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ORIGINAL PAPER

Simulation of strong ground motion for 1905 Kangra earthquake and a possible megathrust earthquake (Mw 8.5) in western Himalaya (India) using Empirical Green's Function technique

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Abstract Earthquakes are deadliest among all the natural disasters. The areas that have experienced great/large earthquakes in the past may experience big event in future. In this study, we have simulated Kangra earthquake (1905, Mw 7.8) and a hypothetical great earthquake (Mw 8.5) in the north-west Himalaya using Empirical Green's Function (EGF) technique. Recordings of Dharamsala earthquake (1986, Mw 5.4) are used as Green function with a heterogeneous source model and an asperity. It has been observed that the towns of Kangra and Dharamsala can expect ground accelerations in excess of 1 g in case of a Mw 8.5 earthquake and could have experienced an acceleration close to 1 g during 1905 Kangra earthquake. The entire study region can expect acceleration in excess of 100 cm/s^2 in case of Mw 7.8 and 200 cm/s^2 in case of Mw 8.5. The sites located near the rupture initiation point can expect accelerations in excess of 1 g for the magnitudes simulated. For validation, the estimates of the PGA for Mw 7.8 simulation are compared with isoseismal studies carried out in the same region after the Kangra earthquake of 1905 by converting PGA values to intensities. It was found that the results are comparable. The target earthquakes (Mw 7.8 and Mw 8.5) are simulated at depth of 20 km and 30 km to examine the effect of PGA for different depths. The PGA values obtained in the present analysis gave us an idea about the level of accelerations experienced in the area during 1905 Kangra earthquake. Future construction in the area can be regulated, and built environ can be strengthened using PGA values obtained in the present analysis.

Keywords Simulation · PGA · Strong ground motion

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1 Introduction

The Mw 7.8 Kangra earthquake (1905) in the north-west Himalaya was the first of the several devastating twentieth-century earthquakes to occur in the northern India. More than 20,000 people are reported killed near the epicentre area, and about 100,000 buildings were destroyed (Sharma and Lindholm 2011). The earthquake was felt extensively all over India, and intensities of the order of X on MMI scale were observed in most of the areas near the source (Ghosh and Mahajan 2013). Although this earthquake is not the only severe event known to have happened in the western Himalaya, it had the largest death toll and was one of the first in the era of instrumental seismology (Sharma and Lindholm 2011). It is also among the four great Himalayan earthquakes to have occurred in the past 200 years. Moderate earthquakes do occur every few decades along the small circle that defines the southern edge of the Tibetan Plateau, but no historical earthquakes have ruptured the surface along the Main Frontal Thrusts bordering the Himalayan foothills (Ambraseys and Bilham 2000; Kumar and Mahajan 2001; Kumar et al. 2001; Bilham 2001). Seeber and Armbruster (1981) have found evidence of strain accumulation in this region. There are lot of uncertainties in defining the northern, southern and western edges of the inferred rupture zone of the Kangra earthquake (Chandra 1978), since 1905, several minor earthquakes have occurred in this region. The region has experienced an earthquake of Mw 5.4 named as Dharamsala Earthquake on 26 April 1986. This earthquake occurred in the Kangra region of Himachal Himalaya and lies in the rupture zone of Kangra earthquake of 1905. This was also the first moderate-sized earthquake recorded at a few strong motion sites of an array in the NW Himalaya (Sriram et al. 2005).

The recurrence of an earthquake similar or bigger to the 1905 Kangra earthquake has been the most talked about issue among the researchers working in this region. It is generally believed that under-thrusting of the Indian Plate beneath the Tibetan Plateau drives earthquakes in the Himalaya. Wallace et al. (2005) found that the Kangra region currently has a slip deficit of at least 1.4 m and could produce an earthquake of Mw 7.5. The region can also rupture as a part of a much bigger earthquake (Mw 8.6). Similarly, Bilham and Wallace (2005) have predicted a worse scenario, wherein re-rupture can accompany a contiguous or enveloping rupture to the north-west or south-east of the region with a much larger magnitude. Ambraseys and Bilham (2000) have suggested that the 1905 Kangra earthquake has occurred on an extended rupture in a major intra-crustal low-angle thrust fault dipping gently under the north-west Himalaya. They indicated the possibility that major earthquakes in this region occur at 50- to 200-year intervals. Furthermore, there are several seismic gaps in the entire Himalayan belt where a segment of an active fault has not slipped since long as compared to other segments along the same structure. In addition to high seismic vulnerability, the surface materials and the methods of construction are further aggravating the underlying problem. Most of the buildings are built on surface material, which is colluvium. The growing number of multi-storied buildings built on unstable slopes and without following building codes is a major concern for the government.

We are always curious to know that if big earthquakes repeat in near future, then what will be the level of acceleration expected in an area. For this purpose, simulation of strong ground motion is very helpful, which in turn may be used for the hazard assessment of an area. There are numerous techniques available to simulate strong ground motions, which are being used all over the world. These techniques include stochastic technique, composite source technique, envelope summation and Empirical Green's Function (EGF) techniques. Many researchers have used stochastic methodology to simulate strong ground motions in various parts of world (Boore and Atkinson 1987; Toro and Mcguire 1987; Ou and Herrmann 1990; Chopra et al. 2010, 2012a, b). Composite source model technique using synthetic Green's functions was introduced by Zeng et al. (1993). EGF technique was proposed by Hartzell (1978) and modified by Irikura (1986) and Irikura et al. (1997). In this technique, the recordings of small earthquakes located near the target earthquake are used as Empirical Green Function. This technique is used by many researchers worldwide (Hartzell 1978; Irikura 1983, 1986; Ordaz et al. 1995; Frankel 1995; Singh et al. 2002; Sharma et al. 2013).

In the present study, we have applied the methodology proposed by Irikura (1986) and Irikura et al. (1997) to simulate strong motions for the 1905 Kangra earthquake (Mw 7.8) and a hypothetical Mw 8.5 earthquake in the Kangra region. The recordings of Dharamsala earthquake are used as Green function (element earthquake). The Dharamsala earthquake (Mw 5.4) was recorded on nine strong motion accelerographs located in the Himachal Himalaya region. Over the years, most of the cities in the region have undergone phenomenal growth for various socio-economic reasons. Thus, the vulnerability of these cities has increased considerably from seismic hazard point of view necessitating seismic hazard evaluation. In view of this, an estimate of strong ground motion in this region is necessary, and an attempt has been made to estimate the level of acceleration from a future major/great earthquake in the Kangra region.

2 Seismotectonics of the region

The collision of the Indian and the Eurasian plates results in crustal shortening along the northern edge of the Indian plate due to which three major thrust planes, i.e. the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT), have been formed (Gansser 1964; Molnar and Chen 1982). This region has experienced four great earthquakes in a span of 53 years: 1897 Shillong (Mw 8.1), 1905 Kangra (Mw 7.8), 1934 Bihar–Nepal (Mw 8.4) and 1950 Assam (Mw 8.7) (Bilham 2004; Kayal 2008). No great earthquake has occurred in the Himalaya since 1950 (Khattri 1999; Bilham 1995; Seeber and Armbruster 1981; Bilham and Gaur 2000). The MCT is considered as one of the most important tectonic surfaces, and it continues throughout the entire Himalaya almost up to the eastern syntaxes. The MBT is not a single thrust plane, and it comprises number of overlapping thrust sheets. The Siwalik belt occupying a sprawling foothill zone consists of outcrops of Tertiary rocks in several folded and faulted strips. The Siwalik presents a picture of folded structural belt with broad synclines alternating with steep, often faulted, narrow asymmetric anticlines. The axial planes as well as the strike faults and thrusts on their limbs are steep at the surface and dip more gently northwards at depth (Valdiya 1988, 2001; Srikantia and Bhargava 1998).

In the Lesser Himalaya, geological formations have suffered extensive tectonic movement and the rock formations were subjected to displacement from its original place of deposition (Valdiya 1988). In Kangra seismic region, MBT tectonically separates the tertiary rocks of the sub-Himalaya from the Lesser Himalaya (Thakur et al. 2000). The Himalayan Frontal Fault demarcates the tectonic boundary between the folded tertiary rocks of sub-Himalaya and the alluvium of Indo-Gangetic plains. The Panjal Thrust, representing the MCT in this region, is the southern boundary of the Chamba Nappe (Thakur et al. 2000; Kumar and Mahajan 2001). The northern boundary of the Chamba Nappe is demarcated along the Chenab Fault against the underlying crystalline rocks of the Higher Himalaya (Thakur et al. 2000). The Lesser Himalaya in Kangra–Chamba region is narrower as compared to sub-Himalaya, which is much wider in the region. This suggests that convergence has consumed most of the Lesser Himalayan formations in Kangra–Chamba region. The fault plane solution of the 1986 Dharamsala earthquake is a thrust fault whose dipping plane striking northwest–southeast direction (Kumar and Mahajan 1990) while Kangra earthquake also has been considered as a part of the same recognized tectonic scenario (Ghosh and Mahajan 2011). So we have considered Dharamsala earthquake as an element earthquake to simulate target great/major earthquakes in the same region under present study. Figure 1 represents the area of present study along with stations, faults, epicentres of Kangra and Dharamsala earthquakes.

3 Method and data

In the present study, EGF technique is used to simulate two earthquakes in the Kangra region. This technique was proposed by Irikura (1983) in which waveforms for target earthquakes are synthesized with the help of the small earthquakes as Green's function (Fig. 2a). The target earthquake is generated using recordings of small earthquakes after applying corrections for slip velocity time function of large and small earthquakes. The equations used to synthesize a large event are given as follows (Irikura et al. 1997):

$$U(t) = \sum_{i=1}^{N} \sum_{j=1}^{N} (r/r_{ij}) \cdot F(t) * (C \cdot u(t)) \quad (1)$$

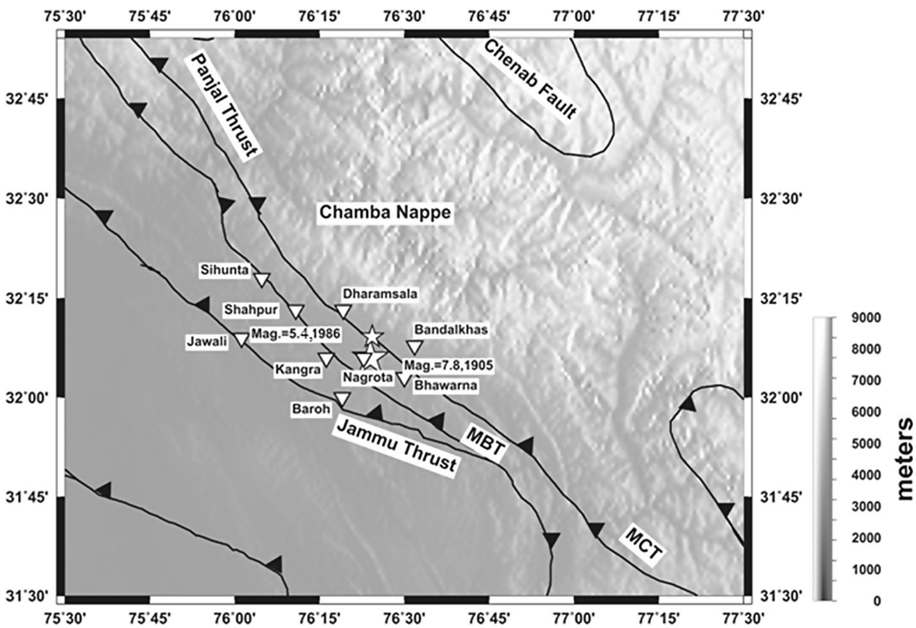


Fig. 1 Seismotectonic set-up of Kangra and surrounding area along with nine stations where SMA data are available. *Red stars* are the epicentres of Kangra (1905) and Dharamsala (1986). *Contour bar* shows elevation in metres

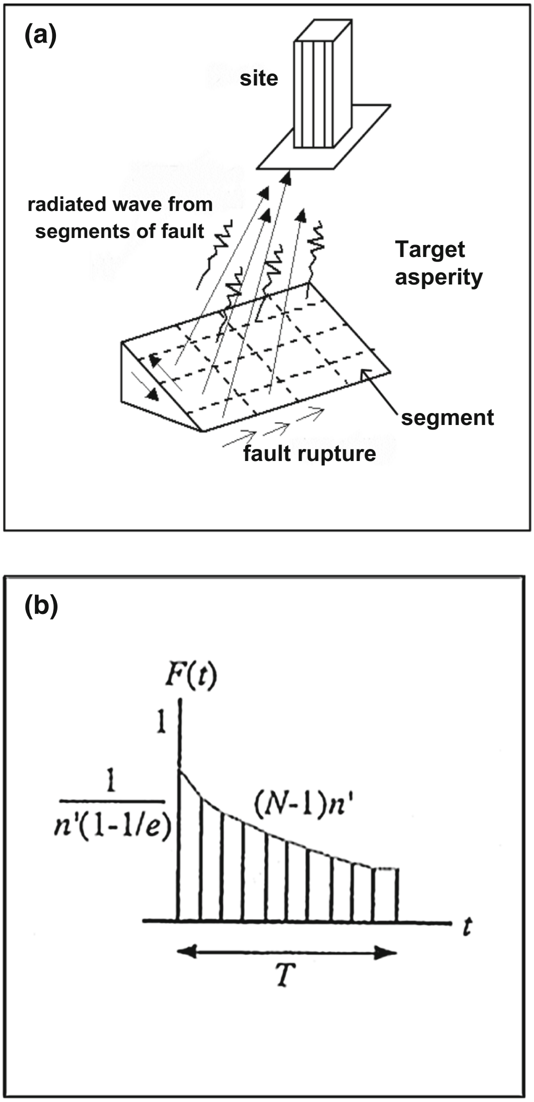


Fig. 2 **a** Idea of the Empirical Green's Function technique to use an observed small event as Green's function for simulation of a large earthquake. **b** An exponential slip function to boost the low-frequency energy in the simulation (after Irikura et al. 1997)

$$F(t) = \delta(t - t_{ij}) + \{1/n'(1 - \exp(-1))\} \times \sum_{k=1}^{(N-1)n'} [\exp\{-(k-1)/(N-1)n'\} \cdot \delta\{t - t_{ij} - (k-1)T/(N-1)n'\}] \quad (2)$$

where $U(t)$: synthesized waveform (large event), $u(t)$: observed element waveform, N: moment ratio of large/small event, T: rise time of large event, C: stress drop of large/small event, r: the hypocentral distance from observation point to the subevent, rij: the distance from the observation point to the subfault with ith row and jth column, tij: the rise time divided by the number of subfaults, n': an appropriate integer to eliminate spurious periodicity and *: convolution. Irikura et al. (1997) introduced an exponential slip function to boost the low-frequency energy in the simulation as shown in Fig. 2b. This improved relation is used to simulate strong ground motion for the Kangra region in the present study.

The difficulty in evaluating the effects of heterogeneities in the earth's structure is removed by using EGF technique, as the element earthquake carries the complex effects of heterogeneous structure from the source to the site. The limitation of this method is that this method can be applied only in the regions where recordings of small earthquakes from a potential source zone are available. Stress drop ratio between the large and the small earthquakes is also an important factor due to which PGA values may be affected. PGA may also vary with the location of asperity on the fault. The position of asperities on a fault plane may relate to background seismicity, which may not be the actual position at the time of a big earthquake. In spite of these limitations, EGF technique is a powerful technique to estimate strong ground motions at a site where small earthquake recordings are available.

Strong ground motions of Dharamsala earthquake, recorded at 9 stations operated by the Department of Earthquake Engineering, IIT, Roorkee, are used as element earthquakes. Figure 1 shows the locations of stations where Dharamsala earthquake was recorded along with seismotectonic set-up of the region. The parameters used for an element and target earthquakes are provided in Table 1. According to Irikura et al. (1997), the difference between the magnitude of the element and the target earthquake should be less than two, but in the present case the difference between simulating earthquakes (Mw 7.8 and 8.5) is more than 2. In view of this, we employed two-stage simulations. In the first step, we have simulated Mw 6.5 (Middle event) earthquake, and then, with the help of the middle event, target events, i.e. Mw 7.8 or 8.5, are synthesized as explained in Fig. 3. We have simulated Mw 7.8 earthquake in order to validate our results with 1905 Kangra earthquake and prove the efficacy of the methodology in predicting ground motions at the site of interest. The intensity maps of the 1905 Kangra earthquake are available in the literature. The PGA obtained in the present study is converted into equivalent intensities using region-specific intensity–PGA relations and then compared with observed values.

Table 1 Parameters used for observed and simulated earthquakes

Element earthquake	Middle earthquake	Future target earthquake	Future target earthquake
Dharamsala earthquake (element earthquake) 26 April 1986, Mw 5.4	(Middle earthquake) Mw 6.5	Future great earthquake (target earthquake) Mw 7.8	Future great earthquake (target earthquake) Mw 8.5
Location 32.18°N, 76.43°E	Same as element earthquake	Same as element earthquake	Same as element earthquake
$M_0 = 2.1 \times 10^{24}$ dyne-cm (Sriram et al. 2005)	$M_0 = 1.97 \times 10^{26}$ dyne-cm (Hanks and Kanamori 1979)	$M_0 = 5.62 \times 10^{27}$ dyne-cm (Hanks and Kanamori 1979)	$M_0 = 6.31 \times 10^{28}$ dyne-cm (Hanks and Kanamori 1979)
Depth = 7 km (source) (Sriram et al. 2005)	Depth = 30 km and 20 km	Depth = 30 km and 20 km	Depth = 30 km and 20 km
Strike = 299°, dip = 19° and slip = 58° (CMT Harvard)	Same as element earthquake	Same as element earthquake	Same as element earthquake

$\tau = 0.0726L$, $V_r = 0.72V_s$, $V_s = 3.6$ km/s (Geller 1976), τ is rise time, L is length of fault, V_r is rupture velocity and V_s is s wave velocity

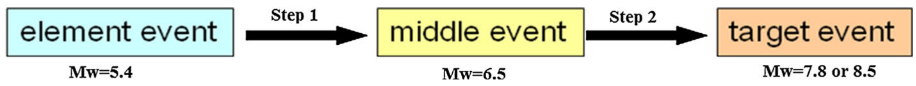
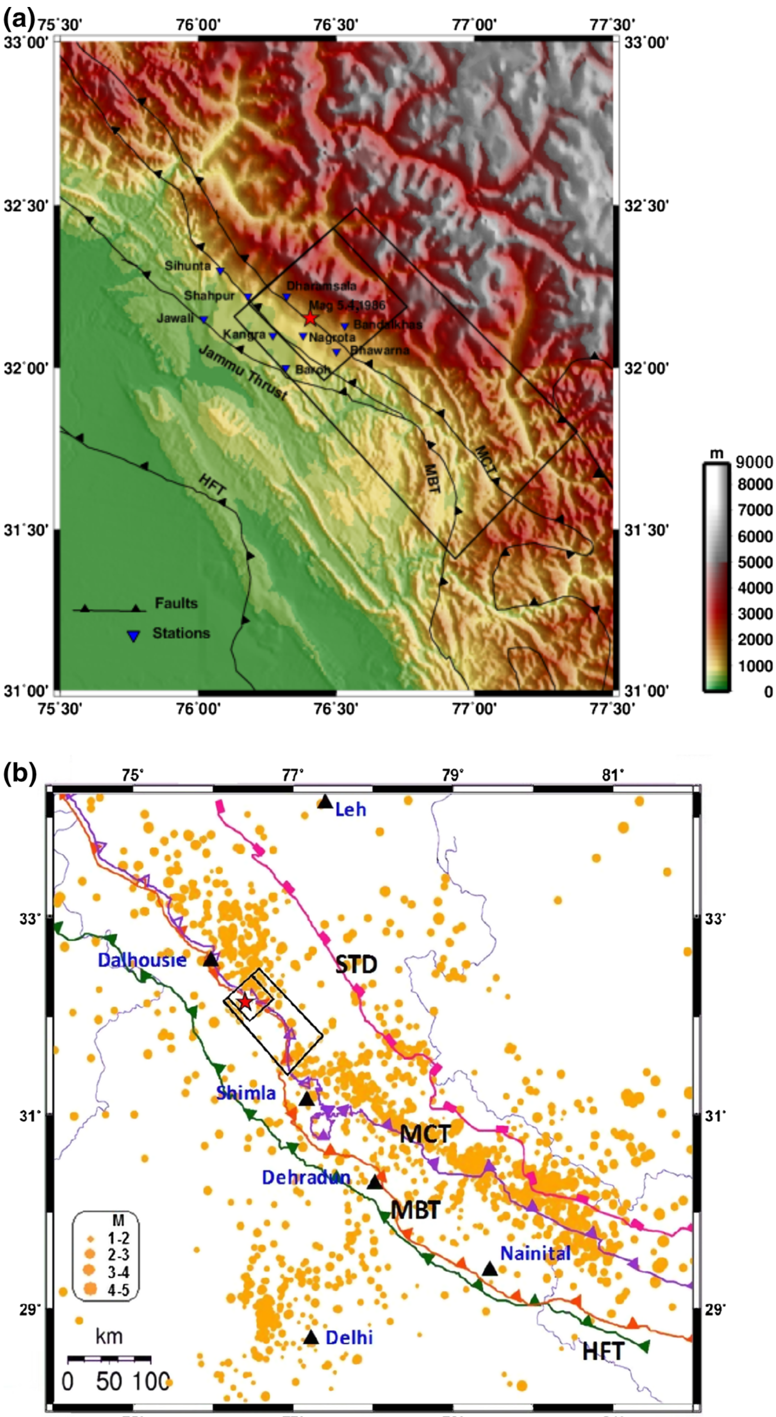


Fig. 3 Diagram to show the two-step simulation used in the present study

The fault plane solution of the Dharamsala earthquake of 1986 was estimated by Sriram et al. (2005). It is important to note that the fault plane solution of the element and the target earthquake should be nearly same, which is a prerequisite of EGF method. Also, Hough et al. (2005) have mentioned that Kangra earthquake of 1905 was a low-angle thrust rupture of the main Himalayan decollement fault, and according to Sriram et al. (2005) Dharamsala earthquake of 1986 had a low-angle thrust rupture plane. Bilham and Wallace (2005) suggested that the rupture for the 1905 Kangra earthquake (Mw 7.8) was around 110×55 km^2 (Fig. 4a). The fault area considered for the Mw 8.5 earthquake is considered to be 313×75 km^2 using the formulations given by Somerville et al. (1999). Some areas on a rupture plane, called asperities, are prone to large slips as compared to the average slip on the fault. These are the potential areas of large accelerations during faulting. Miyake et al. (2001, 2003) found that asperities are the sites where strong ground motions are generated. The location of the asperities on a fault surface can be decided on the basis of surface offsets along a fault, slip rate from the GPS observations or background seismicity (Irikura and Miyake 2011). In the present study in the absence of information about slip rates, surface offsets from the studied region, we utilized background seismicity information for deciding asperity for the target event. We have assumed a heterogeneous fault model consisting of one asperity inside the total rupture area utilizing expressional relationships and source parameters (Somerville et al. 1999). Figure 4b depicts the total rupture area and position of the asperity for the simulation of Mw 7.8 earthquake. The input parameters of the asperity for target earthquake of Mw 7.8 and Mw 8.5 are provided in Table 2. These parameters are estimated according to the formulations suggested by Irikura et al. (1997). The number of subfaults on the main fault depends on the seismic moments of the target and the element earthquakes. The asperity has been placed in such a way that the path of the seismic waves from the target earthquake does not deviate much, which is a precondition of the EGF technique. The area of the asperity in both the simulations on an average occupied around 23–24 % of the total rupture area (Somerville et al. 1999). Rupture initiation point for Mw 7.8 and 8.5 earthquakes is same as that of the element earthquake, i.e. hypocentre of Dharamsala earthquake. Rise time and rupture velocity are estimated by the formulations given by Geller (1976). Most of the earthquakes in the NW Himalaya have found to have stress drop of around 40 bars (Dinesh et al. 2006; Sharma and Wason 1994). In view of this, the ratio of stress drop for the simulated and element earthquakes is assumed to be 1.0 in the present analysis.

4 Results and discussion

In the present study, level of ground motions experienced during the 1905 Kangra earthquake (Mw 7.8) in Kangra and adjoining regions are determined. Additionally, ground motions for a scenario earthquake of Mw 8.5 are also determined. The EGF technique is used (Irikura et al. 1997) to model the expected ground motions. The recordings of Dharamsala earthquake (26 April 1986) are used as element earthquake at each site to model ground motion at various sites. The ground motions for all the three components at


(a)
75°30'
76°00'
76°30'
77°00'
77°30'
33°00'
32°30'
32°00'
31°30'
31°00'
Sihunta
Dharamsala
Shahpur
Mag 5.4,1986
Jawali
Bandalkhas
Kangra
Nagrota
Bhawarna
Baroh
Jammu Thrust
MCT
MBT
HFT
Faults
Stations
m
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
(b)
75°
77°
79°
81°
33°
31°
29°
Leh
Dalhousie
STD
Shimla
MCT
Dehradun
MBT
Nainital
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M
1-2
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km
0 50 100

◀**Fig. 4** **a** Total rupture area and asperity in the Kangra and surrounding region. *Contour bar* shows elevation in metres. **b** Total rupture area and position of asperity for the studied region to simulate Mw 7.8 (Modified after Kumar et al. 2012)

Table 2 Parameters used for asperity models

Parameter	Asperity for Mw 7.8	Asperity for Mw 8.5
Rupture area	38 × 38 km^2 1444 km^2 (Somerville et al. 1999)	75 × 75 km^2 5625 km^2 (Somerville et al. 1999)
No. of subfaults	4 × 4 (Irikura et al. 1997)	10 × 10 (Irikura et al. 1997)
Strike, dip and rake	Strike = 299°, dip = 19° and slip = 58°	Strike = 299°, dip = 19° and slip = 58°
Seismic moment	$M_0 = 5.62 \times 10^{27}$ dyne-cm (Hanks and Kanamori 1979)	$M_0 = 6.31 \times 10^{28}$ (Hanks and Kanamori 1979)

Table 3 PGA (observed and simulated) for each site in Kangra Region at 20 and 30 km depths

Station	Station code	Latitude (°N)	Longitude (°E)	PGA (cm/s^2) observed (Mw 5.4)	PGA (cm/s^2) simulated (Mw 7.8)		PGA (cm/s^2) simulated (Mw 8.5)	
					20 km	30 km	20 km	30 km
Bandlakhas	BAND	32.13	76.53	142	799	723	955	924
Baroh	BARO	32	76.317	58	337	257	536	384
Bhawarna	BHAW	32.05	76.5	36	242	293	293	343
Dharamsala	DHAR	32.22	76.32	183	989	953	1194	1146
Jawali	JAWA	32.15	76.02	17	103	121	172	171
Kangra	KANG	32.1	76.27	145	888	840	1185	1039
Nagrota	NAGR	32.1	76.38	146	372	377	496	408
Shahpur	SHAH	32.22	76.18	243	945	884	1183	1005
Sihunta	SIHU	32.3	76.08	50	145	208	244	234

each station are simulated considering radial propagation of the rupture. The observed and simulated PGA values at all the sites along with the locations are given in Table 3. The time histories of element and target earthquakes (Mw 7.8 and Mw 8.5) for all the nine sites considered in the present study are shown in Fig. 5. The intensity map for the Mw 7.8 Kangra earthquake of 1905 is available in the literature. The epicentre of 1986 Dharamsala Earthquake was located close to the 1905 Kangra earthquake epicentre. We can validate the results obtained from Mw 7.8 simulations using intensity observations. There are several PGA–intensity relationships available in the literature, and we checked the validity of them for the studied region by comparing observed and calculated intensities. The relationships given by Linkimer (2008), Wald et al. (1999), Murphy and O'Brien (1977) and Prajapati et al. (2013) are tested for the purpose. These relationships have been utilized to compare the observed and calculated intensities of Uttarkashi (1991, Mw 6.9) and Chamoli earthquakes (1999, Mw 6.5), which have occurred in the NW Himalaya. The intensity values for these two earthquakes and PGA values are available. Figure 6 depicts

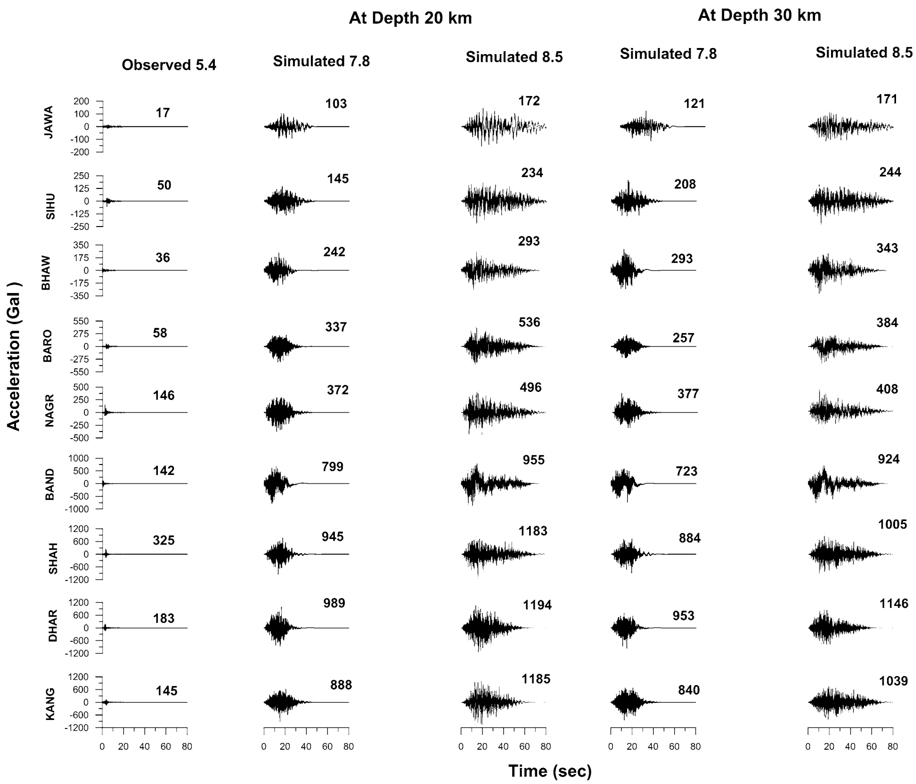

Fig. 5 Observed and simulated earthquakes for nine sites in Kangra and surrounding region. PGA is written for all the earthquakes

the comparison between the observed and the calculated intensities based on the empirical relations given by Linkimer (2008), Wald et al. (1999), Murphy and O'Brien (1977) and Prajapati et al. (2013) using data of Chamoli and Uttarkashi earthquakes. It has been observed from Fig. 6 that the relations given by Wald et al. (1999) and Murphy and O'Brien (1977) show good comparison between the observed and calculated intensities, whereas empirical relations given by Prajapati et al. (2013) and Linkimer (2008) overestimated the intensities. In view of this, the relationships of Wald et al. (1999) and Murphy and O'Brien (1977) can be used to convert PGAs into intensities for the studied region. We have converted PGA values obtained from the simulation for Mw 7.8 earthquake into intensities according to the relationship given by Wald et al. 1999 and Murphy and O'Brien (1977) (Table 4). These values are compared with the intensity values for the 1905 Kangra earthquake estimated from the intensity map (Ghosh and Mahajan 2013) as shown in Fig. 7. It has been observed from Table 4 that the intensity values are comparable with the values of Ghosh and Mahajan (2013). Overall, it seems that PGA values modelled for Mw 7.8 earthquake using EGF technique are predicted reasonably well.

The distribution of simulated PGA in the area is shown in Fig. 8. During Mw 7.8 earthquake, Shahpur and Dharamsala towns can expect pga $\sim$1 g at 20 km depth. The towns of Kangra and Bandlakhas may have experienced PGA $\sim$0.8 g. It has been observed that Kangra, Dharamsala and Shahpur might have experienced PGA in excess of

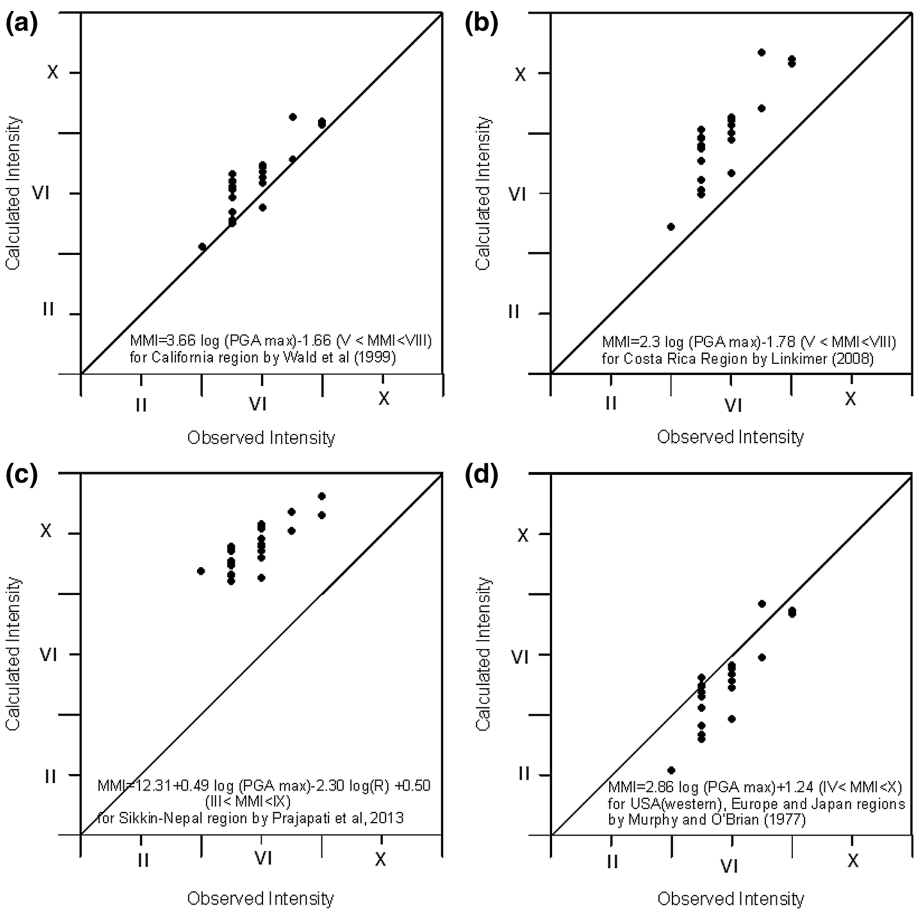

Fig. 6 Observed versus calculated intensities for Chamoli and Uttarkashi earthquakes using four empirical relations. **a** Using relation by Wald et al. 1999, **b** using relation Linkimer (2008), **c** using relation by Prajapati et al. 2013 and **d** using relation by Murphy and O'Brien (1977)

1 g in case of Mw 8.5 earthquake occurring in the same region at 20 km depth (Fig. 8). In both cases, we observed that PGA decreases rapidly in the NW direction as compared to the SE part. The same is true for isoseismal map of 1905 Kangra earthquake as shown in Fig. 7. Kumar and Mahajan (1991) also inferred that the attenuation was faster in NW direction as compared to SE direction for Dharamsala earthquake of (1986). Also, the PGA values at depths 20 and 30 km are estimated in order to see the effect of depth on PGA. It is found that at depth 20 km the PGA is found to be more than that of the PGA at 30 km depth as shown in Fig. 8. The 1905 Kangra earthquake and subsequent 1968, 1978 and 1986 Dharamsala earthquakes are in the same seismogenic zone (Kumar and Mahajan 2001). The depth of the earthquakes is controlled by folded free end of plunging Indian basement (Kumar 1990) lying about 15–20 km in Kangra region. The earthquakes in this region show thrust faults with strike–slip components. In view of this, we considered 1986 Dharamsala earthquake to be in the same seismogenic zone where 1905 earthquake has occurred. Earthquakes in the same seismogenic zone exhibit similar characteristics.

Table 4 Comparison of isoseismal values computed using relation given by Wald et al. 1999 with intensity distribution estimated by Ghosh and Mahajan (2013)

Station	Intensity values (Ghosh and Mahajan 2013) for Kangra earthquake (Mw 7.8)	Intensity values Kangra earthquake (Mw 7.8) (Wald et al. 1999)		Intensity values Kangra earthquake (Mw 7.8) (Murphy and O'Brien 1977)	
		20 km	30 km	20 km	30 km
Bandlakhas	IX	IX	IX	X	IX
Baroh	VIII	VIII	VII	VIII	VIII
Bhawarna	IX	VII	VII	VIII	VIII
Dharamsala	X	IX	IX	X	X
Jawali	VII	VI	VI	VII	VII
Kangra	IX	IX	IX	X	X
Nagrota	X	VIII	VIII	IX	IX
Shahpur	IX	IX	IX	X	X
Sihunta	VII	VI	VII	VIII	VII

Several authors have carried out probabilistic seismic hazard assessment (PSHA) for different parts of the India including NW Himalayan region (Khatri et al. 1984; Bhatia et al. 1999). Khatri et al. (1984) found that Himachal Pradesh can expect PGA between 0.4 and 0.7 g for 10 % probability of exceedance in 50 years, whereas Bhatia et al. (1999) estimated PGA between 0.10 and 0.30 g for 10 % probability of exceedance in 50 years for the Himalayan region which includes NW Himalayan region. Parvez et al. (2003) have carried out deterministic seismic hazard assessment of India and adjoining regions. They have observed wide variation in design ground accelerations (DGAs) across India and found that for the Kangra region, DGA ranges from 0.30 to 0.60 g. On the other hand, Mahajan et al. (2010) found that in the Kangra region and adjoining PGA between 0.020 and 0.50 g is expected for 10 % probability of exceedance in 50 years. These values will be high for a 2 % PE in 50 years, which is considered a worst scenario (Shaligram et al. 2014). Sriram and Khattri (1999) have estimated PGA in the Kangra region for a magnitude of 6.2 scenario earthquake using recordings of Dharamsala Earthquake and composite source model and obtained PGA of 0.7 g. The PGA values obtained in the present study vary from 0.07 to 1.05 g for Mw 7.8 and 0.1 to 1.25 g for Mw 8.5 in the NW Himalaya, which are the worst scenario cases.

It has been observed from the present study and by several other researchers (Khattri 1999; Sriram and Khattri 1999; Bilham and Wallace 2005; Mukhopadhyay et al. 2011; Gupta and Gahalaut 2014) that Himalayan region is prone to large/great earthquakes and PGA in such cases may exceed 1 g in the meizoseismal area. The gap between the 1905 Kangra and 1934 Bihar–Nepal earthquakes is considered as the central seismic gap (Seeber and Armbruster 1981). It is now also understood that the 1905 Kangra earthquake with an Mw 7.8 was not a great earthquake and its rupture was not up to Dehradun, and the length of this gap has increased (Ghosh and Mahajan 2013). Geodetic observations show that strain energy is building up in the region (Chander and Gahalaut 1994; Bilham et al. 2001; Banerjee and Bürgmann 2002). Recently, it has been emphasized by Gupta and Gahalaut (2014) that Kangra region has the potential to generate a great/major earthquake and hence may be declared as a seismic gap. Most of the houses in the region and hilly terrains of NW

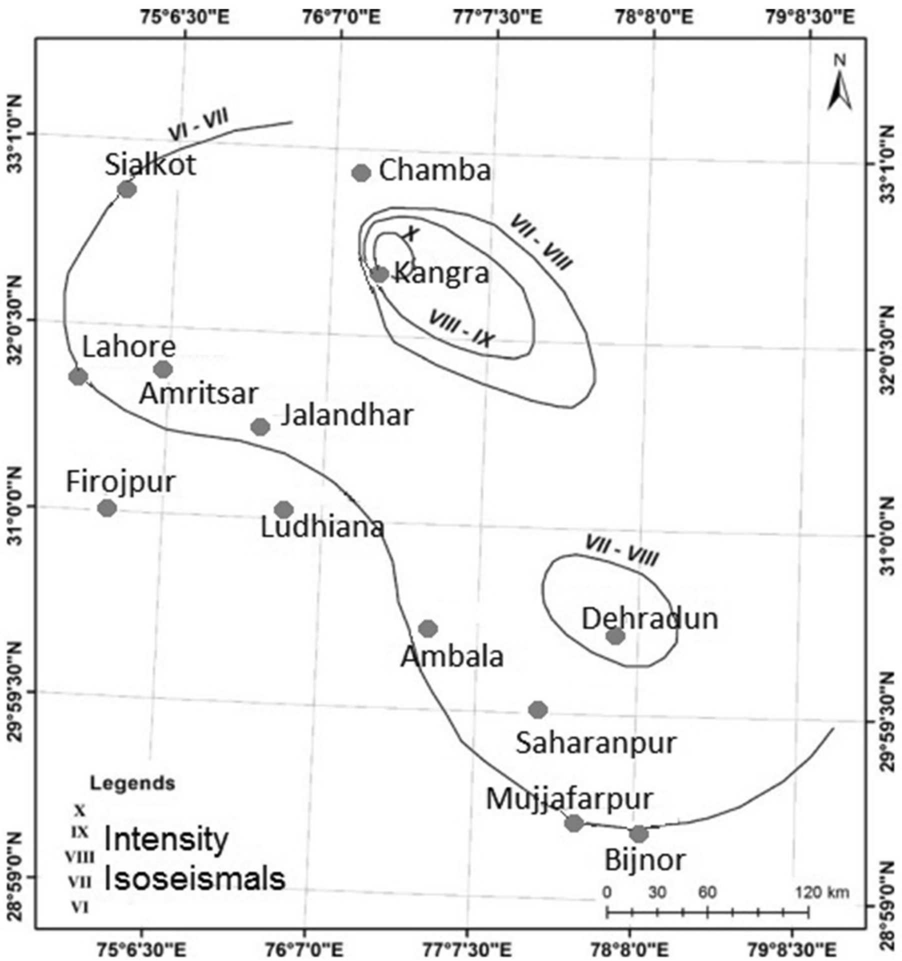

Fig. 7 Intensity map of 1905 Kangra earthquake (after Ghosh and Mahajan 2013)

Himalaya are made up of mud, burnt bricks and stones, which are devoid of strength (Arya 1995). They rest on colluviums that are prone to soil creep which can destroy foundations. The present study and Srivastava et al. (2010) have put seismological constraints on the 1905 Kangra earthquake, and there is a need for earthquake hazard assessment and disaster mitigation in the NW Himalayan region where the influence of surface wave on tall structures and longer duration of shaking need to be ascertained. Kumar et al. (2012) have studied seismogenesis of the clustered seismicity beneath Kangra–Chamba area using tomography and came out with a conclusion that intense seismicity in a block of $30 \times 30\ km^2$ centred NE to the epicentre of Kangra earthquake.

The present study is an attempt to estimate deterministic seismic hazard assessment for Kangra region. Level of ground accelerations expected in this region for 1905 Kangra and the great earthquake has been ascertained. Due to the socio-economic importance of the Kangra region and poor construction practices followed, there is an urgent need to assess

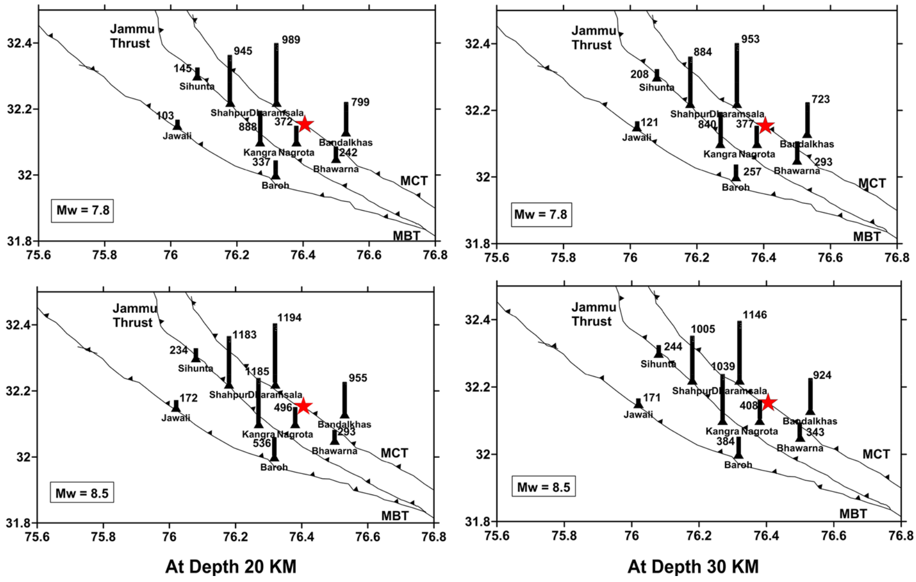

Fig. 8 PGA distribution for simulated Mw 7.8 and Mw 8.5 at two different depths at nine sites in the Kangra and surrounding area. *Vertical bars* show the corresponding PGA values for the particular site estimated at 20 and 30 km depths

seismic hazard in this hilly area. The present study will be quite useful for assessing seismic hazard of Kangra and adjoining region.

5 Conclusions

The NW Himalayan region is considered to be a potential site for the next great earthquake as discussed by several researchers. The region has experienced a Mw 7.8 earthquake in 1905, more than a century ago. Dharamsala earthquake of 1986 (Mw 5.4) occurred very close to the epicentre of 1905 Kangra earthquake. Using EGF approach, we model this earthquake and tried to obtain ground motions for Mw 7.8 earthquake similar to Kangra earthquake. Also, a great earthquake of Mw 8.5 is simulated at same site. The level of ground motions for the Mw 7.8 earthquake is converted into intensities using empirical relationships and is compared with the observed intensities of the 1905 Kangra earthquake. It has been observed that intensity values are found to be comparable. The present study using EGF methodology has provided constraints on the level of accelerations experienced during Kangra earthquake. It has been observed that the towns of Kangra and Dharamsala may have experienced ground accelerations around 1 g during Mw 7.8 and may expect acceleration in excess of 1 g in case of Mw 8.5 scenario earthquake. This study will be helpful to the society because the PGA estimated here is helpful for the engineering community for planning future construction and retrofitting existing structures in the region.

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References

Ambraseys N, Bilham R (2000) A note on the Kangra Ms = 7.8 earthquake of 4 April 1905. Curr Sci 79:101–106

Arya SPS (1995) Modeling and parameterization of near-source diffusion in weak winds. J Appl Meteorol 34:1112–1122

Banerjee P, Bürgmann R (2002) Convergence across the northwest Himalaya from GPS measurements. Geophys Res Lett 29(13):30-1–30-4

Bhatia SC, Ravi Kumar M, Gupta HK (1999) A probabilistic seismic hazard map of India and adjoining regions. Ann Geophys 42(6):1153–1166

Bilham R (1995) Location and magnitude of the Nepal earthquake and its relation to the rupture zones of the contiguous great Himalayan earthquakes. Curr Sci 69:101–128

Bilham R (2001) Slow tilt reversal of the Lesser Himalaya between 1862 and 1992 at 78°E, and bounds to the southeast rupture of the 1905 Kangra earthquake. Geophys J Int 144:1–23

Bilham R (2004) Earthquakes in India and the Himalaya: tectonics, geodesy and history. Ann Geophys 47:2–3

Bilham R, Gaur VK (2000) The geodetic contribution to Indian seismotectonics. Curr Sci 79:2000

Bilham R, Wallace K (2005) Future Mw 8 earthquake in Himalaya: Implication for the 26 December, 2004 M = 9 earthquake on eastern margin. Geol Surv India 85:1–14

Bilham R, Gaur VK, Molnar P (2001) Himalayan seismic hazard. Science 293(5534):1442–1444

Boore DM, Atkinson GM (1987) Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America. Bull Seismol Soc Am 77:440–467

Chander R, Gahalaut VK (1994) Preparations for future great earthquakes seen in levelling observations along 2 lines across the outer Himalaya. Curr Sci 67(7):531–534

Chandra U (1978) Seismicity, earthquake mechanism and tectonics along the Himalayan mountain range and vicinity. Phys Earth Planet Inter 16:109–131

Chopra S, Kumar Dinesh, Rastogi BK (2010) Estimation of Strong Ground Motions for 2001 Bhuj (M 7.6), India Earthquake. Pure Appl Geophys 167:1317–1330

Chopra S, Kumar D, Choudhury P, Yadav RBS (2012a) Stochastic finite fault modelling of M 4.8 earthquake in Kachchh, Gujarat, India. J Seismol 16(3):435–449

Chopra S, Kumar Vikas, Suthar Anup, Kumar Pankaj (2012b) Modeling of strong ground motions for 1991 Uttarkashi, 1999 Chamoli earthquakes, and a hypothetical great earthquake in Garhwal-Kumaun Himalaya. Nat Hazards. doi:10.1007/s11069-012-0289-z

Dinesh Kumar, Sriram V, Kattri KN (2006) A study of source parameters, site amplification functions and average effective shear wave quality factor Qseff from analysis of accelerograms of 1999 Chamoli Earthquake, Himalaya. Pure Appl Geophys. doi:10.1007/s00024-006-0078-2

Frankel A (1995) Simulation strong motions of great earthquakes using recordings of small earthquakes: the Loma Prieta mainshock as a test case. Bull Seismol Soc Am 85:1144–1160

Gansser A (1964) Geology of the Himalayas. Interscience, New York **289**

Geller RS (1976) Body force equivalents for stress drop seismic sources. Bull Seismol Soc Am 66:1801–1804

Ghosh GK, Mahajan AK (2011) Interpretation of intensity attenuation relation in 1905 Kangra earthquake with epicentral distance and magnitude in the northwest Himalayan region. Geol Soc India 77:511–520

Ghosh GK, Mahajan AK (2013) Intensity attenuation relation at Chamba-Garhwal area in north-west Himalaya with epicentral distance and magnitude. J Earth Syst Sci 122:107–122

Gupta H, Gahalaut VK (2014) Seismotectonics and large earthquake generation in the Himalayan region. Gondwana Res 25:204–213

Hanks TC, Kanamori H (1979) A moment magnitude scale. J Geophys Res. doi:10.1029/JB084iB05p02348

Hartzell S (1978) Earthquake aftershock as Green's functions. Geophys Res Lett 5:1–4

Hough SE, Bilham R, Ambraseys N, Feldl N (2005) Revisiting the 1897 Shillong and 1905 Kangra earthquakes in northern India: site response, Moho reflections, and a triggered earthquake. Curr Sci 88:1632–1638

Irikura K (1983) Semi-empirical estimation of strong ground motions during large earthquakes. Bull Dis Prev Res Inst Kyoto Univ 32:63–104

Irikura K (1986) Prediction of strong acceleration motion using empirical Green's function. In: Proceedings of the 7th Japan earthquake engineering symposium, pp 151–156

Irikura K, Miyake H (2011) Recipe for predicting strong ground motion from crustal earthquake scenarios. Pure Appl Geophys. doi:10.1007/s00024-010-0150-9

Irikura K, Kagawa T, Sekiguchi H (1997) Revision of the Empirical Green's function method. In: Program and abstracts of the seismological society of Japan, vol 2, p B25

Kayal JR (2008) Microearthquake seismology and seismotectonics of South Asia. Springer, Heidelberg

Khatri KN, Rogers AM, Algermissen ST (1984) A seismic hazard map of India and adjacent areas. Tectonophys 108:93–134

Khattri KN (1999) An evaluation of earthquakes hazard and risk in northern India. Himal Geol 20:1–46

Kumar S (1990) Gravity anomalies, seismicity, subducting slab folding and surface deformation in the orogenic belts. An example from the Andaman–Nicobar region. J Geodyn 12:39–63

Kumar S, Mahajan AK (1990) Studies of Intensities of 26th April, 1986 Dharamsala earthquake and associated tectonics. Geol Soc India 35:213–219

Kumar S, Mahajan AK (1991) Dharamsala seismotectonics zone, Neotectonic and state of stress in the area. J Himal Geol 21:53–57

Kumar S, Mahajan AK (2001) Seismotectonics of Kangra region, Northwest Himalaya. Tectonophysics 331(4):359–371

Kumar S, Wesnousky WG, Rockwell TK, Ragona D, Thakur VC, Seitz GG (2001) Earthquake recurrence and rupture dynamics of Himalayan Frontal Thrust, India. Science 294:2328–2331

Kumar N, Paul A, Mahajan AK, Yadav DK, Bora C (2012) The *M* 5.0 Kharsali, Garhwal Himalayan earthquake of 23 July 2007: source characterization and tectonic implications. Curr Sci 102(12):1674–1682

Linkimer L (2008) Relationship between peak ground acceleration and Modified Mercalli intensity in Costa Rica. Rev Geol Am Central 38:81–94

Mahajan AK, Thakur VC, Sharma ML, Chauhan M (2010) Probabilistic Seismic Hazard map of NW Himalaya and its adjoining area. Natural Hazards, India, pp 443–457

Miyake H, Iwata T, Irikura K (2001) Estimation of rupture propagation direction and strong motion generation area from azimuth and distance dependence of source amplitude spectra. Geophys Res Lett. doi:10.1029/2000GL011669

Miyake H, Iwata T, Irikura K (2003) Source characterization for broadband ground-motion simulation: kinematic heterogeneous source model and strong motion generation area. Bull Seismol Soc Am 93:2531–2545

Molnar P, Chen WP (1982) Seismicity and mountain building. In: Hsu K (ed) Mountain Building Processes. Academic, New York, pp 41–57

Mukhopadhyay B, Acharyya A, Dasgupta S (2011) Potential source zones for Himalayan earthquake: constraints from spatial–temporal clusters. Nat Hazards 57:369–383

Murphy JR, O'Brien LJ (1977) The correlation of peak ground acceleration amplitude with seismic intensity and other physical parameters. Bull Seismol Soc Am 67:877–915

Ordaz M, Arboleda J, Singh SK (1995) A scheme of random summation of an empirical Green's function to estimate ground motions from future large earthquakes. Bull Seismol Soc Am 85:1635–1647

Ou GB, Herrmann RB (1990) A statistical model for ground motion produced by earthquakes at local and regional distances. Bull Seismol Soc Am 80:1397–1417

Parvez IA, Vaccari F, Panza GF (2003) A deterministic seismic hazard map of India and adjacent areas. Geophys J Int 155:489–508

Prajapati SK, Kumar A, Chopra S, Bansal BK (2013) Intensity map of Mw 6.9 2011 Sikkim–Nepal border earthquake and its relationships with PGA, distance, and magnitude. Nat Hazards. doi:10.1007/s11069-013-0776-x

Seeber L, Armbruster JG (1981) Great detachment earthquakes along the Himalayan arc and long-term forecasting. Earthquake Prediction: An International Review in Maurice Ewing Series4. American Geophysical Union, Washington, D.C., pp 259–277

Shaligram P, Das J, Kumar A, Rout MM, Das R (2014) Probabilistic seismic hazard assessment of Himachal Pradesh and adjoining regions. J Earth Syst Sci 123(1):49–62

Sharma ML, Lindholm C (2011) Earthquake hazard assessment for Dehradun, Uttarakhand, India, including a characteristic earthquake recurrence model for the Himalaya Frontal Fault (HFF). Pure Appl Geophys. doi:10.1007/s00024-011-0427-7

Sharma ML, Wason HR (1994) Occurrence of low stress drop earthquakes in the Garhwal Himalaya region. Phys Earth Planet Inter 85:265–272

Sharma B, Chopra S, Sutar AK, Bansal BK (2013) Estimation of strong ground motion from a great earthquake Mw 8.5 in central seismic gap region, Himalaya (India) using empirical Green's function technique. Pure Appl Geophys. doi:10.1007/s00024-013-0647-0

Singh SK, Mohanty WK, Bansal BK, Roonwal GS (2002) Ground motion in Delhi from future large/great earthquakes in the central seismic gap of the Himalayan arc. Bull Seismol Soc Am 92(2):555–569

Somerville PG, Irikura K, Graves R, Sawada S, Wald D, Abrahamson N, Iwasaki Y, Kagawa T, Smith N, Kowada A (1999) Characterizing earthquake slip models for the prediction of strong ground motion. Seismol Res Lett 70:59–80

Srikantia SV, Bhargava ON (1998) Geology of Himachal Pradesh. Geological Society of India, Bangalore

Sriram V, Khattri KN (1999) Modelling of strong ground motions from Dharmsala earthquake of 1986 (mb 5.7). Curr Sci 76:429–438

Sriram V, Kumar D, Khattri KN (2005) The 1986 Dharamsala earthquake of Himachal Himalaya estimates of source parameters, average intrinsic attenuation and site amplification functions. J Seismol 9:473–485

Srivastava HN, Verma M, Bansal BK (2010) Seismological constraints for the 1905 Kangra earthquake and associated hazard in northwest India. Curr Sci 99(11):1549–1559

Thakur VC, Sriram V, Mundepi AK (2000) Seismotectonics of the great 1905 Kangra earthquake meizoseismal region in Kangra-Chamba, NW Himalaya. Tectonophysics 326:289–298

Toro G, McGuire R (1987) Calculational procedures for seismic hazard analysis and its uncertainty in the eastern United States. In: Proceedings, third international conference on soil dynamics and earthquake engineering, Princeton, NJ, pp 195–206

Valdiya KS (1988) Dynamic Himalaya. Universities Press, Hyderabad

Wald DJ, Quitoriano V, Heaton TH, Kanamori H (1999) Relationship between peak ground acceleration, peak ground velocity, and modified mercalli intensity in California. Earthq Spectra 15(3):557–564

Wallace K, Bilham R, Blume F, Gaur VK, Gahalaut V (2005) Surface deformation in the region of the 1905 Kangra Mw = 7.8 earthquake in the period 1846–2001. Geophys Res Lett. doi:10.1029/2005GL022906

Zeng Y, Anderson JG, Yu G (1993) A composite source model for computing realistic synthetic strong motions. Geophys Res Lett 21:725–728