Modelling of strong motion generation areas for a great earthquake in central seismic gap region of Himalayas using the modified semi-empirical approach

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MS received 1 February 2018; revised 15 September 2018; accepted 19 September 2018;
published online 2 April 2019

Over the past decades, strong motion generation areas (SMGAs) have received significant attention in the modelling of high-frequency records. Herein, we propose the source model for a scenario earthquake (M_w 8.5) in the central seismic gap region of Himalayas. On the rupture plane, three SMGAs have been identified. Further, SMGA parameters are evaluated using available empirical relations. The spatiotemporal distribution of aftershocks is utilised to locate these SMGAs on the rupture plane. Further, the modified semi-empirical technique (MSET) is used to simulate the strong motion records. It has been observed that the study area can expect peak ground acceleration of >100 cm/s² and its distribution is mainly affected by the location of nucleation point in the rupture plane. Furthermore, the estimated peak ground acceleration (PGA) values are comparable with the earlier studies in the region. This confirms the robustness of generated rupture model with three SMGAs and the reliability of MSET to simulate high-frequency records.

Keywords. Central seismic gap; semi-empirical; SMGA; 1991 Uttarkashi earthquake.

1. Introduction

Fifty million years ago, the collision between the Eurasian and Indian plates resulted into the rise of Himalayas. Over the past two centuries, four earthquakes of magnitude above 8 have occurred in the Himalayan belt and no great earthquake had occurred since 1950 (Bilham 1995; Khattri 1999). However, the major portion of the converging plate boundary remains unruptured. Therefore, Khattri and Tyagi (1983) and Khattri (1987) have described three seismic gaps along the Himalayan belt based on the seismicity pattern of the region. The central seismic gap (CSG) is the longest one that stretches between the epicentral locations of

the great 1905 Kangra earthquake and 1934 Bihar earthquake mainshocks (figure 1). They suggested that the CSG can be a possible zone for two future great earthquakes ($M_w \geq 8$). Meanwhile, Bilham *et al.* (2001) also predicted a future earthquake ($M_w \geq 8$) based on the strain accumulation study. Recently, Srivastava *et al.* (2015) demonstrated two different seismic gaps in the Himalayan region by systematically studying the data from different sources. In seismic gap category 1, earthquake of magnitude ≥ 8 has occurred and could reoccur. In seismic gap category 2, earthquakes with magnitude < 8 have occurred or likely to occur,

Figure 1. Stretch between the great 1905 Kangra earthquake and the 1934 Bihar earthquake shows the identified CSG (Khattri 1987). Dotted rectangle shows the study area; solid rectangle represents the possible location of the rupture plane for M_w 8.5 magnitude earthquake in CSG (Yu *et al.* 1995). Seismicity shown in figure is for the time periods of 1505–2011 (map modified after Kayal 2014; Srivastava *et al.* 2015).

as shown in figure 1. The major portion of the Himalayas in the Uttarakhand region lies in category 1 seismic gap and prone to an earthquake of magnitude >8.0 (figure 1). This region comprises many large hydroelectric power plants and hence requires detailed examination of the seismic hazard. For this purpose, the estimation of earthquake engineering parameters such as peak ground motion values using simulated records is desirable. Using the specific source patch models, strong motion records can be successfully modelled. These patches with high slip rate along with the rupture plane are termed as strong motion generation areas (SMGAs) (Miyake *et al.* 2003). Many research groups such as Miyake *et al.* (1999, 2001, 2003), Kamae and Kawabe (2004), Miyahara and Sasatani (2004), Suzuki and Iwata (2007), Takiguchi *et al.* (2011), Kurahashi and Irikura (2011) and Asano and Iwata (2012) have successfully simulated strong motion records using empirical Green's function technique and rupture model incorporating SMGAs. However, the above approach is quite reliable but the requirement of aftershock records is a primary obstacle.

In this context, the semi-empirical technique (Midorikawa 1993) has been developed as a powerful tool that effectively simulates the strong motion records. In this technique, aftershock records have been successfully replaced with the envelope function of time records. Therefore, this paper demonstrates the application of modified semi-empirical technique (MSET) to model SMGAs in the rupture plane of great earthquake in the CSG region.

2. Geology and seismotectonics

The Kumaon and Garhwal regions of Himalayas are the two most putative sites of future devastating earthquakes. The high seismicity and active thrust system demonstrated that the Main Boundary Thrust (MBT) and Main Central Thrust (MCT) are the most significant tectonic features of the above regions. High-grade metamorphic crystalline rocks occurred in the north of MCT while the brittle fracture characterised MBT (figure 2). However, several research groups have contradicted the above view on seismotectonics of Himalayas.

Figure 2. Geological and seismicity map of the Kumaon and Garhwal Himalaya along with 10 recording stations (red triangle). Three rectangles are the rupture planes (Joshi 2004; Wells and Coppersmith 1994) of the 1916 Indo Nepal (M_w 7.0), 1991 Uttarkashi (M_w 6.8) and 1999 Chamoli (M_w 6.5) earthquakes in this region. Black dots represent the epicentre of the earthquakes of $M_w > 4$. MCT, Main Central Thrust; MBT, Main Boundary Thrust; HFT, Himalayan Frontal Thrust (map modified after Chopra *et al.* 2012).

For instance, Ni and Barazangi (1984) proposed that the MCT is less active than the MBT and suggested other adjacent thrusts in the Himalayan arc. On the other hand, Seeber *et al.* (1981) postulated that seismicity is mostly concentrated between the MBT and MCT and the earthquakes of intermediate magnitude are usually occurred on a steeply dipping basement thrust of MCT. According to the IMD catalogue (2012), 11 earthquakes of magnitude between 6 and 7 were reported in the western part of CSG. This comprises 1916 Indo Nepal (M_w 7.0), the 1991 Uttarkashi (M_w 6.8) and the 1999 Chamoli (M_w 6.5) earthquakes. The rupture planes of aforementioned earthquakes have been shown in figure 2.

On the basis of intensity sustained from past earthquakes, the IS:1893 (2002) Bureau of Indian

standard (BIS) has subdivided India into four seismic zones – II, III, IV and V. Seismic zones II and V are the lowest and highest earthquake prone areas, respectively. The Uttarakhand state falls in between the seismic zones IV and V, and hence, it is referred as high earthquake prone area. Moreover, Global Seismic Hazard Assessment Program (GSHAP) data revealed that the state of Uttarakhand falls in a region of high to very-high seismic hazard. However, Joshi and Mohan (2010) reported the assessment of seismic hazards for moderate earthquakes in Himalayas using the deterministic approach. Bhatia *et al.* (1999) identified two source zones of $M_{7.5}$ earthquakes in Himalayas. Furthermore, Nath *et al.* (2008) postulated that the ground motion of a scenario earthquake (M_w 8.5) has 10% exceedance probability for the next 50 yrs. Over

the past decades, this region has also witnessed enormous seismicity (figure 2).

3. Methodology

In this paper, the MSET pioneered by Midorikawa (1993) has been used to simulate strong motion records (Sandeep *et al.* 2014b). Over the past decades, many researchers have successfully used the above-mentioned technique in simulating strong motions (e.g., Joshi and Patel 1997; Kumar *et al.* 1997; Joshi *et al.* 1999, 2001, 2012a, b, 2014, 2015; Joshi 2001, 2004; Joshi and Midorikawa 2004; Sandeep *et al.* 2014a, b, 2015, Sandeep *et al.* 2017a, b, c). In the MSET technique, the rupture plane of the target earthquake is subdivided into equal area grids and called as subfaults. The division is governed by self-similarity laws, suggested by Aki (1967) and later modified by Kanamori and Anderson (1975). After several years, Boore (1983) described the acceleration spectra $A(f, R)$ as follows:

$$A(f, R) = CS(f) D(f) F(f, R), \quad (1)$$

where C is a constant scaling factor, $S(f)$ and $D(f)$ are the source acceleration spectrum (Brune 1970) and attenuation of high frequencies, respectively, and $F(f, R)$ represents the attenuation factor (Boore 1983).

The present technique entails the multiplication of theoretical filters proposed by Boore (1983) with band limited spectrum and finite duration white Gaussian noise. The above-mentioned outcome obtains the acceleration spectra for each subfault, which correspond to acceleration records in the time domain. Due to the difference between the slip duration of the target and small earthquake (subfaults), these acceleration records need to be corrected and thus combining the earlier simulated records $a_{ij}(t)$ with correction function $F(t)$.

The corrected acceleration records $A_{ij}(t)$ are generated by combining the earlier simulated records $a_{ij}(t)$ with the correction function $F(t)$ (Irikura and Kamae 1994; Irikura *et al.* 1997) as follows:

$$A_{ij}(t) = F(t) \times a_{ij}(t), \quad (2)$$

where $A_{ij}(t)$ is the corrected acceleration record and i and j show the subfault position along

the rupture length and width, respectively. The correction function $F(t)$ is represented as follows:

$$F(t) = \delta(t) + [(N - 1)/T_R(1 - \exp(-1))] \times \exp(-t/T_R), \quad (3)$$

where $\delta(t)$ denotes the delta function, N represents the total number of subfaults along the rupture length or width and T_R is the rise time of the target earthquake.

However, this technique demands appropriate windowing of the corrected simulated records. In this regard, Kameda and Sugito (1978) suggested the functional form of acceleration envelope $e_{ij}(t)$, which was further modified by Joshi (2004). The multiplication of corrected simulated acceleration recorded with envelope function $e_{ij}(t)$ generates the final acceleration record $ac_{ij}(t)$ as follows:

$$ac_{ij}(t) = e_{ij}(t) \cdot A_{ij}(t) \quad (4)$$

and the envelope function $e_{ij}(t)$ is described as follows:

$$e_{ij}(t) = T_{ss}(t/T_d) \cdot \exp(1 - t/T_d), \quad (5)$$

where T_d and T_{ss} represent the duration parameter and transmission coefficient, respectively.

The summation of all acceleration records $ac_{ij}(t)$ released from different subfaults in different time periods t_{ij} delivers the final simulated acceleration records $Ac(t)$ for target earthquake and is given as follows:

$$Ac(t) = \sum_{i=1}^N \sum_{j=1}^N ac_{ij}(t - t_{ij}). \quad (6)$$

In recent years, Sandeep *et al.* (2014a) modified the above technique and successfully used to simulate the strong motion for the 1991 Uttarkashi earthquake in the western part of CSG. In this paper, the same approach has been exploited to simulate strong motion results for the scenario earthquake of magnitude 8.5 in the CSG region.

4. Data

In this work, the dataset from three different research papers was used to locate the position of responsible rupture plane and SMGAs within it. The 1991 Uttarkashi earthquake prompted Kayal *et al.* (1995) to install a temporary microearthquake

Table 1. Details of three different data sets used in the present study.

Network	Time period	Total recorded events	Magnitude	Depth range (km)	Source
Temporary microearthquake seismograph network	2 November to 4 December 1991 (33 days)	124	2.5–6.8	≤26	Kayal <i>et al.</i> (1995)
USGS seismograph network	1973–2014	50	2.2–5.5	≤30	USGS
Strong motion station network seismicity project MoES, GoI.	2006–2014	110	2.5–5.4	≤31	https://www.usgs.gov/ Kumar <i>et al.</i> (2015a, b)

Figure 3. Estimated source model with three SMGAs for the probable great earthquake (M_w 8.5) in CSG. Solid and hollow circles are the events located by Kayal *et al.* (1995) and Department of Earth Sciences, Indian Institute of Technology Roorkee, in this region. Solid and hollow stars show the events from USGS and three major events in the region. Dimension of the total rupture area is taken after Yu *et al.* (1995). (Map after Mukhopadhyay *et al.* 2011.) MCT, Main Central Thrust; MBT, Main Boundary Thrust; MFT, Main Frontal Thrust.

network in the region. A total of 124 aftershocks were recorded at this microearthquake network and were used for the present study (Kayal *et al.* 1995).

Under a seismicity project funded by the Ministry of Earth Sciences, Government of India, a network of 14 stations in the highly mountainous terrain of the Kumaon Himalaya was installed. These work stations are maintained by the Department of Earth Sciences, Indian Institute of Technology Roorkee. A total of 110 events were recorded on this network during 2006–2014 and were included in this work. In addition, USGS recorded 50 events in the same region during

the period 1973–2014 and were also incorporated in the present study (<https://www.usgs.gov/>). A brief description and spatial distribution of these events are represented in table 1 and figure 3, respectively.

5. Rupture model for scenario earthquake in CSG

Yu *et al.* (1995) proposed a rupture plane of dimensions 240 km $\times$ 80 km for a scenario earthquake having a magnitude 8.5 in the CSG region and was used in the present study. However, other

Table 2. Source parameters of SMGAs identified in the present study.

SMGAs	<i>N</i>	Strike	Dip	Length (km)	Width (km)	M_0 dyne cm
References	Kanamori and Anderson (1975)	Yu <i>et al.</i> (1995) (suggested for great earthquake)		Wells and Coppersmith (1994)		CMT Harvard; USGS
SMGA1	5	317°	6°	48	36	0.8×10^{26}
SMGA2	4	317°	6°	44	32	7.77×10^{25}
SMGA3	4	317°	6°	45	32	8.25×10^{25}

N: number of subfaults.

Table 3. Velocity model (Yu *et al.* 1995) of the region.

Thickness (km)	V_s (km/s)	Density (kg/m ³)
0.4	2.00	1800
1.0	2.86	2400
15.0	2.97	2600
30.0	3.43	2900

research groups including Araya and Kiureghian (1988) and Wells and Coppersmith (1994) estimated 260 km × 80 km rupture dimensions using

different empirical relations. Wyss (1979) postulated the magnitude–rupture area relation that successfully predicted the earthquake of magnitude 8.43 for the above suggested rupture dimensions. The current and past seismicity of the Himalaya region demonstrated that the rupture plane is placed in the north of MBT. Therefore, we utilised a northeast dipping fault at a depth of 18 km with strike of 317° and dip of 14° for this scenario earthquake (Yu *et al.* 1995). Considering the surface offsets along a fault and background seismicity of the region, the high slip rate area on the fault plane can be determined (Irikura and Miyake 2011). In

Figure 4. Simulated acceleration records for the probable great earthquake (M_w 8.5) at BARK, GHAN, KOSA, RUDR, TEHR, BHAT, KARN, PURO, SRIN and UTTA stations assuming the epicentre of the probable great earthquake as the location of nucleation point of: (a) SMGA1, (b) SMGA2 and (c) SMGA3.

the present study, three SMGAs were identified based on three different clusters of 284 earthquake events in the Himalaya region (figure 3). Each cluster serves as different source of energy and possible location of SMGAs in the rupture plane. These are modelled as SMGAs and termed as SMGA1, SMGA2 and SMGA3. During a future great earthquake, the actual location of SMGAs may alter, which directly influences the acceleration results. However, dense GPS network may provide better slip rates and absolute locations of SMGAs. On the basis of self-similarity relations (Kanamori and Anderson 1975), the rupture plane of SMGA1, SMGA2 and SMGA3 was partitioned into 5×5 , 4×4 and 4×4 grids, respectively, as shown in figure 3 and table 2. Event of M_w 5.4 was used as a subfault for rupture division of SMGA1 and SMGA2, whereas M_w 5.2 was utilised for SMGA3. The selection of the events was carefully done as these have similar faulting mechanism and focal depth as that of the target earthquake.

The seismicity of the study area described that the epicentres of Uttarkashi and Chamoli earthquakes are situated in SMGA1 and SMGA2, respectively. On the basis of this study, these events (i.e., rupture planes and seismic moments) are considered as SMGA1 and SMGA2. On the other hand, SMGA3 is located in the Kumaon region along the boundary of India and Nepal. Therefore, the 1980 Nepal earthquake (M_w 6.5) in the eastern Kumaon region is considered as SMGA3. The USGS and Global Centroid–Moment–Tensor (CMT) provided the fault plane mechanism for 1991 Uttarkashi ($\phi = 296^\circ$, $\delta = 5^\circ$ and $\lambda = 90^\circ$), 1999 Chamoli ($\phi = 282^\circ$, $\delta = 9^\circ$ and $\lambda = 95^\circ$) and 1980 Nepal China earthquake ($\phi = 290^\circ$, $\delta = 21^\circ$ and $\lambda = 91^\circ$), which have been used for SMGAs. The high dip (21°) for the 1980 Nepal earthquake than the Uttarkashi ($\sim 5^\circ$) and Chamoli ($\sim 9^\circ$) earthquakes suggests that the Main Himalayan Thrust (MHT) is much steeper in the Kumaon region than in the Garhwal region. In addition, Kumar *et al.* (2015b) reported two different attenuation relations $96f^{1.06}$ and $65f^{1.07}$ for Garhwal and Kumaon regions, respectively, which have been considered for the strong motion study in this work. These two aforementioned factors, i.e., steeper dip of fault plane and different attenuation characteristics of the Kumaon region explain the different distribution pattern of predicted PGA values in the case of SMGA3.

Yu *et al.* (1995) derived a velocity model for this region as described in table 3. The rupture plane

Figure 5. Variation of simulated PGA at every site for three different possible locations of mainshock.

Figure 6. Comparison of simulated PGA values in the present study with other studies in the region. ‘ r ’ represents the correlation coefficient values between simulated PGA and other three studies in the region.

was situated at a depth of 18 km in the fourth layer of this velocity model.

6. Results and discussion

In the present work, the entire study area (extending between latitude $76\text{--}83^\circ\text{E}$ and longitude $28\text{--}32^\circ\text{N}$) was divided into $0.5^\circ \times 0.5^\circ$ square grids. MSET was used to simulate the horizontal

Table 4. PGA values at different locations for three different locations of mainshock in rupture plane.

Station	Station code	PGA (gal) mainshock location in SMGA1	PGA (gal) mainshock location in SMGA2	PGA (gal) mainshock location in SMGA3	Geology of the region (Sharma <i>et al.</i> 2013)
Barkot	BARK	252	266	112	Quartzite and phyllites
Ghansali	GHAN	400	402	240	Quartzite and phyllites
Kosani	KOSA	101	109	350	Quartzite, schist and granite
Rudra Prayag	RUDR	210	203	310	Quartzite, schist and granite
Tehri	TEHR	516	535	273	Quartzitic phyllite and schistose phyllite
Bhatwari	BHAT	630	520	178	Quartzites, schists and gneisses
Karan Prayag	KARN	197	212	332	Quartzitic phyllites and massive quartzites
Purola	PURO	439	430	102	Quartzite and phyllites
Sri Nagar	SRIN	230	219	300	Quartzite
Uttarkashi	UTTA	855	840	197	Quartzite and phyllites
New Delhi	NDL	100	80	220	Alluvium
Chandigarh	CHD	300	220	100	Alluvium
Haridwar	HDW	600	500	250	Alluvium

Figure 7. Isoacceleration map of the region assuming the location of the probable earthquake in SMGA1 close to the mainshock of the 1991 earthquake in the Uttarkashi region.

component of strong motion records at every corner of the grid. Figure 4 shows the simulated records at 10 real recording sites. In the source model, SMGAs led to the peculiar shapes at different stations (SRIN, TEHR and UTTA). As a consequence, three different cases correspond to three different possible locations of nucleation point of the probable earthquake (8.5) were assumed. The epicentre

of the probable earthquake was considered as the nucleation point of SMGA1, SMGA2 and SMGA3 (the extreme northeast of every SMGA). The variation of simulated PGA at every site for three different locations of mainshock is described in figure 5 and table 4.

Moreover, the simulated PGA values are compared with earlier studies for the same region using

Figure 8. Isoacceleration map of the region assuming the location of the probable earthquake in SMGA2 close to the mainshock of the 1999 earthquake in the Chamoli region.

Figure 9. Isoacceleration map of the region assuming the location of the probable earthquake in SMGA3.

the correlation coefficient (r) as shown in figure 6. (Chopra *et al.* 2012; Sharma *et al.* 2013; Sharma and Bungum 2006). Isoacceleration maps for all the three possible locations of mainshock have been developed using simulated records at every corner of the grid (figures 7–9).

7. Conclusions and future scope

In conclusion, a source model with three SMGAs for a future probable earthquake (M_w 8.5) in the

CSG region has been estimated. An attempt is made to evaluate the PGA distribution in the region using MSET. It is observed that PGA values are comparable for the assumed epicentre of probable earthquake in SMGA1 and SMGA2. The highest PGA is estimated at Uttarkashi station, whereas the lowest is obtained at Kosani. However, Kosani would experience the highest PGA for mainshock location in SMGA3, whereas Purola site would observe the lowest. Haridwar, Chandigarh and New Delhi would observe PGA values of 600, 300 and 100 gal, respectively, for the

mainshock location in SMGA1 and 500, 220 and 80 gal, respectively, for the mainshock in SMGA2. From the above analysis, we concluded that PGA would be higher in Haridwar and Chandigarh than New Delhi city for SMGA1 and SMGA2. In contrast, New Delhi would observe a higher PGA value than Chandigarh for nucleation point located in SMGA3. The variation in PGA values with mainshock location can be attributed to the directivity effects of the rupture propagation. Furthermore, the simulated PGA values in the present work are more or less comparable with previous studies in the same region.

Acknowledgements

The authors are grateful to Dr Preeti for her valuable efforts to improve the quality of the paper. The authors sincerely acknowledge the editorial board and two anonymous reviewers for their critical review and constructive suggestions. The authors sincerely thank Kayal *et al.* (1995), USGS (<https://www.usgs.gov/>), CMT Harvard (<http://www.globalcmt.org/>), Ministry of Earth Sciences (project reference no. MoES/P.O.(Seismo)/1(42)/2009) for using earthquake data. This work is an outcome of project reference no. ECR/2016/000737 supported by the Science and Engineering Research Board, DST, India. We gratefully acknowledge the Department of Geophysics, Banaras Hindu University, Varanasi and Department of Earth Sciences, Indian Institute of Technology, Roorkee, for providing basic facilities for this research work. The author AS is highly thankful to Prof N P Singh for his valuable suggestions to improve the quality of research work. The author PK sincerely acknowledges the Director, Wadia Institute of Himalayan Geology, Dehradun.

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Corresponding editor: ARKOPROVO BISWAS