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Probabilistic seismic hazard assessment in the vicinity of MBT and MCT in western Himalaya

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ABSTRACT- *Major seismic activity in India is concentrated along the Himalayan arc including the western Himalaya. A region in the vicinity of Main Boundary Thrust (MBT) and Main Central Thrust (MCT) bounded by latitude 29^o N to 36^o N and longitude 73^o E to 80^o E was considered for the study. Nine Seismogenic Source Zones (SSZ), were identified on the basis of seismicity and the tectonics around it. Seismic hazard parameters were computed for each source zone and return periods were calculated for different magnitude earthquakes. For validation of return periods, seven recent earthquakes were studied. Out of seven earthquakes three earthquakes of magnitude between 5.0 and 6.0 occurred in Kangra SSZ . Two Ground Motion Prediction Equations (GMPE's) were used to estimate peak ground acceleration (PGA) in the region. PGA in the region was estimated to vary between 0.013 g to 0.315 g for 10% probability of exceedance in 50 years, and between 0.024 g to 0.68 g for 2% probability of exceedance in 50 years. Highest PGA values ≥ 0.31 g were observed in Kangra and Chamba district of Himachal Pradesh. For the Kangra SSZ, a return period of 141 years was estimated for magnitude M_w = 8.0, 44 years for M_w = 7 and 14 years for M_w = 6. Results obtained in the present study were compared with other studies. This hazard analysis study underlines the urgency for carrying out vulnerability analysis to estimate the populations that are at risk to this threat perception, so that appropriate mitigation measures can be put in place.*

Keywords: *Hazard Parameters, Probabilistic Seismic Hazard Assessment (PSHA), Peak Ground Acceleration (PGA), Seismogenic Source Zone (SSZ), Western Himalaya*

I. INTRODUCTION

Major seismic activity in India is concentrated along the geologically young and seismo-tectonically active Himalayan arc due to the ongoing continent-continent collision between the Indian and the Eurasian plates. As a part of the Alpine Himalayan seismic belt, this arc has experienced four great earthquakes within a short span of 53 years during 1897 to 1950. The great Kangra earthquake of 4th April 1905, with its epicentre in the vicinity of the Main Boundary Thrust, in the state of Himachal Pradesh in western Himalaya, is one of these. As damage to ground and the built environment was phenomenal in the meizo-seismal and adjoining areas of this great earthquake, and as the region is going through a phase of rapid techno economic development, it is pertinent to assess seismic hazard in the light of the available seismicity, tectonics and attenuation relationships.

Seismic hazard describes the potentially damaging natural phenomena associated with earthquakes, such as ground shaking, surface fault rupture, soil liquefaction, landslides, fissures and tsunami. This phenomenon could result in adverse consequences to the society such as destruction of the built environment and loss of life. Seismic hazard assessment involves quantitative estimation of ground shaking. Seismic hazards can be assessed deterministically as and when a particular earthquake scenario is assumed, or probabilistically, in which uncertainties in earthquake size, location, and time of occurrence are explicitly considered [1].

In the present study, an attempt is made to assess the probabilistic seismic hazard in the vicinity of Main Boundary Thrust (MBT) and Main Central Thrust (MCT) in the western Himalaya region, within latitudes 29.0º to 36.0ºN and longitudes 73.0º to 80.0ºE. A total of 117 tectonic features which include thrusts, faults, lineaments, anticlines and suture zones were identified. Nine Seismogenic Source Zones (SSZ), were identified on the basis of seismicity and the tectonics around it. Seismic hazard parameters were computed for each source zone. For validation of return periods obtained for different magnitude earthquake, seven recent earthquakes were studied. Two Ground Motion Prediction Equations (GMPE's) were used to estimate peak ground acceleration (PGA) in the region. The result of this study has useful applications in land use planning, preparedness, and mitigation measures that can be taken before another destructive earthquake ravages the area.

II . STUDY AREA

Western Himalayas in India, a part of the seismically active Alpine Himalayan belt, and comprise of the states of Jammu & Kashmir, Himachal Pradesh and Uttarakhand. This region lies in the seismic zones IV and V of the seismic zoning map of India [2], and is prone to earthquake hazard. In Zone IV, MM intensity between VIII and IX, and peak ground accelerations of 0.24 g are expected. Zone V is a more severe zone, and earthquakes of magnitude larger than 7.0, with MM intensity IX or greater, with peak ground accelerations of 0.36 g are prevalent [2]. This region has experienced several moderate to large-sized earthquakes including the great Kangra earthquake of 4th April 1905 (M_s = 8.6, [3]; M_s = 8.0, [4]). It was one of the most devastating earthquakes of the last century in the Western Himalaya. The maximum observed intensity at the epicentre was X on the Rossi-Forel scale. It caused massive destruction of buildings over a large area, from Kangra to Mandi and in the region around Dehradun including foothills of the Himalaya, with a death toll of more than 19,000 [5]. On the basis of intensity distribution the length of fault rupture was estimated to be between 100 and 150 km ([6]; [7]), and the focal depth was estimated as 35 km (ISC). Aftershocks of this earthquake were scattered over a large area and continued for many years [5]. For the purpose of estimating probabilistic seismic hazard (PSHA) in the vicinity of the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT) in the western Himalaya, a large region bounded by latitude 29^o N to 36^o N and longitude 73^o E to 80^o E was considered for this study, and is shown in Fig. 1.

III. SEISMO-TECTONICS OF THE REGION

A comprehensive database of seismicity and tectonics was prepared for the study area. Seismicity of the region is attributed mainly to the convergence between the Indian and the Eurasian plates, with continent – continent collision. The region has witnessed several destructive earthquakes, such as the Kinnaur earthquake in 1975, Uttarkashi earthquake in 1991, Chamoli earthquake of 1999 and the Kashmir earthquake of 2005. Seismicity of the region was compiled from various earthquake catalogues provided by different agencies, viz. India Meteorological Department (IMD), International Seismological Centre (ISC) and United States Geological Survey (USGS). The compiled data consisted of 2749 events with different magnitude types, such as m_b, M_s and M_L. The compiled catalogue was homogenized to unified moment magnitude, M_w, using appropriate magnitude conversion relations given by [8] and [9]. The homogenized catalogue was then declustered using the method of [10], in which 1172 events emerged as the main shocks. The salient features of this homogenised and declustured catalogue, henceforth referred to as the MHD earthquake catalogue for Western Himalaya , are given in table 1, and an epicentral plot of the events is shown in Fig.1.

Due to continent – continent collision between the Indian and the Eurasian plates, the study area is manifest with complex tectonics. A total of 117 tectonic elements were identified in the study area perusing the Seismotectonic Atlas of India and its Environs [11], which were digitized in ArcGIS 9.3. These tectonics elements were used in hazard analysis and are shown in Fig. 1.

Of these 117 tectonic features, 30 tectonic elements comprised of thrusts, faults, suture zones and anticlines. The 14 thrusts are: Drang Thrust, Jwalamukhi Thrust, Main Boundary Thrust (MBT), MBT-A (a thrust close to, parallel and south of MBT), Main Central Thrust (MCT), Main Frontal Thrust (MFT), Main Karakoram Thrust (MKT), Main Mantle Thrust (MMT), North Almora Thrust (NAT), Ramgarh Thrust, Reasi Thrust, Salt Range Thrust, South Almora Thrust (SAT) and Vaikrita Thrust; the 13 faults were: Alaknanda Fault, Altyn Tagh Fault, Beng Co Fault, Jhelum Fault, Kallar Kabar Fault, Karakoram fault, Kaurik Fault System, Kishtwar Fault, Mangla Fault, Mahendragarh Dehradun Fault, Ropor fault, Sundarnagar Fault and Tso Morari Fault; the two suture zones were: Indus Suture zone and Shyok Suture; and Mastgarh anticline. The 87 unnamed tectonic units in the Seismotectonic Atlas were assigned names for digitization and for purposes of further analysis. Of these, 18 thrusts were named as TH-01 to TH-16 and TR-01 and TR-02. Seven additional thrusts were in the form of complex closed loops, and were named as T-1 to T-7, and these exist in the region between the MBT and the MCT, southeast of Sundarnagar Fault. Further, 16 neo-tectonic faults were named as FR-01 to FR-16, 28 lineaments were assigned names L01 to L28, 15 faults involving basement and cover were named as FG-01 to FG-15, and 3 gravity faults were named as GF-01 to GF-03.

Several mega thrusts, faults and suture zones are parallel and sub parallel to the Himalayan arc, having an almost NW-SE trend in the study area. From north to south these are: the Indus Suture Zone (ISZ), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT). These mega tectonic features manifest throughout the Himalayan arc, and have prominent surface manifestations at several places in Western Himalaya. The MCT terminates against the Kishtwar fault in Jammu and Kashmir. MFT is also known as the Frontal Foothill Thrust (FFT) and is a neo-tectonic thrust.

The Karakoram Fault (KF), north of the ISZ, exhibits a huge offset and extends for more than 1,000 km from Central Pamir to North of Uttarakhand Himalayas. The region between the MBT and MFT is traversed by several thrusts and faults. Some of these, such as Jwalamukhi Thrust (JT) and Drang Thrust (DT), can be traced over long distances. In addition to the tectonic features mentioned here, several prominent faults and lineaments transverse to the Himalayan trend, such as the Kishtwar Fault, Sundernagar Fault (SNF), and the Mahendragarh Dehradun (MHD-DDN) subsurface fault.

Seismo-tectonics of the region is related to the regional tectonic features like thrusts and faults and clustering of epicentres. A very interesting pattern emerged with respect to the MCT and the MBT. Several clusters of dense seismicity were obvious; viz. in the western syntaxes, another cluster exists in the area bound by the MBT in the south, MCT in the north, Kishtwar Fault in the west and Sundarnagar Fault in the east. Epicentre of the great Kangra earthquake of 1905 is a part of this cluster, and it is in the vicinity of the MBT. Another prominent cluster of seismicity lies further east, along the MCT. Uttarkashi earthquake of 1991 and Chamoli earthquake of 1999 are part of this cluster. A prominent cluster of seismicity was observed transverse to the Himalayan trend, along the Kaurik Fault system. The Kinnaur earthquake of 1975 is part of this cluster. Another cluster of dense seismicity is observed east of Karakoram fault and along Beng Co fault in the north eastern part of the study area. Compared to the regions already discussed, seismicity is sparse in three regions, viz. south of the MBT; along the Jhelum fault; and in the region along ISZ, roughly defined between MCT, Shyok Suture, Kishtwar Fault and Tso Morari Fault. A combination of tectonics and seismicity was used in identification and demarcation of seismogenic source zones.

IV. PROBABILISTIC SEISMIC HAZARD ASSESSMENT

The goal of PSHA is to estimate the probability of exceedance of various ground-motion levels at a site, considering all earthquakes and tectonic sources in the near vicinity. The method initially formalized by [12] is adopted in this paper. PSHA starts with identification of seismogenic source zones (SSZ) within a study area. Each SSZ is characterized by its geometry, earthquake potential and probability distribution of potential rupture locations within the SSZ.

4.1 Seismogenic source zones

Based on seismicity and tectonics of the region the study area was divided into nine seismogenic source zones (SSZ). The criteria for their identification were based on the density of seismicity clusters, which were further demarcated by tectonic elements around them. For example, SSZ 1 is the area demarcated by MBT, MCT and Kishtwar and Sundarnagar faults. It has a dense cluster of earthquakes within this zone. SSZ 1 refers to the Kangra source zone. It shows a dense cluster of seismicity and is demarcated by the MBT in the south, MCT in the north, Kishtwar fault in west and Sundarnagar fault in the east. The great Kangra earthquake is part of this cluster. SSZ 2 refers to the Uttarakhand source zone and is demarcated by the MBT in the south, MCT in the north, Sundarnagar Fault in the west and 80°E longitude in the east. Most epicentres are either close to MCT or north of MCT. Uttarkashi and Chamoli earthquakes are part of this zone. SSZ 3 is the Western Syntaxes source zone and has a dense cluster of earthquakes along the Main Mantle Thrust (MMT) and the MBT. The Kashmir earthquake of 2005 is a part of this zone. Another prominent cluster of earthquakes was observed along the Kaurik fault system, which is transverse to the Himalayan arc. The MCT delineates its southern boundary, the Karakoram fault its northern boundary, the north-south extension of the Tso Morari Fault its western extremity and sparse seismicity east of Kaurik Fault marks its eastern boundary. This is demarcated as SSZ 4. The Kinnaur earthquake of 1975 is part of this dense cluster.

SSZ 5 is the Kashmir zone and compared to SSZ 1 to 4 shows sparse seismicity. It is demarcated by the MCT in the south, Shyok suture in the north, northward extension of the Kishtwar fault in the west, and north-south extension of the Tso Morari Fault in the east. SSZ 6 is the Western Tibet source zone, and has the lowest seismicity of all source zones. It is delineated by the MCT in the south, Karakoram fault in the north, longitude 80° in the East and boundary of the SSZ 4 in the west. SSZ 7 is the Karakoram source zone, and occupies a large corner in the north eastern part of the map. Its southern edge is demarcated by the Shyok suture in the North West which continues into the Karakoram Fault in the south east, its northern boundary is demarcated by 36°N latitude, its western boundary is bound by the eastern boundary of SSZ 3, and eastern boundary is delimited by 80° E latitude. SSZ 8 is the Jhelum zone. It is the smallest of all source zones and shows a cluster of earthquakes distributed along the north south trending strike slip Jhelum fault. SSZ 9 is the Indo Gangetic source zone. It is the largest source zone in terms of area and shows sparse seismicity. The identified seismogenic source zones are shown in Fig. 1, and table 2 shows salient features in terms of area, magnitude wise distribution of events and prominent tectonic features.

4.2 Estimation of seismic hazard parameters, M_c, a, b value, λ_m, and $M_{max,cal}$

Estimation of magnitude of completeness, M_c, is defined as the lowest magnitude at which all events in a space–time domain are detected. In the present study, M_c was estimated by using the Entire Magnitude Range (EMR) method given by [13], as this considers the entire magnitude range and also includes events below M_c. Their model consists of two parts: Gutenberg - Richter law for the complete part and cumulative normal distribution for the incomplete part of the non cumulative frequency magnitude distribution. This method is stable under most conditions and provides a comprehensive seismicity model. It determines the magnitude of completeness, M_c, and its uncertainty consisting of the self-similar complete part of frequency-magnitude distribution and incomplete portion. M_c was determined by this method for all seismogenic source zones, except for zone 6, for which the Maximum Curvature method was applied instead [14], due to sparse seismicity. This method is based on defining points of the maximum curvature by computing the maximum value of the first derivative of the frequency-magnitude curve. In practice, this matches the magnitude bin with the highest frequency of events in the non-cumulative frequency magnitude distribution. This is a fast and reliable method, although it slightly underestimates the magnitude of completeness [13].

For each seismic source zone maximum observed magnitude ($M_{max,obs}$) was identified from the MHD catalogue. Nearest prominent tectonic feature to $M_{max,obs}$ is also identified, and is assumed that it is generated in the vicinity of that feature. Table 3 gives salient features of the maximum observed magnitude ($M_{max,obs}$) and a prominent tectonic feature closest to it. [15], introduced an empirical relationship between magnitude and frequency of earthquakes, as $\log\lambda_m = a - bM$ or $\lambda_m = 10^{a-bM}$, where λ_m is the annual rate of exceedance of an earthquake of magnitude greater than or equal to M. The regression parameter *'a'* signifies seismic activity and '*b'* value reflects the relative likelihood of occurrence of large and small magnitude earthquakes. A low '*b'* value indicates frequent occurrence of high magnitude earthquakes whereas a high '*b'* value indicates frequent occurrence of low magnitude earthquakes. The activity rate λ_m and return periods were computed for different magnitudes of earthquakes. In the present study, Z-MAP software [16] was used to compute seismic hazard parameters for each source zone.

Since historical earthquake data are often too sparse to reflect the full potential of faults or thrusts, maximum magnitude becomes an important variable in seismic hazard estimation as it reflects maximum potential of strain released in larger earthquakes. $M_{max,cal}$ is defined as the upper limit of magnitude for a given source zone so that no earthquake is to be expected with magnitude exceeding $M_{max,cal}$. There are various ways of estimating maximum magnitude. $M_{max,cal}$ was estimated for each source zone, based on the doubly truncated G-R relationship, as per [17], programmed in MATLAB. Table 4 shows the seismic hazard parameters (M_c, *a*, *b*, λ_m, $M_{max,cal}$) estimated for nine source zones and return period for earthquakes of magnitude 5.0, 6.0, 7.0 and 8.0.

V. INTERPRETATION

For each seismogenic source zone, seismic hazard parameters, return period for different magnitudes and M_{max} were computed. Seismic hazard parameters and return period for each SSZ are given in table 4 whereas $M_{max,obs}$ is given in table 3. The significance of all these parameters is discussed in the following section.

5.1 '*a*' and '*b*' values in seismogenic source zones

'*a*' and '*b*' values for the 9 SSZs are given in table 4. The highest '*b*' value was obtained for SSZ 4. This is due to the fact that small earthquakes in this zone were more compared to lager magnitude earthquakes, i.e., SSZ 4 has only three earthquakes of magnitude greater than 6.0 out of 61 earthquakes. Since the slope of best fit line between magnitude, and log of cumulative number of earthquakes per year becomes steeper, the '*b*' value also increased and '*a*' value also increased although this zone had only 61 earthquakes. This SSZ can be interpreted as the zone which will witness low magnitude earthquakes. SSZ 3 has the highest number of earthquakes, 361, out of which 19 earthquakes have magnitude greater than 6.0. The slope tends to decrease hence the '*b*' value and the '*a*' value also decreased slightly, when compared to values for SSZ 4. This SSZ can be interpreted as the zone which will witness not only low magnitude earthquakes but also earthquakes of magnitude 6. For SSZ 1, the '*b*' value is low, 0.51, because this zone has more earthquakes (34 in number) of magnitude range 5.0 to 5.9. This tends to decrease the slope and hence it yields low '*b*' and '*a*' values. SSZ 8 shows lowest '*a*' and '*b*' values because it has small number of earthquakes (51) and only 2 earthquakes of magnitude 6.0 and above are present.

5.2 Return periods in different seismogenic source zones

Return periods for different magnitudes were computed for each SSZ, and are given in table 4. The significance of these is discussed in the following section.

5.2.1 Kangra seismogenic source zone

In SSZ 1, 181 earthquakes occurred in the time span 1827-2011. The maximum observed magnitude ($M_{max,obs}$) was 8.0, which was the great Kangra earthquake and it occurred in Kangra District of Himachal Pradesh. Nearest prominent tectonic feature to this earthquake was Main Boundary Thrust (MBT). Salient features of $M_{max,obs}$, are given in table 3. Maximum calculated magnitude ($M_{max,cal}$) for this SSZ was 8.71 ± 0.87. It means that in SSZ 1, the maximum magnitude can vary between 7.84 and 9.58. The return period of $M_{max,obs}$ = 8.0, was estimated to be 141 years, with a minimum of 98 years and a maximum of 204 years. The great Kangra earthquake occurred in 1905, and the next magnitude 8 earthquake is expected in the temporal range between the years 2003 and 2109, and space defined by SSZ 1. The return period of M_w = 7.0, in SSZ 1 was estimated to be 44 years, with a minimum of 32 years and a maximum of 60 years. An earthquake of M_w = 7.0 occurred in 1906 (epicenter: 77.00˚E, 32.00˚N, depth 33 km, 28/02/1906, IMD) and the next magnitude 7 earthquake is expected in the temporal range between the years 1938 and 1966. However, no earthquake of magnitude 7 or more originated after 1906 in SSZ 1. The return period of Mw = 6.0, in SSZ 1 was estimated to be 13 years, with a minimum of 10 years and a maximum of 18 years. An earthquake of magnitude M_w 6.5 (epicenter: 75.90˚E, 32.60˚N, depth 33 km, 22/06/1945, IMD) and another of 6.2 (epicenter: 75.90˚E, 32.60˚N, depth 33 km, 10/07/1947, IMD) originated within this SSZ within a time span of almost two years, indicating that this magnitude earthquake is recurring faster than that computed by this method. It is also interesting to note that no earthquake of comparable magnitude has occurred after 1947. The return period of M_w = 5.0, in SSZ 1 was estimated to be 4 years, with a minimum of 3 years and a maximum of 5 years. The last earthquake of M_w = 5.0 occurred in 2004, and the next earthquake is expected in the temporal range between the years 2007 and 2009, and space defined by SSZ 1. Earthquakes of magnitude 5.1 and 5.2 originated in the years 2005 (epicenter: 76.27˚E, 33.13˚N, depth 47.6 km, 26/05/2005, ISC) and 2009, (epicenter: 75.79˚E, 33.23˚N, depth 19.2 km, 19/05/2009, ISC) respectively. This indicates that the Kangra SSZ is the most vulnerable SSZ in terms of return period and magnitude.

5.2.2 Uttarakhand seismogenic source zone

In SSZ 2, 158 events occurred in the time span 1803-2012. The maximum observed magnitude ($M_{max,obs}$) was 6.8, which was Uttarkashi earthquake of 1991, and it occurred in Uttarkashi District of Uttarakhand. Nearest prominent tectonic feature to this earthquake was Main Central Thrust (MCT). Maximum calculated magnitude ($M_{max,cal}$) for this SSZ was 6.94 ± 0.52. It means that in SSZ 2 the maximum magnitude can vary between 7.46 and 6.42. The return period of M = 8.0 was estimated to be 372 years, with a minimum of 178 years and a maximum of 776 years. No earthquake of magnitude 8 originated in SSZ 2, as per MHD catalogue. However, it is pertinent to note that this SSZ is within the seismic gap defined by the Kangra earthquake of 1905 and the Bihar – Nepal earthquake of 1934, therefore, an earthquake of this magnitude cannot be ruled out within this SSZ. This also applies to earthquakes of magnitude in the range 7 - 8. The return period of M_w = 7.0 in SSZ 2 was estimated to be 91 years, with a minimum of 48 years and a maximum of 174 years. For the Uttarkashi earthquake of 1991, M_w = 6.8, the return period was estimated to be 69 years, with a minimum of 37 years and a maximum of 129 years. The Uttarkashi earthquake occurred in 1991, and the next magnitude M_w = 6.8 earthquake can be expected in the temporal range between the years 2028 and 2120. The Chamoli earthquake of 1999, M_w = 6.7, almost comparable in magnitude to the Uttarkashi earthquake of 1991, occurred within this SSZ, with return period estimated to be 60 years, with a minimum of 32 years and a maximum of 111 years. The return period of M_w = 6.0, in SSZ 2 was estimated to be 22 years, with a minimum of 13 years and a maximum of 39 years. Two earthquakes of magnitude 6 originated in 1809 (epicentre: 79.00˚E, 30.00˚N, depth 33 km, 01/01/1809, IMD) and 1883 (epicentre: 79.60˚E, 29.40˚N, 30 km, 30/05/1883, IMD) in SSZ 2, therefore, the next earthquake was expected in the temporal range between the years 1896 and 1922. Several earthquakes of this magnitude are overdue in this SSZ, indicating that strains are building up in this region, and may be released any time soon. The return period of M_w = 5.0, in SSZ 2 was estimated to be 5 years, with a minimum of 3 years and maximum of 9 years. Last earthquake of M_w = 5.0 occurred in 1990 and the next earthquake is expected in the temporal range between the years 1993 and 1999, and space defined by SSZ 2. However, the last earthquake of magnitude 5.1 (epicentre: 77.40˚E, 31.59˚N, depth 20 km, 20/01/1991, ISC) occurred in 1991.

5.2.3 Syntaxes seismogenic source zone

SSZ 3 shows the highest number of earthquakes when compared to all other SSZs. 361 earthquakes occurred in SSZ 3 in the time span 1552-2012. Two earthquakes of magnitude 7.7 occurred in this SSZ. One of them occurred in the year 1554 in the region near Nanga Parbat in Jammu and Kashmir. Prominent tectonic feature to this earthquake was Main Mantle Thrust (MMT). Another earthquake occurred in year 1778, near Muzaffarabad, and the prominent tectonic feature was MBT. These earthquakes occurred in time span of 224 years. However the return period of magnitude M_w = 7.7, was estimated to be 343 years, with a minimum of 169 years and a maximum of 697 years. The last earthquake of M_w = 7.7 occurred in 1778 and the next earthquake is expected in the temporal range between the years 1947 and 2475. Maximum calculated magnitude ($M_{max,cal}$) was 7.78 ± 0.51. It means that in SSZ 3, the maximum magnitude can vary between M_w = 8.29 to 7.27. The return period of M_w = 7.0, in SSZ 3 was estimated to be 120 years, with a minimum of 63 years and a maximum of 229 years. The last earthquake of M_w = 7.0 occurred in 1885 and the next earthquake is expected in the temporal range between the years 1948 and 2114, and space defined by SSZ 3. The return period of M_w = 6.0, in SSZ 3 was estimated to be 27 years, with a minimum of 15 years and a maximum of 47 years. An earthquake of magnitude 6 occurred in 2002 in SSZ 3; therefore, the next earthquake is expected in the temporal range between the years 2017 and 2049. The return period of M_w = 5.0, in SSZ 3 was estimated to be 6 years, with a minimum of 4 years and a maximum of 10 years. The last earthquake of M_w = 5.0 occurred in 2005 and the next earthquake is expected in the temporal range between the years 2009 and 2015, and space defined by SSZ 3. However, it is pertinent to note that after the 2005 Kashmir earthquake of M_w = 7.2, no earthquake of magnitude greater than 7.0 originated in SSZ 3, for which the return period is approximately 124 years.

5.2.4 Kaurik seismogenic source zone

In SSZ 4, 61 earthquakes occurred, in the time span 1955-2009. The maximum observed magnitude ($M_{max,obs}$) was 6.6, which was Kinnaur earthquake of 1975, and it occurred in Lahaul Spiti District of Himachal Pradesh. Nearest prominent tectonic feature for this earthquake was MCT. Maximum calculated magnitude ($M_{max,cal}$) for this SSZ was 6.85 ± 0.56. It means that in SSZ 4 the maximum magnitude can vary between M_w = 7.41 to 6.29. No earthquake of magnitude 8 and 7 originated in SSZ 4. This SSZ is also in the seismic gap of the two great earthquakes of 1905 and 1934.The return period of Kinnaur earthquake, M_w = 6.6, (epicentre: 78.50˚E, 32.39˚N, depth 1.40 km, 19/01/1975, ISC) which is also $M_{max,obs}$ for this zone was estimated to be 52 years, with a minimum of 44 years and a maximum of 60 years. The next such earthquake is expected in the temporal range between the years 2019 and 2035, and space defined by SSZ 4. The return period of M_w = 6.0, in SSZ 4 was estimated to be 19 years, with a minimum of 16 years and a maximum of 21 years. An earthquake of magnitude 6 originated in 1955; therefore, the next earthquake was expected in the temporal range between the years 1971 and 1976. The return period of M_w = 5.0, in SSZ 4 was estimated to be 3 years, with a minimum of 2 years and a maximum of 5 years. The last such earthquake, of M_w = 5.0, occurred in 2000 (epicentre: 78.41˚E, 32.00˚N, depth 38.80 km, 17/06/2000, ISC) and the next earthquake is expected in the temporal range between the years 2002 and 2005, and space defined by SSZ 4. However, it is pertinent to note that this zone showed the lowest return period of 3 years for M_w = 5.0. Fourteen earthquakes of magnitude greater than 5.0 were observed in this zone, till the year 2000, and none after that. Therefore earthquakes of magnitude 5 and above are overdue in this SSZ.

5.2.5 Kashmir seismogenic source zone

SSZ 5 shows sparse seismicity. 53 earthquakes occurred in this zone in the time span 1871-2011. The maximum observed magnitude ($M_{max,obs}$) was 6.0, which occurred in Leh Laddakh district of Jammu and Kashmir and in the vicinity of Indus Suture Zone. Maximum calculated magnitude ($M_{max,cal}$) was 6.19 ± 0.54. It means that in SSZ 5, the maximum magnitude can vary between M_w = 6.73 to 5.65. No earthquake of magnitude 8 and 7 occurred in SSZ 5. The return period of magnitude M_w = 6.0 (epicentre: 77.50˚E, 34.20˚N, depth 6 km, 17/05/1917, IMD) which is $M_{max,obs}$ for this zone was estimated to be 54 years, with a minimum of 27 years and a maximum of 107 years. The last earthquake of M_w = 6.0 occurred in 1917 and the next earthquake is expected in the temporal range between the years 1944 and 2024. The return period of M_w = 5.0, in SSZ 5 was estimated to be 14 years, with a minimum of 8 years and a maximum of 25 years. The last earthquake of M_w = 5.0 occurred in 1871 and the next earthquake is expected in the temporal range between the years 1879 and 1896, and space defined by SSZ 5. Earthquakes of magnitude 5 and 6 are overdue in this SSZ.

5.2.6 Western Tibet seismogenic source zone

SSZ 6 shows the lowest number of earthquakes. 16 earthquakes occurred in this zone, in the time span 1871-2011. The maximum observed magnitude ($M_{max,obs}$) was 6.0, which occurred in 1906, in Uttarkashi district of Uttarakhand. Maximum calculated magnitude ($M_{max,cal}$) was 6.18 ± 0.53, which implies that the maximum magnitude can vary between M_w = 6.71 to 5.65. No earthquakes of magnitude 8 and 7 occurred in SSZ 6. Therefore, return periods were large for magnitude 7.0 and 8.0. The return period of magnitude M_w = 6.0 which is $M_{max,obs}$ for this zone was estimated to be 76 years, with a minimum of 44 years and a maximum of 132 years. The last earthquake of M_w = 6.0, (epicentre: 79.00˚E, 31.00˚N, depth 33 km, 13/06/1906, IMD) occurred in

1906 and the next earthquake is expected in the temporal range between the years 1950 and 2038, and space defined by SSZ 6. The return period of M_w = 5.0, in SSZ 6 was estimated to be 21 years, with a minimum of 13 years and maximum of 22 years. The last earthquake of M_w = 5.0 occurred in 1994 and the next earthquake is expected in the temporal range between the years 2007 and 2028, and space defined by SSZ 6.

5.2.7 Karakoram seismogenic source zone

In SSZ 7, 235 earthquakes occurred in the time span 1669-2012. Two earthquakes of magnitude 6.5 occurred in this SSZ. One of them occurred in the year 1669 in the Leh (Laddakh) region of Jammu and Kashmir. Prominent tectonic feature to this earthquake was Karakoram fault. Another earthquake occurred in year 1996, in the Leh (Laddakh) region of Jammu and Kashmir, and the prominent tectonic feature was a neo-tectonic Fault. These earthquakes occurred in time span of 327 years. The return period of magnitude M_w = 6.5 for this zone was estimated to be 58 years, with a minimum of 32 years and a maximum of 106 years. The last earthquake of M_w = 6.5 occurred in 1996 (epicentre: 78.20˚E, 35.31˚N, depth 35.5 km, 19/11/1996, ISC) and the next earthquake is expected in the temporal range between the years 2028 and 2102. Maximum calculated magnitude ($M_{max,cal}$) for this SSZ was 6.63 ± 0.52. It means that the maximum magnitude can vary between M_w = 7.15 to 6.11. No earthquake of magnitude 8 and 7 occurred in SSZ 7. The return period of M_w = 6.0 was estimated to be 30 years, with a minimum of 17 years and a maximum of 51 years. An earthquake of magnitude 6 was recorded in 1975 (epicentre: 79.86˚E, 35.80˚N, depth 32.50km, 28/04/1975, ISC) in SSZ 7, therefore, the next earthquake can be expected in the temporal range between the years 1992 and 2026. The return period of M_w = 5.0, in SSZ 7 was estimated to be 8 years, with a minimum of 5 years and a maximum of 12 years. The last earthquake of M_w = 5.0 occurred in 2001 (epicentre: 79.72˚E, 34.13˚N, depth 46.80km, 06/11/2001, ISC) and the next earthquake is expected in the temporal range between the years 2006 and 2013, and space defined by SSZ 7. Therefore, an earthquake of magnitude range 5.0 is over due in SSZ 7.

5.2.8 Jhelum seismogenic source zone

In SSZ 8, 51 earthquakes occurred in the time span 1669-2010. The maximum observed magnitude ($M_{max,obs}$) is 6.5 occurred in Pakistan in the vicinity of Jhelum Fault. Maximum calculated magnitude ($M_{max,cal}$) was 6.89 ± 0.63. It means that the maximum magnitude can vary between M_w = 7.52 to 6.26. No earthquake of magnitude greater than 7 originated in SSZ 8. The return period of magnitude M_w = 6.5, which is $M_{max,obs}$ for this zone, was estimated to be 145 years, with a minimum of 79 years and a maximum of 263 years. The last earthquake of M_w = 6.5 occurred in 1669 (epicentre: 73.30˚E, 33.40˚N, depth 33km, 04/06/1669, IMD) and the next earthquake was expected in the temporal range between the years 1748 and 1932. The return period of M_w = 6.0, in SSZ 8 was estimated to be 81 years, with a minimum of 47 years and a maximum of 141 years. The last earthquake of M_w = 6.5 occurred in 1852 and the next earthquake was expected in the temporal range between the years 1899 and 1993, and space defined by SSZ 8. The return period of M_w = 5.0, in SSZ 8 was estimated to be 26 years, with a minimum of 16 years and maximum of 41 years. The last earthquake of M_w = 5.0 occurred in 1970 and the next earthquake was expected in the temporal range between the years 1970 and 2011, and space defined by SSZ 8. Earthquakes of magnitude 6 and 5 are overdue in this SSZ.

5.2.9 Indo Gangetic seismogenic source zone

In SSZ 9, the largest of all SSZs, 56 earthquakes occurred in the time span 1827-2010. The maximum observed magnitude ($M_{max,obs}$) was 6.5, occurred in Pakistan in the vicinity of south end of Jhelum fault and a Ridge Boundary. Maximum calculated magnitude ($M_{max,cal}$) was 6.96 ± 0.68. It means that the maximum magnitude can vary between M_w = 7.52 and 6.26. No earthquake of magnitude greater than 7 occurred in SSZ 9. The return period of magnitude M_w = 6.5 was estimated to be 178 years, with a minimum of 98 years and a maximum of 324 years. The last earthquake of M_w = 6.5 occurred in 1827 and the next earthquake is expected in the temporal range between the years 1925 and 2151. No earthquake of magnitude 6 was recorded in SSZ 9. The return period of M_w = 5.0 was estimated to be 15 years, with a minimum of 9 years and a maximum of 23 years. The last earthquake of M_w = 5.0 occurred in 1975 (epicentre: 77.87˚E, 29.61˚N, depth 15.90 km, 06/11/1975, ISC) and the next earthquake was expected in the temporal range between the years 1984 and 1998, and space defined by SSZ 9.

VI. VALIDATION OF RESULTS

The MHD catalogue consists of events up to year 2012. Seven recent earthquakes of magnitude m_b or M_s for time span January 2013 to September 2014 were studied from USGS. These magnitudes were converted to M_w by using the General Orthogonal Regression (GOR) relations given by [9]. These seven earthquakes as mentioned were not in the seismicity data set used to compute the seismic hazard parameters. It is very important to note that out of seven three events of magnitudes 5.0, 5.2 and 5.7 were observed in SSZ 1. Also one event is on the border of SSZ 1 and SSZ 3. As per table 4, the return period of magnitude 5 is 4 years and magnitude 6 is 11 years. This indicates that the return periods of magnitude 5 and above are lower than that estimated for SSZ 1. It makes SSZ 1 the most venerable zone of all in terms of return period. It is also pertinent to note that these events are in the vicinity of Kishtwar Fault and in the region between MBT and MCT. Two earthquakes occurred in SSZ 7 and one is on the borderline of SSZ 4 and SSZ 5. Table 5 gives the salient features of these earthquakes and the seismic source zone in which they occurred.

VII. GROUND MOTION PREDICTION EQUATION

Peak Ground Acceleration (PGA) is an important engineering parameter used for computing hazard. Ground motion prediction equation (GMPE) given by [18] was used to calculate PGA. This model gives average horizontal component of ground motion which is a function of earthquake magnitude, distance from source to site, local average shear wave velocity and fault type. The general attenuation model is described by the equation (1):

$$\ln Y = F_M (M) + F_D(R_{JB},M) + F_S (V_{S30},R_{JB},M) + \varepsilon\sigma_T \quad (1)$$

where, F_M is the magnitude scaling function, F_D is the distance function, R_{JB} is the closest distance to surface projection of rupture (Joyner–Boore distance in km), M is moment magnitude, F_S is site amplification function, V_{S30} is shear-wave velocity in m/s in the top 30 m. ε is standard deviation of a single predicted value of lnY from the mean value of lnY. This model can be used to compute PGA and 5% damped pseudo-absolute acceleration spectra (PSA) at periods from 0.01 to 10 s. This model is applicable for magnitude range 5 to 8, with R_{JB} < 200 km and V_{S30} = 180 to 1300 m/s. Since most of the source zones are in the Himalayan and contiguous regions, V_{S30} was used as 1300 m/s. This GMPE was used by [19] for estimating PSHA of Himachal Pradesh and adjoining regions. GMPE developed by [20] was also considered for calculation of PGA. This model is applicable for magnitude range 4 to 8.5, with R_{rup} =0-200 km. This GMPE was one of the GMPE's used by [21], for estimating PSHA for western Himalaya, in Indian subcontinent.

PSHA was used for calculation of seismic hazard in terms of PGA for probability of exceedance of 10% and 2% in 50 years for a return period of 475 and 2475 years, respectively, by using software CRISIS-2012, [22]. The code uses sources as area, line and point sources. All the seismogenic sources were considered as area source. These sources are originally given by the user as 3D polygons; the user gives the coordinates (longitude, latitude and depth) of the N vertex defining the area source. Depth is assumed to be zero in this case to consider it as area source and not volumetric source. Input parameters to this software were M_c, a, b, λ_m, $M_{max,cal}$, distance, and GMPE's. The logic tree approach introduced by [23] was used for estimation of PGA. Each attenuation relation was assigned an equal weightage on the assumption that both are correct. PGA in the region varied between 0.013 to 0.315 g for 10% probability of exceedance in 50 years, and between 0.024 to 0.680 g for 2% probability of exceedance in 50 years. Contour maps were developed for these two conditions and are shown in Fig.s 2(a) and 2(b). Hazard maps were also developed and are shown in Fig.s 3(a) and 3(b), respectively. Contouring interval for hazard map was taken as 0.1g.

VIII. INTERPRETATION OF HAZARD MAPS

Interpretation of hazard map shown in Fig. 3(a) is given here in terms of expected peak ground acceleration, seismic source zones, districts affected and tectonics. PGA in the entire region varied between 0.013 to 0.315 g for 10% probability of exceedance in 50 years.

Highest PGA of range greater than or equal to 0.31 g was observed in Kangra and Chamba district of Himachal Pradesh. MBT and MCT are the prominent tectonic features in this zone. This is observed mainly in the region north of MBT. It is also observed in Kathua and Doda districts of Jammu and Kashmir in south east of Kishtwar fault, and Lahual- Spiti district of Himachal Pradesh and Leh (Laddakh) of Jammu and Kashmir in SSZ. Tectonics associated with this is the Kaurik Fault System.

The next PGA contour, with a range 0.21 g to 0.30 g, occupied almost the total area of SSZ 1. Prominent tectonic elements which traverse this contour are MBT, MCT, Vaikrita Thrust, Kishtwar, Jwalamukhi thrust, Mastgarh anticline, and several unnamed lineaments at several places. In addition to this large area, the contour was also observed in SSZ 2 (Kinnaur and Kullu district, on MCT), SSZ 3 (Distt. Anantnag and Doda, North West of Kishtwar fault), SSZ 4 (50% of SSZ 4 area, Kinnaur and Lahual Spiti district of Himachal Pradesh and south east Laddakh Jammu and Kashmir on Kaurik Fault System), and in SSZ 5 (Lahaul Spiti district of Himachal Pradesh on MCT and Leh Laddakh).

The next contour encompasses the range 0.11 g to 0.20g, and is depicted by a large area surrounding the above contour. This occupies more than 20 % of the study area. This spreads in several SSZs, e.g., in SSZ 1

(Kangra, Hamirpur, Bilaspur, parts of Mandi, and Solan in Himachal Pradesh). Prominent tectonic features in this area are MBT, MCT, Vaikrita Thrust, Kishtwar fault, Sundernagar fault, Jwalamukhi thrust, Drang Thrust, Mastgarh anticline, and several unnamed lineaments, at several places. Entire SSZ 2 is showing PGA of this range. In Himachal Pradesh (Kullu, Mandi, Shimla, Solan, Sirmaur and parts of Kinnaur districts) in Uttarakhand (Dehradun, Uttarkashi, Chamoli, Rudraprayag, Tehri Garhwal, Pauri Garhwal, Almora, Nainital and small parts of Bageshwar district). It includes the region between MBT and MCT. Several complex tectonic features in the form of closed thrusts, Alaknanda Fault, North Almora Thrust, South Almora Thrust, Ramgarh Thrust and several transverse unnamed lineaments are prominent in this region. In SSZ 3, Srinagar, Anantnag, Doda, Udhampur, Jammu districts of Jammu and Kashmir show this contour. More than 30% of SSZ 4 which includes Kinnaur in Himachal Pradesh and south eastern Laddakh this range of PGA is observed. Prominent tectonic features are Kaurik fault System and Indus Suture Zone. In SSZ 5, it includes Lahaul Spiti and Chamba districts of Himachal Pradesh and regions in Laddakh. A small part of SSZ 8 and SSZ 9 also shows PGA in this range. The lowest contour interval is of PGA less than 0.10 g, and exists in SSZ 5, SSZ 6, SSZ 7 SSZ 8 and SSZ 9. Extension of Indus Suture Zone and an unnamed lineament are associated with SSZ 5 and SSZ 6. SSZ 7 includes Karakoram fault range and SSZ 8 includes the Jhelum fault.

IX. COMPARISON

In the present study, PSHA was carried out for the region in the vicinity of MBT and MCT which included Himachal Pradesh Uttarkahand and Jammu and Kashmir. PGA was calculated for 2% and 10 % probability of exceedance in 50 years for 2475 and 475 years return periods, respectively using [18] and [20] attenuation relations. PGA obtained in the present study was compared with studies carried out by several researchers, who attempted the PSHA approach for computing hazard in the Indian sub continent, and in parts of the Himalayan arc.

Khattri et al. [24] estimated PGA for the Indian subcontinent by Eastern United States acceleration attenuation relationship which ranges from 0.4 to 0.7 g for Himachal Pradesh. Parvez et al. [25] used probabilistic approach for assessment of earthquake hazards in North-East India and also in the Hindu Kush region. In 1999 [26], they extended this study for the Indian subcontinent. For both the studies of the occurrence of great earthquakes with magnitude greater than 7.0 during a specified interval of time has been estimated on the basis of four probabilistic models, namely, Weibull, Gamma, lognormal and exponential. The model parameters have been estimated by the method of Maximum Likelihood Estimates (MLE) and the Method of Moments (MOM). Bhatia et al. [27], under global seismic hazard assessment program (GSHAP), calculated probabilistic seismic hazard for India and adjoining regions for a grid interval of 0.5^ox0.5^o by using [28] attenuation relationship and estimated expected PGA for the Himalayan region between 0.10g and 0.30g. Under the global seismic hazard assessment program (GSHAP), the international lithosphere programme and other supporting agencies prepared a global seismic hazard map using advanced method for probabilistic seismic hazard assessment ([29]). Mahajan et al. [30] prepared a seismic hazard map of north-west Himalaya at a grid interval of 0.25^ox0.25^o and Kumar et al. [31] attenuation relationship. The results showed PGA values varying between 0.02 - 0.50g for Kangra region, 0.35 to 0.70g for Kashmir region, 0.20- 0.45 g to for Kaurik-Spitti region, 0.20- 0.50 g for Garhwal region and 0.20- 0.50 g for Darchula region. National Disaster Management Authority (NDMA) in 2011 estimated various probabilistic seismic hazard maps showing the ground motion parameters for different return periods for the whole country [32]. For Himachal Pradesh, the estimated PGA ranges from 0.10 - 0.12 g. Nath et al. [21] carried out PSHA for the entire country for a grid interval of 0.2^o x 0.2^o and attenuation relationships given by [33], [34], [35] and [36]. PGA estimated for Himachal and adjoining regions was in the range between 0.20 - 0.45g. Patil et al. (2014) [16] carried out PSHA for Himachal Pradesh and adjoining regions using Boore and Atkinson [18] relation for a grid interval of 0.2^o x 0.2^o. Two cases, i.e., varying b-value and constant b-value were considered. PGA obtained was in the range of 0.08 - 0.15g when b- value is varying, and 0.09-0.26 g when *b*-value is constant for entire region.

X. CONCLUSIONS

The highest PGA contour of 0.013g - 0.315g was observed is SSZ 1 for a return period of 475 years. Also, the highest observed magnitude in SSZ 1 was 8.0, and the calculated maximum magnitude was 8.71 ± 0.87, which means that it can vary between M_w = 7.8 and 9.5. When the validation of results was done with recent seismic data, it was observed that three out of seven earthquakes of magnitude greater than 5.0 were in SSZ 1. Since one of the lowest '*b*' values (0.51) was computed for SSZ 1, it implies that this zone has a likelihood of large earthquakes, and the '*a'* value indicates large seismicity. Therefore, the most vulnerable zone in terms of return period, PGA, maximum observed and computed magnitude, and '*a'* and '*b'* values is SSZ 1, the Kangra Seismic Source Zone. Similar interpretation for all other SSZs zones indicates that the Kaurik and the Syntaxes SSZ can together be ranked as the next most vulnerable source zones, followed by the

Uttarakhand SSZ. This underlines the urgency for carrying out vulnerability analysis of areas and of structures and also to estimate the populations that are at risk to this threat perception.

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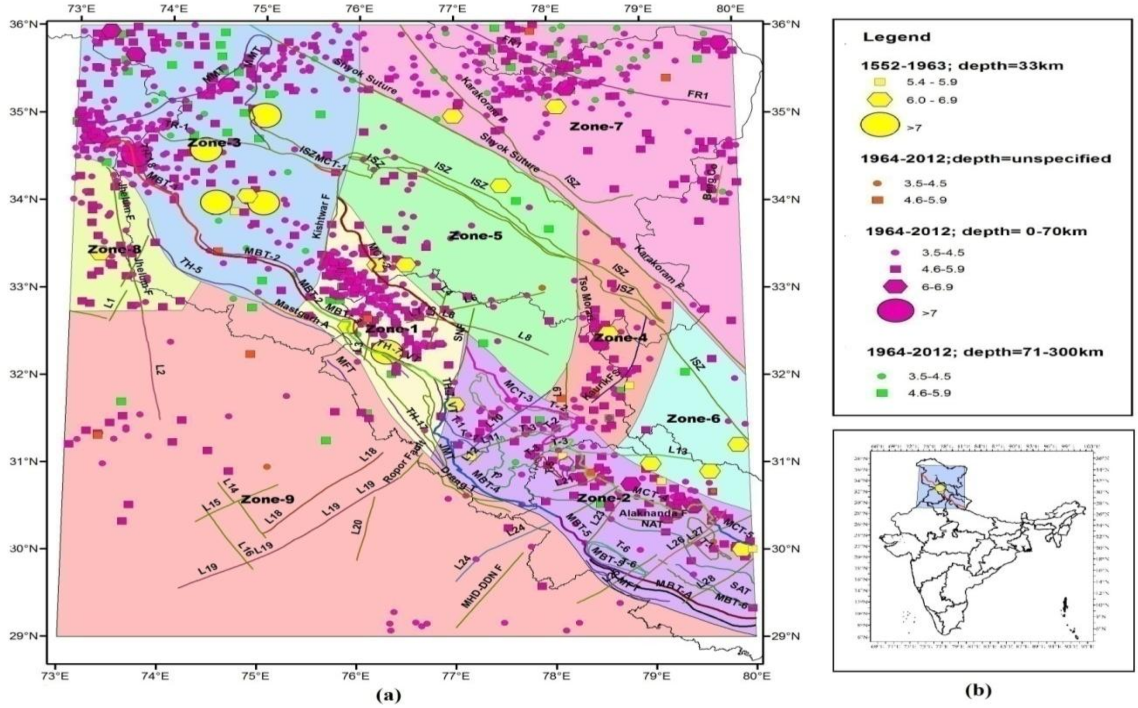

Figure 1. (a) Seismo-tectonics and Seismogenic Source Zones delineated for Himachal Pradesh and contiguous regions, (b) Main Boundary Thrust (MBT), Main Central Thrust (MCT) and epicenter of Kangra earthquake shown on Map of India. Box shows study area.

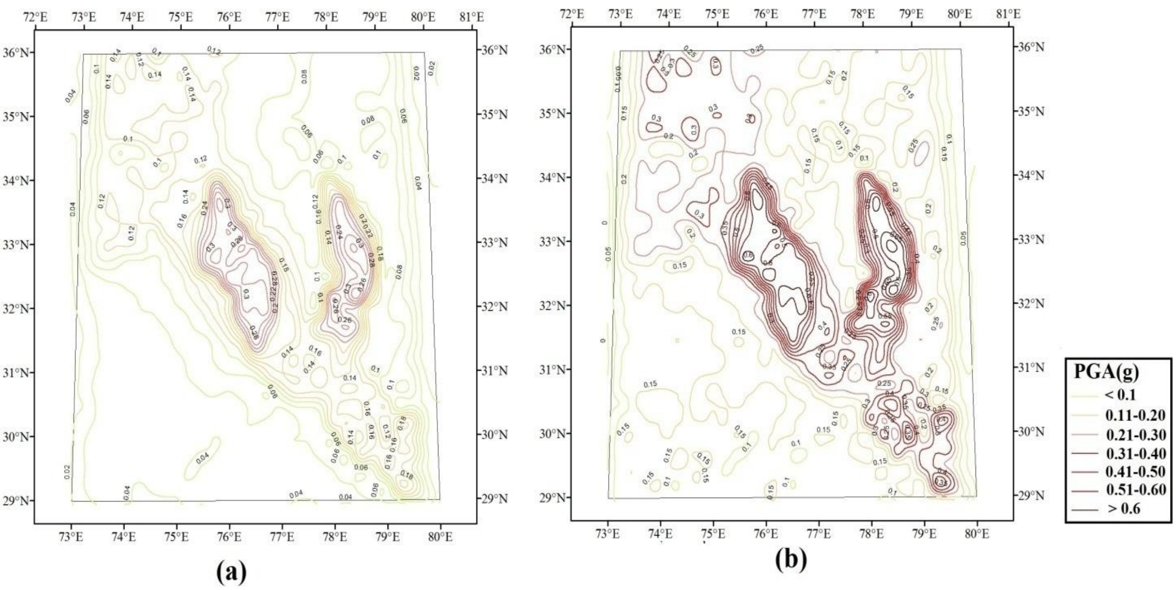

Figure 2. Contour map for (a) 10% probability of exceedance in 50 years for a return period of 475 years, (b) 2% probability of exceedance in 50 years for a return period of 2,475 years.

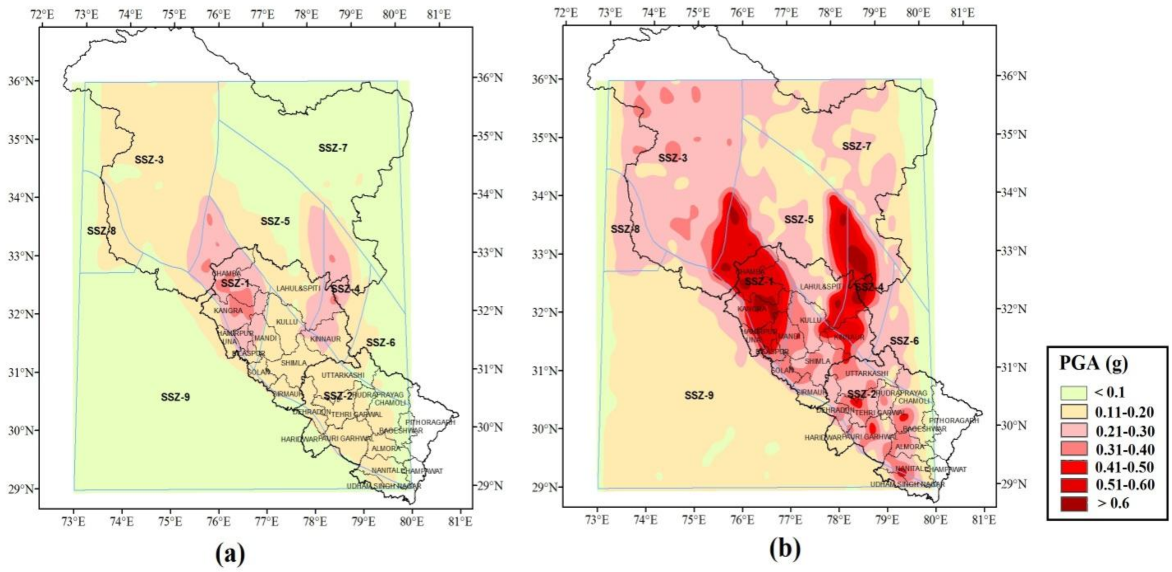

Figure 3. Hazard map showing Peak Ground Acceleration (PGA) for; (a) 10% probability of exceedance in 50 years for a return period of 475 years, (b) 2% probability of exceedance in 50 years for a return period of 2,475 years.

Table 1. Salient features of MHD catalogue for western Himalaya and its environs, for the area between latitude 29°N to 36°N and longitude 73°E to 80°E

No	Magnitude Range	No of Epicentres
1.	*≥7.0*	*14*
2.	6.0-6.9	32
3.	*4.6-5.9*	*491*
4.	*3.5-4.5*	*635*
		Total=1172

Table 2. Salient features of nine seismogenic source zones.

Source zone	**Name of zone**	**Area (km²)**	**Seismicity of region (No. of events)**					**No. of events**	**Prominent Tectonic features**
			≤ 4.9	**5-5.9**	**6-6.9**	**7-7.9**	**≥ 8**		
SSZ 1	Kangra source zone	24,013	143	34	2	1	1	181	• MBT • MCT • Sundernagar F • Kistwar F • Jwalamukhi Thrust • Vaikrita Thrust • Drang Thrust • Mastgarh Anticline • Unnamed lineaments
SSZ 2	Uttarakhand source zone	49,310	123	27	8	0	0	158	• MBT • MCT • MFT • Alaknanda F • NAT • SAT • Other complex tectonic features in the form of closed curve • Unnamed lineaments

SSZ 3	Syntaxes source zone	75,638	310	32	8	11	0	361	• MBT • MCT • MMT • Kishtwar F
SSZ 4	Kaurik source zone	20,085	46	12	3	0	0	61	• Kaurik fault System • Indus Suture Zone
SSZ 5	Kashmir source zone	50,363	47	5	1	0	0	53	• Indus Suture Zone • Unnamed lineaments
SSZ 6	Western Tibet source zone	19,664	10	4	2	0	0	16	• Indus Suture Zone
SSZ 7	Karakoram source zone	82,364	203	27	5	0	0	235	• Karakoram F • Shyok Suture • Neotectonic F
SSZ 8	Jhelum source zone	15,733	41	8	2	0	0	51	• Jhelum Fault
SSZ 9	Indo Gangetic source zone	168,215	46	9	1	0	0	56	• Mahendragarh-Dehradun Subsurface fault • Many unnamed lineaments
							Total number of events =	**1172**	

Table 3. Nearest prominent Tectonic feature in each SSZ for $M_{max,obs}$

SSZ	YYYY	MM	DD	Long (°E)	Lat (°N)	Depth (km)	$M_{max,obs}$ (M_w)	District	Nearest Prominent Tectonic Feature
SSZ 1	1905	4	4	76.25	32.30	-	8.0	Kangra	MBT
SSZ 2	1991	10	19	78.79	30.77	13.2	6.8	Uttarkashi	MCT
SSZ 3	1554	-	-	75.00	35.00	-	7.7	Nanga Parbat	MMT
	1778	-	-	75.00	34.00	-	7.7	Near Muzzarfarabad	MBT
SSZ 4	1975	1	19	78.50	32.39	1.40	6.6	Lahaul Spiti	Kaurik fault system
SSZ 5	1917	5	17	77.50	34.20	-	6.0	Leh Laddakh	Indus Suture Zone
SSZ 6	1902	6	16	79.00	31.00	-	6.0	Uttarkashi	MCT
SSZ 7	1669	6	22	77.00	35.00	-	6.5	Leh Laddakh	Karakoram Fault
	1996	11	19	78.20	35.31	35.50	6.5	Leh Laddakh	Neotectonic Fault
SSZ 8	1669	6	4	73.30	33.40	-	6.5	Pakistan	Jhelum fault
SSZ 9	1827	9	24	74.40	31.60	-	6.5	Pakistan	Tip of Jhelum fault and Ridge Boundary

Table 4. Seismic hazard parameters (M_c, *a*, *b*, λ_m, M_{max}) estimated for nine source zones and return period for magnitudes 5.0, 6.0, 7.0 and 8.0.

No.	Source zones	M_c	*a*	*b*	± δb	λ_m	$M_{max,cal}$ ± Standard deviation	Return period (years)			
								M_w=5	M_w= 6	M_w=7	M = 8
1	Kangra source zone	3.8	1.93	0.51	0.02	0.982	8.71 ± 0.87	4	14	44	141
2	Uttarakhand source zone	4.1	2.31	0.605	0.04	0.675	6.94 ± 0.52	5	21	84	339
3	Syntaxes source zone	4.0	2.47	0.652	0.04	0.728	7.78 ± 0.51	6	28	124	557
4	Kaurik source zone	4.4	3.17	0.741	0.10	0.812	6.85 ± 0.56	3	19	104	573
5	Kashmir source zone	3.8	1.81	0.588	0.05	0.376	6.19 ± 0.54	14	52	202	783
6	Western Tibet source zone	4.2	1.42	0.548	0.10	0.131	6.18 ± 0.53	21	74	261	920
7	Karakoram source zone	3.8	2.07	0.588	0.03	0.685	6.63 ± 0.52	7	28	111	431
8	Jhelum source zone	3.8	1.09	0.503	0.04	0.151	6.89 ± 0.63	26	85	270	859
9	Indo Gangetic source zone	4.1	2.43	0.723	0.08	0.292	6.96 ± 0.68	15	81	428	2259

Table 5. Seven recent (January 2013 to September 2014) earthquakes studied from USGS ..... Table shows coordinates (latitude, longitude), depth, magnitude from USGS, converted M_w, and the source zone in which they occurred for validation

	YYYY-MM-DD	Origin time (UTC)	Long (°E)	Lat (°N)	Depth (km)	Mag (USGS)	M_w (GOR)	Location (USGS)	Validation
1.	2014-06-13	3:32:52	75.58	33.29	42.74	m_b 5	5.2	17km W of Kishtwar	In SSZ 3
2.	2013-10-21	02:27:13	77.08	35.34	48.7	M_w 5.4	5.4	NNE of Thang, India	In SSZ 7
3.	2013-10-20	9:45:07	77.41	35.75	96.76	m_b 5.4	5.7	111km NNE of Thang	In SSZ 7
4.	2013-08-02	1:37:46	75.95	33.29	44.2	m_b 5.2	5.5	17km E of Kishtwar,	In SSZ 1
5.	2013-08-02	2:32:47	75.93	33.26	14.12	M_w 5	5.0	16 km ESE of Kishtwar	In SSZ 1
6.	2013-07-09	3:49:14	78.21	32.77	17.61	m_b 5.1	5.3	ENE of Kyelang, India	In SSZ 5
7.	2013-05-01	06:57:12	75.83	33.10	9.8	M_w 5.7	5.7	17km NE of Bhadarwah	In SSZ 1