the surface level attenuation relation and incorporating it into the PSHA methodology are briefly discussed further. The predictions of the attenuation relation are compared with actual events and the results of PSHA are presented in a simplified form that can be directly used for design purposes.

## 2 Geography of the Study Region

The state of Himachal Pradesh comprises of two geographically classified regions viz., Indo-Gangetic region in the South-West and the Himalayan region in the North. Remarkably, all the three geological divisions of Himalayas pass through the state with the altitudes varying from 320 m (Una district) at the low lying Siwalik regions in the South to 6,975 m (Kinnaur District) in the mountainous Greater Himalayas in the North. The altitude of the region increases from the South West towards North East (see Fig. 1). The district of Una and parts of the districts of Sirmaur, Solan, Bilaspur, Hamirpur and Kangra lie in the Indo-Gangetic plain. These regions are characterised either by the unconsolidated formations of the Siwalik sediments belonging to Quaternary era in the Southern parts to semi-consolidated formations of Tertiary era in the Northern parts with the presence of gravel or boulder embedded beds [22]. The district of Mandi, Shimla, Chamba, Kullu and parts of the districts of Bilaspur, Hamirpur, Kangra, Sirmaur and Solan are located in the lower hills of

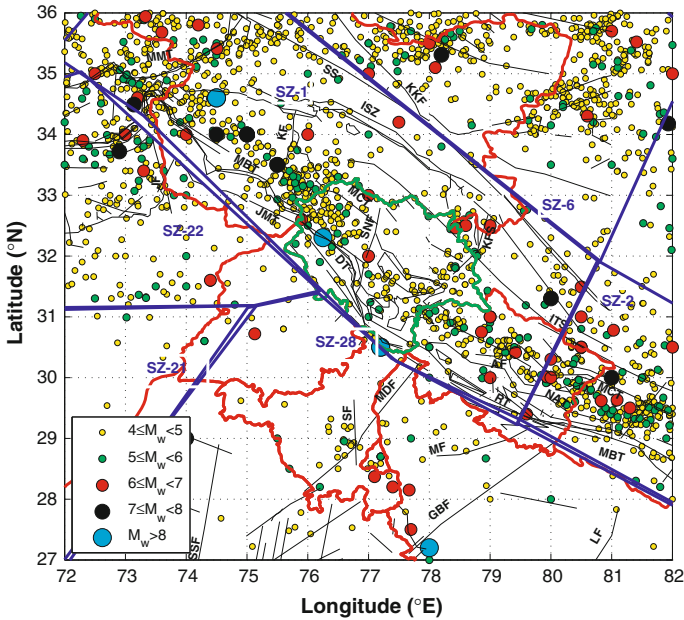
Himalayas while the districts of Kinnaur and Lahaul and Spiti lie in the outer Himalayas [12]. The lower Himalayan regions are characterised by semi-consolidated formations of Tertiary, Mesozoic and Upper Paleozoic era [22]. The upper Himalayas are characterised by consolidated formations of Mesozoic, Paleozoic and Precambrian era and marked by highly weathered residuum of the Tethyan basin and fractured formations [22]. The districts of Bilaspur, Hamirpur, Kangra, Mandi, Sirmaur, Solan and Una generally have brown, alluvial and grey brown podzolic soils, the districts of Kullu and Shimla have grey-wooded podzolic soils, while Kinnaur, Lahaul and Spiti and some parts of Chamba have humus mountain speletal soils [5].

This extreme topographic and climatic conditions has resulted in the bunching of population in the favourable lower altitude regions such as Hamirpur, Bilaspur, Una, Kangra, etc. with population density of over 250 per sq.km. compared to the harsher higher altitude regions such as Kinnaur, Lahaul and Spiti, etc. with population density lesser than 15 per sq.km [7]. Additionally, the decadal population growth exceeding 12 % in the state highlights the elevated seismic risk level posed to these clustered population centers and reinforces the need to judiciously estimate the seismic hazard level of this region.

### 3 Seismotectonics and Seismicity of the Study Region

The identification of the probable potential sources is the initial step of the PSHA methodology. It can be observed from Fig. 2 that several prominent faults are situated in the study region. The locations of these faults, that lie within a 500 km radius of the study region, have been obtained from the Seismotectonic Atlas of India [8]. A total of 192 faults were identified to lie within 500 km around the state of Himachal Pradesh and were considered as probable sources in this study and are shown in Fig. 2. It can be seen that several major faults run across or close to some important cities, namely, Jwala Mukhi Thrust (JMT) across Hamirpur; Main Frontal Thrust (MFT) near Una; Drang Thrust near Nahan, Solan, Hamirpur, Mandi and Dhramshala; Main Boundary Thrust near Solan, Mandi and Dhramshala; Main Central Thrust (MCT) near Kullu, Manali, Kalpa, Keylong; Sundernagar Fault (SF) across Sundernagar.

Figure 2 also shows the past seismicity of this region between 1664 AD to 2011 AD taken from the available literature [17, 21]. It can be observed that the region had experienced some major earthquakes of magnitude exceeding 6 ( $M_w > 6$ ) in the past. This high seismic activity of this region can be attributed to its location on the converging plate boundary between the Indian and the Asian tectonic plates. It can be seen that certain regions exhibit similar level of seismic activity and some of the past earthquakes can be associated with the identified faults. National Disaster Management Authority [17] has classified the Indian subcontinent into 32 seismogenic zones and estimated the recurrence parameters for these regions. Six of these seismogenic zones (1, 2, 3, 6, 21, 22, 28) that are present within 500 km distance of the study region have been considered in this study.



**Fig. 2** Seismicity and fault map of HP. Also, showing the seismogenic zones of India considered for this study (*AF* Alaknanda Fault, *DT* Drang Thrust, *GBF* Great Boundary Fault, *ISZ* Indus Suture Zone, *ITS* Indus Tsangpo Suture, *JF* Jhelum Fault, *JWT* Jwala Mukhi Thrust, *KKF* Karakoram Fault, *KF* Kishtwar Fault, *KFS* Kaurik Fault Sytem, *LF* Lucknow Fault, *MBT* Main Boundary Thrust, *MCT* Main Central Thrust, *MDF* Mahendragarh-Dehradun Fault, *MF* Moradabad Fault, *MMT* Main Mantle Thrust, *NAT* North Amora Thrust, *RT* Ramgarh Thrust, *SF* Sohna Fault, *SNF* SunderNagar Fault, *SS* Shyok Suture, *SSF* Sardar Shahar Fault [8, 17, 21, 23])

## 4 Site Characterisation by MASW Test

The local soil conditions are known to significantly alter the ground motion and this becomes of engineering importance when the soil strata amplifies the ground motion across certain frequency ranges that are close to the structural frequency. It is widely accepted that the elastic response of the soil medium can be characterised by means of its shear wave velocity [9]. In this study, the shear wave velocity profiles of 73 sites located in 22 important cities, including all the 12 district headquarters, were estimated through Multichannel Analysis of Surface Waves (MASW) tests [18].

In short, an artificial source initiates the surface (Rayleigh) waves which will be recorded by multiple receivers spread along a survey line. Spectral analysis of these records will reveal the dispersion characteristics of the medium resulting in what is known as a dispersion curve, which indicates the variation in the wave velocity with depth. By inversion technique, the shear wave velocity profile is estimated by iterative comparison with the measured dispersion curve in a least-squares sense [18].

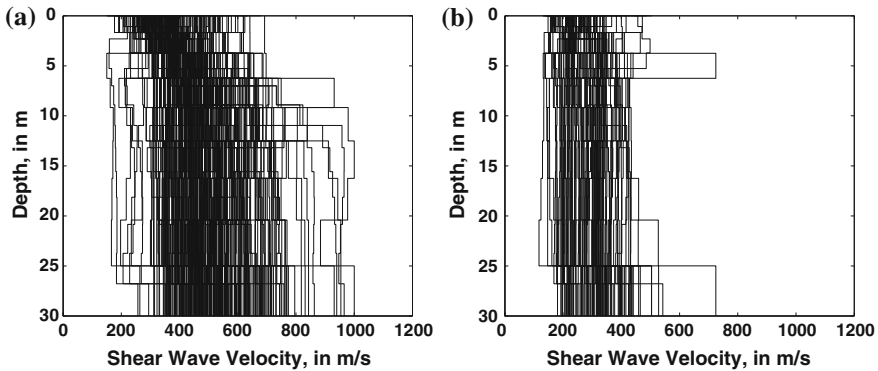


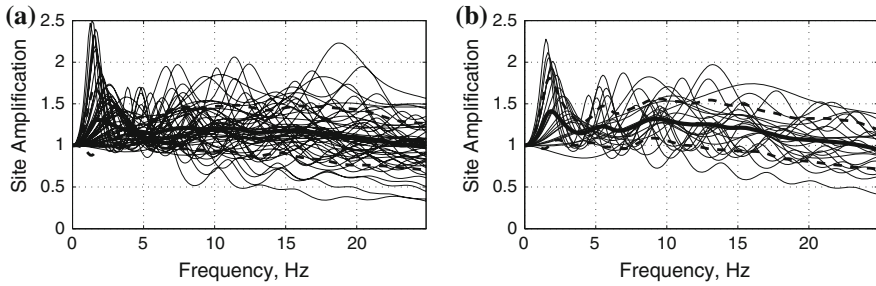
Fig. 3 Shear wave velocity profiles **a** C-Type sites, **b** D-Type sites

The active seismic source used was a 8 kg hammer, with an automatic trigger, struck against a metal plate which was always placed at a known offset from a equally spaced linear array of geophones or receivers (4.5 Hz frequency). The data was collected by a 24-channel Geode and stored in a laptop. A minimum of 3 shots were stacked at each source location to improve the Signal/Noise ratio.

The test locations at each of these cities were chosen based on their proximity to important structures, open area and low noise level. Based on the average shear-wave velocity in the top 30 m or  $V_s,30$  values, these sites were classified according to IBC 2009 site classification. Among the 73 test sites, it was found that 2 were of B-type, 50 were of C-type and 21 were of D-type. Since the  $V_s,30$  values of the two B-type sites were on the lower end, their  $V_s$  profiles were grouped along with the C-type sites for estimation of the site response coefficient. The shear wave velocity profiles for C and D-type sites are shown in Fig. 3a, b.

## 5 Site Response Function and Surface Level Ground Motion Simulations

From the MASW tests, it shows that the site conditions at the important cities were of either C or D type. The computed shear wave velocity profiles of these test sites indicate the variability in the soil layering within the top 30 m. Using these profiles, we perform a nonlinear site response analysis using SHAKE91 [10] to estimate the frequency response function of the site coefficient. For this analysis, 20 acceleration time histories were simulated using a finite source seismological model [3] for a A-type site or at bed rock level, simulated for both Himalayan and Indo-Gangetic regions, and were used as the input wave at the bedrock level. The frequency response function of the site coefficient or the site response function ' $F_s(f)$ ' is evaluated as the ratio of the spectral acceleration at the surface and the bedrock level. These site response functions were evaluated for all the 73 sites. Figure 4a, b



**Fig. 4** Soil response function **a** C-Type sites, **b** D-Type sites

shows these functions grouped based on their site classification to evaluate the mean site response function and its standard deviation for both the site types.

In the absence of ground motion database with records complete for all magnitudes ( $M$ ) and hypocentral distances ( $r$ ), it has become acceptable to use a database of simulated ground motion [17]. In this study, the site response function, that were computed earlier, were used in the place of the site dependent function used in the stochastic finite fault approach of Boore [2] to simulate the synthetic ground motion time histories at the surface level. These ground motions were simulated for 10 values of  $M$  (ranging from 4 to 8 at 0.5 units), 20 values of  $R$  (ranging from 1 to 500 km), 8 azimuths (ranging from  $0^\circ$  to  $315^\circ$  at  $45^\circ$  interval) and 50 random combinations of 7 other uncertain seismic parameters such as: stress drop; focal depth; dip; radiation coefficient and pulsing percentage area, whose ranges were reported in the NDMA report [17] for the two geological regions. As a result, the synthetic database reflects the dynamic response of the local soil conditions observed in the study region. The intensity measures (such as PGA) of these surface level ground motions can be utilised to develop the region-specific attenuation relation described in the following section.

## 6 Surface Level Ground Motion Prediction Equations

The purpose of performing the site characterisation and developing a database of synthetic ground motion is to account for the uncertainty in the medium characteristics or the source-to-site path that causes the attenuation of the ground motion. The ground motion generated at a source attenuates as it travels through the medium and the extent of attenuation depends on several factors such as source-to-site distance (radiation damping), medium properties (anelastic damping), rupture characteristics, etc. Using the simulated database of surface level ground motion, region-specific surface level ground motion prediction equation (also known as attenuation relation), for C and D type sites in the two geological regions, have been



developed using the functional form proposed by the NDMA report [17] which is given as follows,

$$\ln\left(\frac{Y}{g}\right) = c_1 + c_2M + c_3M^2 + c_4r + c_5 \ln(r + c_6e^{c_7M}) + c_8 \log(r)f_0 + \ln(\varepsilon) \quad (1)$$

where,  $Y$  is the ground motion intensity measure (PGA),  $M$  is the magnitude,  $R$  is the hypocentral distance and  $f_0 = \max(\ln(r/100), 0)$ . The coefficients  $c_1, \dots, c_8$  are determined by a two-step regression method proposed by Joyner and Boore [11] and the values are presented in Table 1. The term  $\varepsilon$  accounts for the aleatory uncertainty in the attenuation relation. The predictions of the developed GMPE compares agreeably with that of the response spectrum of measured events (35 Hz low-pass filtered data available [16]) as can be seen in Fig. 5a, b. For this comparison, the coefficients of the GMPE were evaluated for 28 natural periods and the values presented in Table 1 correspond to the  $S_a$  values at  $T = 0$ s.

With the development of these relations, it is now possible to estimate the surface level hazard at any site within the state of Himachal Pradesh due to any seismic activity at any of the 192 probable seismic sources.

## 7 Probabilistic Seismic Hazard Analysis

The PSHA methodology using Cornell-McGuire approach has been discussed widely in the literature [4, 14, 17] and was carried out using an in-house MATLAB<sup>®</sup> code. The aim of PSHA is to estimate the probability of the ground motion, at a site, to exceed certain intensity level due to earthquakes of any magnitude occurring at any or all of the probable seismic sources. If the earthquakes occurring at a fault are assumed to be independent then the number of earthquakes occurring at a fault follows a stationary Poisson process. Then, the probability of the ground motion at a site ( $Y$ ) exceeding a certain level ( $y^*$ ) in a time frame of  $T$  years will be,

$$P(Y > y^* \text{ in } T \text{ years}) = 1 - e^{-\mu_{y^*}T} \quad (2)$$

where,  $\mu_{y^*}$  is the mean annual rate of exceedance and is determined by,

$$\mu_{y^*} = \sum_{i=1}^K N_i(m_0) \times \int_{m=m_0}^{m_u} \int_{r=r_{min}}^{r_{max}} P[Y > y^* | m, r] p_{R|M}(r|m) p_M(m) dr dm \quad (3)$$

where,  $p_M(m)$  is the probability density function of the magnitude expressed as an exponential random variable and accounts for the magnitude uncertainty,  $p_{R|M}(r|m)$  is the probability density function of the hypocentral distance computed numerically by the method of Der Kiureghian and Ang [6] and accounts for the uncertainty



**Table 1** Coefficients of the attenuation relation in Eq. 1

| Site class                  | $c_1$   | $c_2$  | $c_3$   | $c_4$   | $c_5$   | $c_6$  | $c_7$  | $c_8$  | $\sigma(\epsilon)$ |
|-----------------------------|---------|--------|---------|---------|---------|--------|--------|--------|--------------------|
| <i>Himalayan region</i>     |         |        |         |         |         |        |        |        |                    |
| C                           | -4.7738 | 1.5004 | -0.0204 | -0.0048 | -1.4216 | 0.0465 | 0.8748 | 0.0912 | 0.3864             |
| D                           | -4.5304 | 1.4623 | -0.0175 | -0.0049 | -1.4392 | 0.0365 | 0.8948 | 0.0985 | 0.3881             |
| <i>Indo-Gangetic region</i> |         |        |         |         |         |        |        |        |                    |
| C                           | -4.3477 | 1.2807 | -0.0087 | -0.0064 | -1.2940 | 0.0084 | 1.0489 | 0.1234 | 0.3930             |
| D                           | -4.3343 | 1.2847 | -0.0090 | -0.0064 | -1.2983 | 0.0086 | 1.0439 | 0.1238 | 0.3941             |

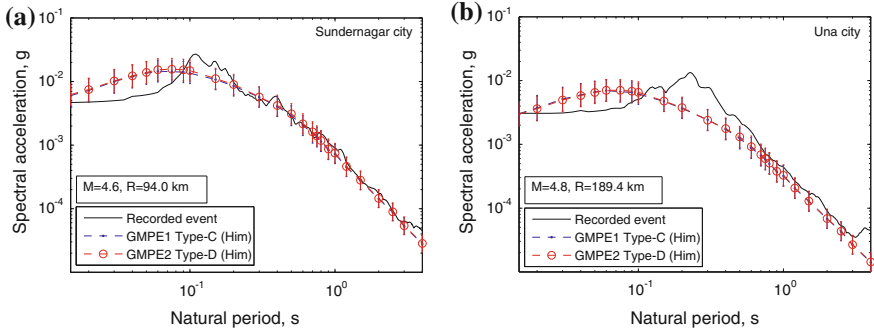


Fig. 5 Comparison the GMPE estimations with response spectrum of recorded events

in the hypocentral distance.  $P[Y > y^* | m, r]$  is the conditional exceedance probability of  $y^*$  to be exceeded at the surface level, for a specified magnitude and hypocentral distance, and is determined using the developed GMPE. This accounts for the uncertainty in the medium characteristics and is expressed as a lognormal random variable.

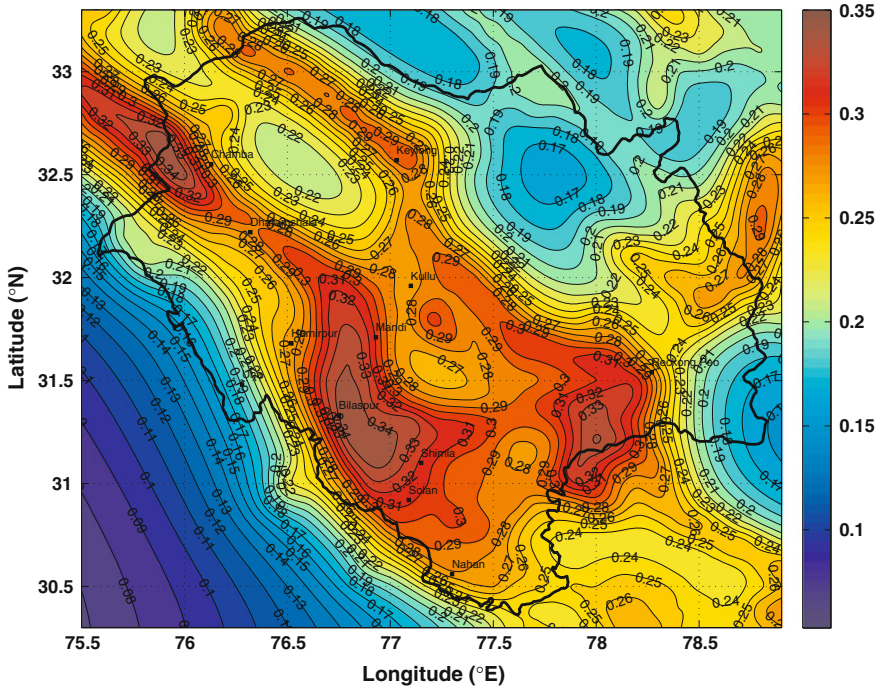


Fig. 6 PGA map for C-type sites for 2475 years return period

## 8 Results and Discussions

The region considered for this study spreads over  $30^{\circ} 20'N$  to  $33^{\circ} 15'N$  latitudes and  $75^{\circ} 45'E$  to  $79^{\circ} 00'E$  longitudes and encompasses the entire state of Himachal Pradesh and the surface level seismic hazard has been estimated at a  $0.2^{\circ} \times 0.2^{\circ}$  grid level covering the entire study region as shown in Fig. 1. The MASW results indicate that the C and D type sites are prevalent at the populated regions of the state. B-type sites were detected at only 2 locations amongst all the tested locations and have been considered as C-type for conservative estimates, since their  $V_s30$  values were bordering with that of C-type. Since, it is neither possible nor necessary to accurately determine the site condition at all location across the state, we have estimated the surface level hazard for this region considering it entirely to be of either C or D type. Thus, the surface level peak ground acceleration values were estimated for a return period of 2475 years, which corresponds to a 2 % probability of exceedance in 50 years, for these two site conditions and are shown in Figs. 6 and 7. It can be observed from these plots that the obtained PGA values are in the range of 0.16–0.35 g for C-type sites and 0.16–0.38 g for D-type sites. These values are higher than the values presented for A-type sites in NDMA [17] and Patil et al. [20] (with variable 'b') due to the consideration of the site effects.

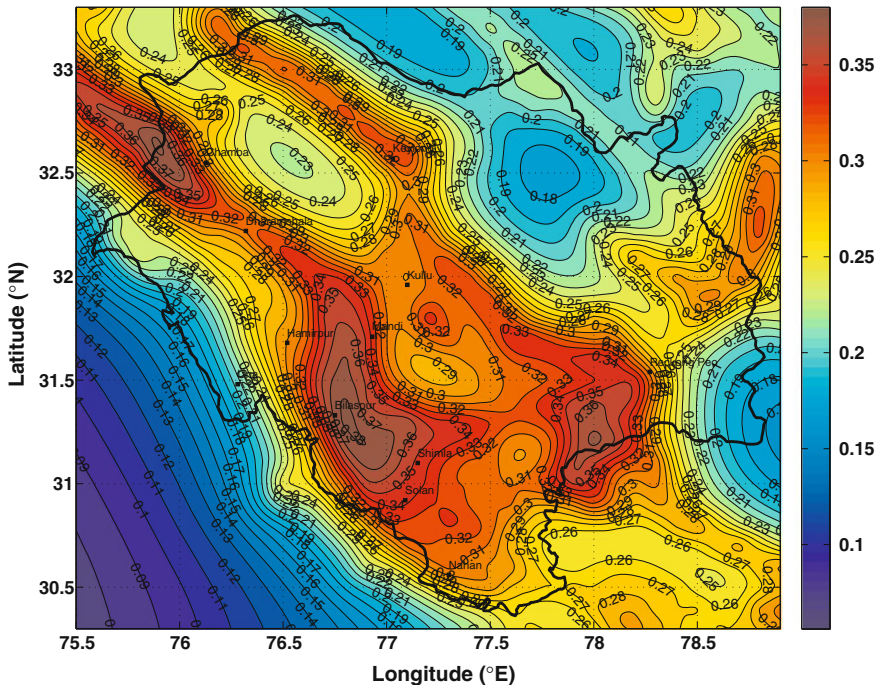
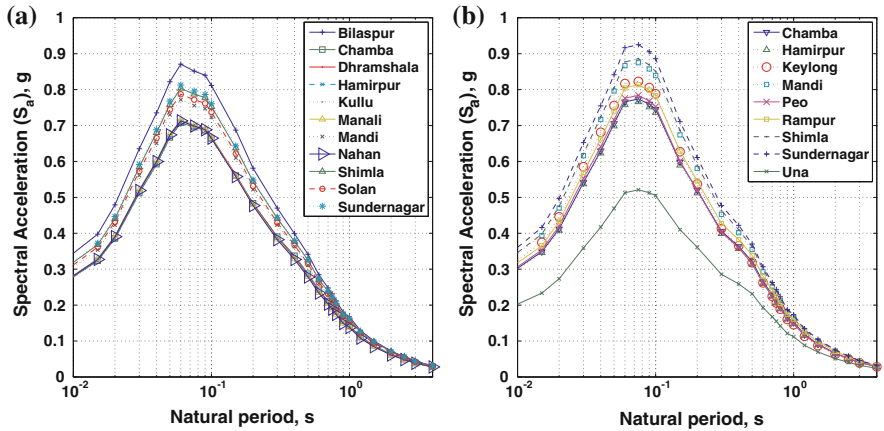


Fig. 7 PGA map for D-type sites for 2475 years return period



**Fig. 8** Uniform hazard response spectrum for 2475 years return period. **a** C-type sites. **b** D-type sites. *Note* Some cities exhibit the same site type at all local test sites and UHRS is shown for that site type alone

Apart from the PGA contour maps, the Uniform Hazard Response Spectrum (UHRS) has also been estimated for all the district headquarters as shown in Fig. 8a, b. In order to obtain the UHRS curves, the ground motion prediction equations were developed using spectral acceleration values at 28 time periods. Each value in these response spectrums have uniform probability of exceedance for all the 28 spectral values. It can be observed from these plots that among all C-type cities, Bilaspur exhibits the highest hazard while Solan being the lowest. Also, Una being the only city in the Indo-Gangetic region exhibits the lowest hazard level among the D-type sites while the highest being Sundernagar. It can also be seen that for certain cities with both site types (e.g. Chamba, Sundernagar, etc.), the D-type sites exhibit higher hazard levels as expected.

### 9 Conclusions

In this study, MASW tests were conducted at 73 sites located in 22 important cities of Himachal Pradesh, to estimate the dynamic characteristics of these site conditions. Based on the evaluated site response functions, ground motion prediction equations have been developed to predict the surface level peak ground acceleration values for the widely prevalent C and D type sites in the two geological regions, viz., Himalayan and Indo-Gangetic regions. The predictions of the GMPE agrees with the measured values of actual events. Using these attenuation relations, the probabilistic seismic hazard analysis has been carried out for the state of Himachal Pradesh by adopting the framework proposed in the report of the National Disaster Management Authority [17]. The seismicity of 192 faults identified within a

500 km distance from this region have been considered while carrying out PSHA. The estimated surface level seismic hazard (PGA) of the Himachal Pradesh are presented for the both C and D site conditions. Also, Uniform Hazard Response Spectrum (UHRS) plots for some important cities are presented.

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