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Ground motion prediction equation considering combined dataset of recorded and simulated ground motions

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ABSTRACT

Himalayan region is one of the most active seismic regions in the world and many researchers have highlighted the possibility of great seismic event in the near future due to seismic gap. Seismic hazard analysis and microzonation of highly populated places in the region are mandatory in a regional scale. Region specific Ground Motion Predictive Equation (GMPE) is an important input in the seismic hazard analysis for macro- and micro-zonation studies. Few GMPEs developed in India are based on the recorded data and are applicable for a particular range of magnitudes and distances. This paper focuses on the development of a new GMPE for the Himalayan region considering both the recorded and simulated earthquakes of moment magnitude 5.3–8.7. The Finite Fault simulation model has been used for the ground motion simulation considering region specific seismotectonic parameters from the past earthquakes and source models. Simulated acceleration time histories and response spectra are compared with available records. In the absence of a large number of recorded data, simulations have been performed at unavailable locations by adopting Apparent Stations concept. Earthquakes recorded up to 2007 have been used for the development of new GMPE and earthquakes records after 2007 are used to validate new GMPE. Proposed GMPE matched very well with recorded data and also with other highly ranked GMPEs developed elsewhere and applicable for the region. Comparison of response spectra also have shown good agreement with recorded earthquake data. Quantitative analysis of residuals for the proposed GMPE and region specific GMPEs to predict Nepal–India 2011 earthquake of Mw of 5.7 records values shows that the proposed GMPE predicts Peak ground acceleration and spectral acceleration for entire distance and period range with lower percent residual when compared to exiting region specific GMPEs.

1. Introduction

Ground shaking during an earthquake is responsible for structural damages and ground failures within the epicentral region as well as at far distances. Seismic hazard analysis of any region focus to arrive precise ground shaking parameters such as PGA (Peak Ground Acceleration) or Peak ground velocity (PGV). The region specific Ground Motion Prediction Equation (GMPE) is playing important role in the seismic hazard analysis for macro- and micro-level hazard mapping. Developed countries are in the process of arriving the Next Generation of ground motion Attenuation (NGA) for the better prediction of ground shaking due to any future earthquake events [20,39]. However, studies towards developing regional representative GMPEs are limited in India. Also limited regional GMPEs are available to estimate the representative seismic hazard both at bedrock at the surface by accounting the local site effects in India and other parts of the world [10,54,9]. The seismic zonation map given in Indian standard in its current form does not provide a quantitative seismic hazard values at micro-level. Many recent studies have highlighted that macro-level zonation factor (or PGA) given in Indian standard code [34] is either higher or lower than that of the micro-level PGA obtained after seismic hazard studies at regional scale [8,46,54]. Thus, the zonal values given in IS code are required to be updated after rigorous micro-level findings. Such micro-level ground motion estimation studies should be based on the past seismicity and region specific GMPE. Several seismic hazard maps are being produced in India using available GMPEs with limited validity of the degree of suitability of representative GMPEs for the region [9].

Many researchers ([40,77]) have highlighted the chances of large seismic event in Himalayan region considering the seismic activity and gap. Based on the recorded earthquake data from different parts of Himalayan region, numerous researchers have attempted for GMPEs for the region. Such GMPEs have been

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extensively used in the seismic hazard studies in and around Himalayan region. Review of existing region specific GMPEs reveals that each GMPE has its own limitations and merits. Regional GMPEs were developed considering limited range of magnitude and distance, limited near source region data, limited higher magnitude earthquakes ground motions and use of other region ground motion data. In spite of such serious limitations, these GMPEs are being used extensively for hazard mapping in Himalayan Region. Present work highlights in detail the shortcoming in the existing GMPEs and further a new GMPE is proposed using region specific ground motions. The region under study evidences plate boundary and intraplate earthquakes with majority of events following the strike-slip fault mechanism.

Initially a large ground motion data collected from the recorded ground motions from a number of earthquakes in Himalayan region. This dataset does not cover an entire distance and magnitude range. In order to make a consistent database, additional ground motions have been generated synthetically using regional seismotectonic parameters. Each earthquake synthetic ground motions have been verified by comparing with available recorded data acceleration time history and response spectra. Once, sufficient validation between the recorded and synthetic ground motion has been found, more number of ground motions have been generated which are distributed uniformly around the epicentre covering a wide range of distances. Further to account large magnitude in GMPE, synthetic ground motions for major and great earthquakes have been generated which have been verified by comparing with PGA values from the isoseismal maps. Real and synthetic ground motions at rock level are used to arrive the PGA and spectral acceleration at different period, which are used to develop a new GMPE for Himalayan region. The new GMPE proposed has been validated by comparing with the PGA of the recent earthquake, which was not the part of database. The proposed GMPE is derived using more realistic and large regional dataset when compared to earlier published GMPEs. The predicated PGA and spectral acceleration values by proposed GMPE match well with recent recorded earthquakes and is valid for wide range of magnitudes and distances.

2. Existing regional GMPE models

In order to develop the best suitable GMPEs for any region, capturing of tectonic setting is a prerequisite. In order to understand this, a large number of recorded ground motions which are distributed over a wide range of magnitude, distance, source and site parameters should be known. Various researchers have analysed the attenuation characteristics of the Himalayan region based on the available data. Region specific GMPEs developed by Singh et al. [69], Sharma [65], Iyenger and Ghosh [35], Nath et al. [52,51], Sharma and Bungum [63], Das et al. [23], Baruah et al. [11], Sharma et al. [64] and Gupta [28] are based on the recorded as well as simulated earthquake data in the Himalayan region. In addition to these equations, NDMA (National Disaster Management Authority, 2010) [78], Government of India, developed indigenous GMPEs for the probabilistic seismic hazard mapping of India considering only the simulated data. A summary of the existing GMPEs for the Himalayan region in terms of magnitude range, distance range, frequency ranges and the database used for the development is presented in Table 1.

Singh et al. [69] had developed attenuation relation for Himalayan region based on the recorded earthquake data. General form of the attenuation equation given by Kanai [42] was used for the analysis. Singh et al. [69] had estimated the coefficients in the attenuation relation for felt earthquakes based on isoseismal maps. The authors then correlated the coefficients from PGA attenuation relation with the Modified Mercalli Intensity scale (MMI) attenuation relation and compiled the final coefficients of GMPE for Himalayan region. This final form of GMPE given by Singh et al. [69] is applicable to the magnitude range of 5.5–6.8 and up to hypocentral distance of 100 km. Similarly, Sharma [65] had developed the attenuation relation for Himalayan region based on 66 peak ground acceleration records from 5 earthquakes with a magnitude range from 5.5–6.8, reported from 1986 to 1991. Most of these earthquake data cover an epicentre distances of up to 150 km. Earthquake data set used by Singh et al. [69] and Sharma [65] were similar and no standard error terms were incorporated in both the GMPEs. In the absence of the standard error term, these GMPEs have limited application in the Probabilistic Seismic Hazard Analysis (PSHA). Hence, these two GMPEs are not considered in this study.

Iyenger and Ghosh [35] have highlighted the limitations of GMPE by Sharma [65] for PSHA. Iyenger and Ghosh [35] proposed a new GMPE by combining the earthquake data used by Sharma [65] and earthquakes data recorded around Delhi region. The input data consist of events recorded within 300 km radial distance around Delhi for an earthquake magnitude range of 4.0–7.0. Iyenger and Ghosh [35] have shown that the annual rate of earthquake occurrence in Delhi is much lesser compared to the Himalayan region.

Nath et al. [52] had developed GMPE based on 80 earthquakes recorded in the Shillong Strong Motion Array (SSMA) during the period of 1998–2003. These earthquakes were in local magnitudes

Table 1
Summary of GMPEs developed for the Himalayan region.

SL. no.	Study	Range of magnitude (Mw)	Distance range (km)	Distance function used	Spectral coefficients available for periods	Remarks
1.	Singh et al. [69]	5.5–6.8	≤100	R_{HYPO}	zero	Felt earthquake isoseismal maps of 5 events are used
2.	Sharma [65]	5.5–6.8	≤150	R_{HYPO}	zero	66 recorded data from 5 earthquakes
3.	[35]	4.0–7.0	≤300	R_{HYPO}	zero	Earthquakes data recorded around Delhi region
4.	Nath et al. [52]	3–8.5	≤100	R_{HYPO}	0.06–0.4	80 recorded events in Shillong Strong Motion Array (3.0–5.6) and 25 simulated events (5.6–8.5)
5.	Das et al. [23]	5.5–7.2	≤300	R_{EPIC}	0.04–1.0	261 recorded data from 6 moderate earthquakes at 87 stations
6.	Sharma and Bungum [63]	4.6–7.6	≤200	R_{HYPO}	0.04–2.5	Combined dataset of 175 ground motions of 14 earthquake from India (4.6–6.6) and 9 earthquakes from Europe (6.2–7.6).
7.	Baruah et al. [11]	2.5–5.0	≤145	R_{HYPO}	zero	82 recorded earthquakes at 8 broadband stations
8.	Nath et al. [51]	4.8–8.1	≤100	R_{RUP}	0.05–4.0	Simulated ground motions considering model parameters used in Mw of 4.8 simulation
9.	Sharma et al. [64]	5.2–6.9	≤ 100	R_{JB}	0.04–2.5	Combined dataset consisting of 6 recorded earthquakes from India and 10 recorded earthquakes from Zegros region
10.	Gupta [28]	6.3–7.2	> 150	R_{RUP}	0.02–3.0	56 recorded data from 3 events
11	NDMA [54]	4–8.5	≤500	R_{HYPO}	0.0–4.0	1600 Simulated ground motions

(M_L) scale ranging from 3.0 to 5.6 and recorded within 100 km distance from the epicentre. In order to incorporate events with magnitude higher than 5.6 in the database, synthetic ground motions were generated using the Brune [18] point source model. Synthetic ground motions were generated in the magnitude range from 5.6 to 8.5 and up to a hypocentral distance of 100 km. Based on combined data set of recorded and simulated ground motions, a new GMPE was proposed for the Himalayan region.

Das et al. [23] had developed GMPE for northeast India in terms of Peak Spectral Velocity (PSV) based on six moderate size earthquakes recorded at 87 stations. Authors had considered 261 earthquake records consisting of all the three components of ground motion (2 horizontal and 1 vertical) at each station together to develop the GMPE for the region. In usual practice, GMPEs are developed considering either peak of two horizontal components or arithmetic mean of the two horizontal components to develop GMPEs. However, GMPE developed by Das et al. [23] was based on all the three components recorded at each station. This was done to enhance the total number of earthquake data points for the analysis. The catalogue consists of earthquakes with a magnitude range of 5.5–7.2 and epicentral distance up to 300 km. Proposed GMPE can be used to predict PSV values and the PSA (peak spectral acceleration) values by multiplying PSV values by $2\pi/T$.

The GMPE proposed by Sharma and Bungum [63] for Himalayan region consisted of 175 ground motions based on combined earthquake data from Himalayan region and European region. The Himalayan data consist of events with magnitude of 4.6–6.6 and of hypocenter distance of beyond 20 km. In lack of near source recorded data from the Himalayan region, additional data have been taken from the Europe region in the magnitude range of 6.2–7.6. Other region specific GMPEs for Himalaya region include GMPE by Baruah et al. [11]. This GMPE had been developed for Shillong plateau based on 80 small to moderate size earthquake events with M_D (duration magnitude) of 2.5–5 which has occurred during 2001–2006. The arithmetic mean of two horizontal components recorded at each station was considered for the analysis. Input data covers a hypocentral distance range between 3.5 km and 145 km. Nath et al. [51] presented the attenuation relation for northeast Himalayas as part of seismic microzonation study for Guwahati city. In the absence of recorded earthquake data, EXSIM [48] was used for simulating the ground motions covering a wide range of earthquakes (4.8≤Mw≤8.1) up to distances of 100 km. In the first step, the model validation was done by simulating ground motion for 2nd February 2006 earthquake of Mw 4.8 and comparing with recorded data at two stations. Thereafter, the same model parameters were used to generate the ground motions for magnitude range of 4.8–8.1, using source and event parameters of 1897 Shillong, 1934 Bihar–Nepal, 1950 Assam and 1988 Manipur earthquakes. This GMPE is purely based on simulated data with limited verifications, Nath et al. [51] proposed a GMPE for northeast Himalayas. This GMPE is valid for a magnitude range of 4.8–8.1 (Mw) and up to a hypocentral distance of 100 km.

Sharma et al. [64] developed a GMPE by combining earthquake data from the Himalayas and Zagros region in Iran after highlighting tectonic and geological similarities between the two regions. The database consists of earthquakes with a magnitude Mw of 5.0–7.0 and hypocentral distance up to 100 km. Out of total input used for the analysis, about 71% of earthquake data had been from Zagros region. Gupta [28] developed another GMPE for Himalayan region based on three events occurred in Indo-Burmese subduction zone. This region is adjacent to the active Shillong region. These events were in the magnitude range of 6.3–7.2 (Mw) recorded at 56 strong motion recording stations both at rock site and at soil sites. The combined earthquake data from both types of sites were used for the analysis. In addition, all the 56 recording stations were located beyond 150 km from the epicentre. Thus, near source earthquake data was absent in the database used which was for the regression analysis.

National Disaster Management Authority (NDMA), Government of India, developed a probabilistic seismic hazard map of India by constituting the Working Committee of Experts (WCE) [54]. For the study, India had been divided into 7 tectonic zones as per Seeber et al. [62] with 32 sources. GMPEs for every zone were developed using synthetic ground motion data and compared with the available records. Finite Fault source model with regional seismotectonic parameters was used to simulate ground motions for each of the 7 tectonic zones. These simulated data were used to develop GMPEs for each zone. NDMA [54] GMPE is applicable for Mw of 4.0–8.5 and up to a distance of 500 km.

3. Comparison of GMPEs

In addition to region specific GMPEs, there are several GMPEs developed for similar tectonic conditions which can also be applicable to Himalayan region. GMPEs developed elsewhere and applicable to Himalayan regions include Youngs et al. [76], Ambraseys et al. [4], Kanno et al. [44], Zhao et al. [79], Campbell and Bozorgnia [21], Idriss and An [32] and Akkar and Bommer [3]. All these equations were developed for other regions of the world and are being used for seismic hazard studies of Himalayan region. These GMPEs were developed for different distances such as R_{jb} (called as "Joyner–Boore" distance), R_{hyp} (called as hypocentre distance), R_{epi} (called the epicentre distance). In order to compare GMPEs in single plot, the PGA values are estimated considering distance used to develop respective GMPEs and simultaneously hypocentre distance is also estimated. Estimated PGA as per GMPE distance is plotted with hypocentral distance. It can also be noted here that the use of multiple distances for GMPE comparison only affects short distance <20 km and above 20 km, the effects are negligible [17]. Fig. 1 shows the plot of region specific available GMPEs and applicable GMPEs for Himalayan region considering Mw 6.8 and hypocenter distance of up to 300 km. From Fig. 1, it is very difficult to assess applicability of the particular GMPE for the region. Also it is very difficult to identify the appropriate region specific GMPEs for the hazard analysis and microzonation purposes. Hence best suitable GMPEs identified by Nath and Thinbaijam [50] for Himalayan region are taken as reference to compare region specific GMPEs. Nath and Thinbaijam [50] identified best suitable GMPEs for Himalayan region by efficacy tests proposed by

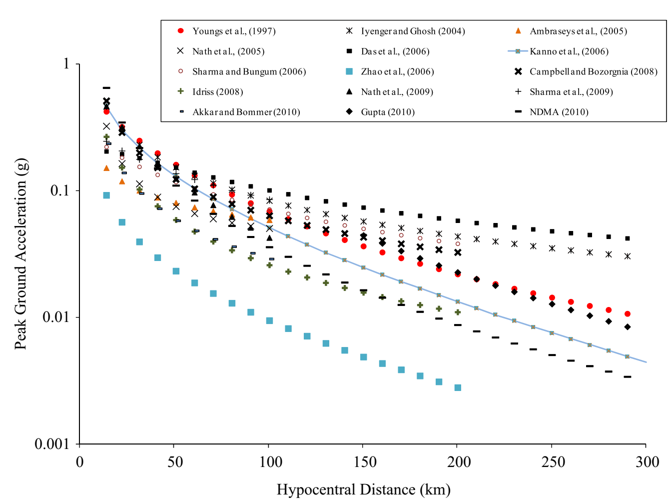

Fig. 1. Comparison of ground motion prediction equations applicable to Himalayan region for earthquake moment magnitude of 6.8.

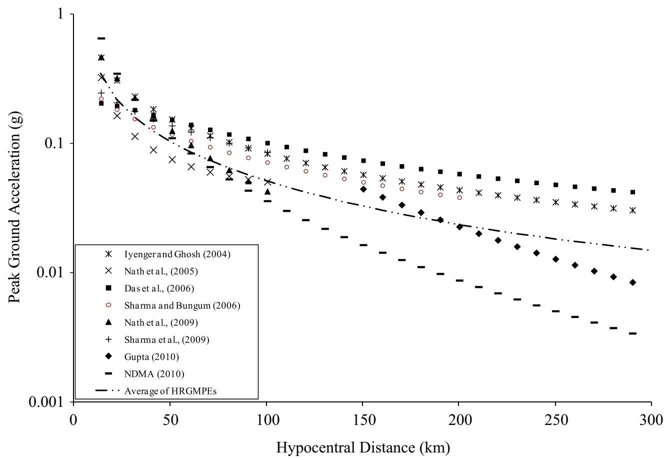

Fig. 2. Comparison of region specific ground motion prediction equations with the average of first five high ranked ground motion prediction equations (HRGMPEs) for an earthquake moment magnitude of 6.8.

Delavaud et al. [24]. Nath and Thinbaijam [50] listed highly ranked GMPEs for Himalayan region and of these, the first five are best suitable GMPEs. First five GMPEs suitable for Himalayan regions are Kanno et al. [44] [KAN06], Campbell and Bozorgnia [21] [CABO08], Sharma et al. [64] [SHAR09], Akkar and Bommer [3] [AKBO10] and Idriss and An [32] [IDR08]). In order to compare, these five GMPEs have been combined and average value is considered. PGA for Mw of 6.8 was estimated considering five highly rankled GMPEs [HRGMPE] and average values are plotted. This average PGA value from best suitable five GMPEs for the Himalayas and the region specific GMPEs developed in India are shown in Fig. 2.

From Fig. 2 it can be observed that GMPEs given by Iyenger and Ghosh [35] overestimates the hazard values when compared to average of HRGMPEs throughout the hypocentral distance of up to 300 km. Suitability of Nath et al. [52] GMPE has been assessed by comparing with HRGMPEs as given in Fig. 2. It can be concluded from Fig. 2 that the GMPE proposed by Nath et al. [52] under-predicts the PGA values when compared to HRGMPEs. Also, this GMPE is valid only up to hypocenter distance of 100 km. On comparing the GMPE proposed by Das et al. [23] with that of HRGMPEs, it was observed that till 40 km the values of PGA from both the relations are matching fairly with each other. However, beyond 40 km hypocentral distance, Das et al. [23] predict values much higher than PGA values from HRGMPE.

Although, Sharma and Bungum's [63] GMPE was based on two similar region ground motion data, its comparison with HRGMPE shows a fair matching between the PGA values upto 70 km (see Fig. 2). Further, Sharma and Bungum [63] GMPE gives slightly higher values when compared to HRGMPE beyond 70 km up to a hypocentral distance of 200 km beyond which this GMPE is not valid (Fig. 2). The GMPE by Baruah et al. [11] is valid up to magnitude 5.0 and which is not compared with HRGMPE.

Comparison of Nath et al. [51] GMPE with HRGMPEs can be seen in Fig. 2. Based on comparison, it can be observed that Nath et al. [51] predict ground motions close to HRGMPE upto 100 km beyond which Nath et al. [51] is not applicable. Comparison of GMPE by Sharma et al. [64] in Fig. 2 shows that Sharma et al. [64] GMPE under-predicts values compared with HRGMPEs up to 40 km hypocentral distance. However, beyond 40 km, GMPE by Sharma et al. [64] gives values higher than HRGMPE and this GMPE is valid up to 100 km.

Gupta [28] GMPE has been compared with HRGMPE in Fig. 2 for hypocentral distance of 150 km and above, because GMPE by Gupta [28] is applicable beyond 150 km only. It can be observed from Fig. 2 that PGA values from both the equations are slightly matching for distances of 150–200 km range. However, beyond 200 km, GMPE by Gupta [28] under-predicts the values. Comparison of GMPE by NDMA [54] for Himalayan region and HRGMPE is shown in Fig. 2, which show that up to a hypocentral distance of 70 km, both the GMPEs are predicting closer PGA values. However, beyond 70 km, NDMA [54] underestimates the PGA values when compared to HRGMPE. It can be noted here that GMPE given by NDMA [54] is purely based on simulated data and validated with lower magnitude records.

From the above discussion, it can be concluded that the region specific GMPEs are incapable of predicting hazard values close to highly ranked GMPEs for the entire hypocentral distance range of interest. Thus, there is a demand for a new attenuation relation for Himalayan region. The new GMPE's should overcome above shortcomings in the existing GMPEs and should be usable for seismic hazard mapping of the Himalayan region and adjoining areas in future. Hence, the generation of a new attenuation relation has been attempted in this study considering both instrumented and felt earthquakes.

4. Instrumented ground motion data

Instrumented ground motion data are best suitable to develop a more appropriate GMPE for any region. However, unfortunately the available recorded earthquakes are very limited for such studies. In India, very few recorded ground motions are available. The Dharmsala earthquake of 1986 was the first event in the highly active western Himalayan region whose ground motions are recorded. After the 1986 event, ground motion recording arrays were installed in different regions along the Himalayan terrain. These arrays include Kangra array, Shillong array and Uttar Pradesh array Singh et al. [69]. These arrays have recorded many moderate size earthquakes after 1986 in the Himalayan region. Detailed discussion about these arrays and the recorded data can be found in Chandrasekaran and Das [22]. Numerous researchers have used these recorded data for the development of GMPEs for Himalayan region. GMPEs developed by Singh et al. [69], Sharma [65], Sharma and Bungum [63], Iyenger and Ghosh [35] and Sharma et al. [64] were mainly based on above seismic arrays data. Shrikhande [66] published “Atlas of Strong ground motions in India” which consisted of instrumented data from 1980 India–Nepal earthquake to 2001 Bhuj earthquake. The dataset is composed of site condition i.e. whether the recording instrument is installed on rock or soil site for each station, co-ordinates of stations, stations name and recorded ground motion in terms of acceleration, velocity and displacement time histories at each station. The same dataset of instrumented earthquakes, which was used by many researchers are used in the present study. In addition to this data set, instrumented data of the earthquakes reported after 2001 was taken from PESMOS [55]. PESMOS is online data supply and storage place for the earthquakes events in the Himalayan region. Department of Earthquake Engineering and Institute of Technology Roorkee installed about 300 strong ground motion accelerographs in Himalayan region [41]. Recorded data from each of these stations are transferred to NIC headquarters in Delhi from where the data are further transferred to Roorkee through 2 MBPS lease line. All the data are pre-processed and uploaded in online website called PESMOS. In total, 9 instrumented earthquakes ground motion data are considered and which are presented in Table 2 as bold italic text. These instrumented earthquake events have been marked with stars in Fig. 3. The stations which had recorded these 9 earthquakes are shown in small diamonds in Fig. 3. The distributions of available recorded data with respect to epicentral distance for various magnitude values are

Table 2
Significant earthquake in Himalayan region considered for the study with source parameters for each event.

Sl. No	Earthquake (EQ) Detail	Latitude (N)	Longitude (E)	Moment Magnitude (Mw)	Strike (O)	Dip (O)	Focal depth (km)	Source of fault plane solution
1	1897 Shillong EQ	26	91	8.1	292	40	35	Nath et al. [51]
2	1905 Kangra EQ	32.50	76.60	7.8	322	55	18	Singh [68]
3	1934 Bihar–Nepal EQ	26.60	86.80	8.0	280	30	14.8	Nath et al. [51]
4	1950 Assam EQ	28.38	96.68	8.7	333	57.5	35	Nath et al. [51]
5	***1986 NE India EQ***	***25.42***	***92.08***	***5.4***	***253***	***20***	***43***	Singh [68]
6	***1986 Dharmsala EQ***	***32.18***	***76.29***	***5.4***	***299***	***19***	***7***	***CMT Harvard***
7	***1987 India–Burma EQ***	***25.27***	***94.20***	***5.9***	***34***	***32***	***50***	Singh [68]
8	***1988 India–Bangladesh EQ***	***24.64***	***91.51***	***6.0***	***110***	***28***	***15***	Singh [68]
9	***1988 Manipur EQ***	***25.15***	***95.13***	***7.1***	***284***	***45***	***90***	Nath et al. [51]
10	***1991 Uttarkashi EQ***	***30.75***	***78.86***	***6.8***	***317***	***14***	***15***	***CMT Harvard***
11	***1999 Chamoli EQ***	***30.41***	***79.42***	***6.5***	***280***	***7***	***21***	***CMT Harvard***
12	**2005 Kashmir EQ**	***34.37***	***73.47***	***7.6***	***318***	**29**	***15***	**Raghukanth** [57]
13	***2005 Chamoli EQ***	***30.90***	***79.30***	***5.4***	***280***	***7***	***25***	***CMT Harvard***
14	***2007 Uttarkashi EQ***	***31.20***	***78.20***	***5.3***	***317***	***14***	***33***	***CMT Harvard***

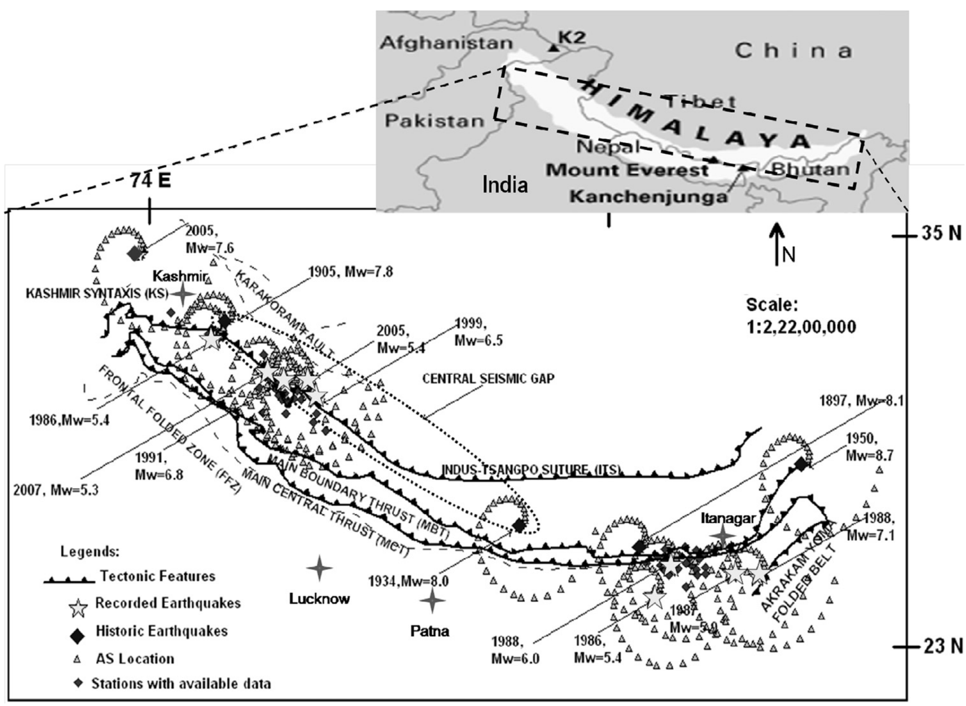

Fig. 3. Himalayan region with significant earthquake considered in this study along with Central Seismic gap and locations of ground motions used for attenuation relation (Modified after [40]).

shown in Fig. 4 in square shape. It can be noted from Fig. 4 that the recorded data are available up to Mw of 7.1. Also the recorded data consisted data of both at rock sites (solid in Fig. 4) and at soil sites (hollow squares in Fig. 4). The lack of existing instrumented data at different hypocentral distances for various magnitudes (gap) is easily noticed from Fig. 4. Thus to fill this gap, additional ground motions for each of these earthquakes have been generated synthetically at unavailable hypocentral distances. The limitations of earlier published GMPEs in terms of their applicability for higher magnitudes were already highlighted in the last section. Since, the recorded data were available upto a magnitude of 7.1, data for higher magnitude earthquakes have been taken from the felt earthquakes report. The felt earthquakes are called for those earthquakes with no instrumented records available but reported MMI (Modified Mercalli Intensity) values are available in the form of respective isoseismal maps. A total of 5 felt earthquakes namely; Shillong 1897, Kangra 1905, Bihar–Nepal 1934, Assam 1950 and Kashmir 2005 are considered in the study. These are selected to fill the magnitude gap in the existing database. Reported MMI values during each of the felt earthquakes are presented as solid triangles in Fig. 4. Nath et al. [51]

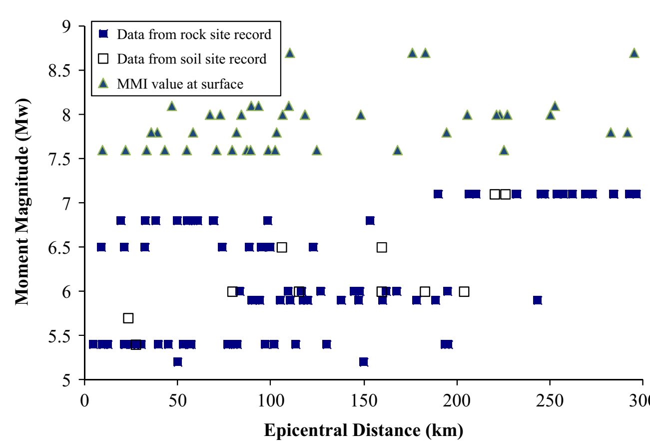

Fig. 4. Distribution of recorded data used in the study.

simulated ground motions of Shillong 1897, Kangra 1905 and Assam 1950 earthquakes for seismic microzonation of Guwahati. Singh and Gupta [67] presented the source mechanism for Bihar–Nepal 1934 earthquake. The model and source parameters given by Nath et al. [51] and Singh and Gupta [67] were to generate synthetic ground motions for the felt earthquakes. Acceleration time history of felt earthquake is generated at an epicentre distance interval of 10 km. Details about the synthetic ground motion model, the source and model parameters for each earthquake and validation of simulated ground motions can be found in upcoming sections.

5. Synthetic ground motion model and model parameters collection

From the above discussions, it is clear that instrumented data are available for magnitude (Mw) range of 5.3–7.1 at selected hypocentral distances. In addition, no instrumented records are available for higher magnitudes (Mw > 7.1). Thus, with the available instrumented data (see Fig. 3) it is difficult to develop an appropriate GMPE, which will be applicable for all the range of magnitudes and distances. Mixing of other regional-recorded data with the Himalaya data may result in error due to differences in the seismic activity and seismotectonic parameters. Also, the regional propagation path effects may not be captured properly due to difference in tectonic settings. Hence, the simulation of earthquake ground motions for the unavailable values of magnitudes and distances are attempted in this study.

For the regions where limited recorded earthquake data are available, synthetic models have been effectively used for hazard estimations and for the development of regional specific ground motion prediction equations [15,70,57,58,51,6,54]. Brune [18] point source model was used in many studies to model ground motions. Boore [16] first introduced point source simulation for ground motion using stochastic seismological model. Thereafter many researchers have used this model for ground motion simulation and hazard mapping [33,15,72]. The amplitude, frequency content and duration of ground shaking transferred at any site are controlled by directivity and rupture propagation effects [30,33]. The point source model was unable to capture these effects accurately. Thus, instead of modelling the whole event as a single point source, dividing the entire rupture area into a number of subfaults with each sub-fault modelled as a single point source was first introduced by Hartzell [30]. The main event will be obtained by the summation of the contributions from each sub-fault with appropriate time delay [29,30,43,31,14]. Number of researchers has used the Finite fault models for ground motion simulations using different form of source and path models [43,33,31]. Most of the approaches either used empirical relations to determine the source and path models and dependence of ground motions upon the distance to model propagation path. However, none of these models was checked for prediction capability. Beresnev and Atkinson [13] developed Finite Fault Simulation (FINSIM) model based on shear dislocation theory [1]. The source effect and the path were captured using time functions representing the realistic physical processes.

Finite fault simulation (FINSIM) model given by Beresnev and Atkinson [13] is used in the present study. The acceleration spectrum is typically modelled by a spectrum with a ω^2 (omega-square) shape, where ω = angular frequency [2,18,16]. It consists of modelling the acceleration spectrum at a site by ω^2 spectrum. Displacement values are estimated using shear dislocation theory [14]. Out of all possible time functions, only those functions, which can satisfy a physical problem, are used for further analysis. Corner frequency ω_c (in radian) is related to fault dimensions so that the modelled Fourier series can also be related to fault size. Further details for the model can be found in Atkinson and Beresnev and Atkinson [12].

Fault parameters used in this study for each earthquake are given in Table 2. Regional crustal density (ρ) and the shear wave velocity (β) at the focal depth are 2.6 g/cc and 3.6 km/s for Himalayan region [67]. The value of the rigidity of the crustal rock (μ) for Himalayan region is given as 3×10^{11} dyne/cm^2 [67]. The rupture length L and rupture area A for a particular moment magnitude (Mw) are usually obtained using Wells and Coppersmith [75] relationship. For the study area, the similar region specific relationship developed by Singh and Gupta [67] is used.

In all the simulations, hypocenter is assumed to be located at the centre of the main fault similar to Nath et al. [51] and Raghukanth [57]. The rupture starts at hypocenter and spreads radially to other subfaults with a velocity of $y\beta$, where y is the ratio of rupture velocity to the shear wave velocity taken as 0.80. The quality factor Q, which account for attenuation of Fourier spectrum due to propagation path and is region specific. For Indian shield the value of Quality factor of $Q(f)=508f^{0.48}$ has been given by Singh et al. [71]. The events given in Table 2 belong to the same type of tectonic province and same quality factor is used for all the simulations. Each subfault size 1 km × 1 km is adopted, because this size of subfault has limited the effect on ground motion simulations [57]. Strength factor (S_{fact}) controls the strength of high frequency radiations [13]. The value of S_{fact} ranges between 0.5 and 2.0 [51] and is obtained by trial and error such that it provides a best fit for high frequency vibrations [59]. Kappa operator 'κ' is a factor that controls near surface attenuation of propagating seismic waves in the upper 3–4 km of the crust. This parameter is also region specific like quality factor Q. In the study, κ value of 0.05 is taken from Nath et al. [51].

Stress drop ($\Delta\sigma$) is an important parameter, which describes the amplitude of acceleration spectrum in the near field region. It controls the high frequency radiations in the epicentral region. Since, the values of $\Delta\sigma$ for all the events were not known, these are calculated as per Eshelby [25] for Historic earthquakes considering seismic moment, average slip and rupture area of the fault. Singh and Gupta [67] also adopted a similar procedure successfully to calculate stress drop parameters for 1934 Bihar–Nepal and 1935 Quetta earthquake. Nath et al. [51] developed GMPE for northeast India using the stress drop parameter estimated by Singh and Gupta [67]. For recorded events, the value of stress drop was estimated based on corner frequency 'f_c' obtained from the Fourier spectra of recorded ground motion and equivalent radius of rupture area 'r_o' using Brune [18,19] equation. Similar approach was applied for simulating the ground motions for the Himalayan region by Joshi [37] and Nath et al. [53].

6. Simulation of instrumented ground motion

For ground motion simulation in the present work, FINSIM [14] is used. In order to check the suitability of this model for the study region synthetic ground motions are generated using different model parameters collected, as discussed in the previous section. Parametric study is carried out to select unknown model parameter of 'strength factor (S_{fact})' by matching synthetic ground motion with recorded ground motion data. Initially the synthetic ground motion is generated for site having recorded data at bedrock using the model parameters discussed in the previous section and assuming various values of unknown strength factor (S_{fact}). Using each value of S_{fact}, synthetic ground motion is generated. These synthetic ground motions are compared with the recorded ground motion in terms of response spectrum. Fig. 5 shows response spectrum from different simulation using different values of S_{fact} and recorded data response spectrum. It can be noted from Fig. 5 that S_{fact} of 1.3 gives the best matching response spectrum and thus S_{fact} of 1.3 is fixed for multiple simulations of same earthquake at different locations. Further comparisons are made both in terms of Peak Ground Acceleration (PGA) and spectral acceleration (SA) of final synthetic ground motion with the recorded data. Fig. 6(a–o) shows the comparison of selected acceleration time histories of synthetically generated and recorded at bedrock level. It can be observed from Fig. 6(a–o) that the recorded and simulated ground motions match well for all the locations. Fig. 7(a–o) shows comparisons of response spectra from synthetic ground motions and recorded motions for acceleration time history given in Fig. 6(a–o). It can be seen from Fig. 7(a–o) that the synthetic response spectra are comparable with recorded response spectra up to 2 s. It has to be highlighted here that most of the structures have natural period less than 2 s. Above comparison shows that the simulated data have captured the frequency content and amplitude of recorded ground motions within the period of interest accurately. Also, these comparisons show that the selected model parameters have captured the source and path effects for the region representatively. For further verification of synthetic response spectra with respect to actual response spectra, plots of error between the two response spectrums and frequency of error are generated. Fig. 8(a–o) shows error versus frequency plots corresponding to response spectrum in Fig. 7(a–o). It can be clearly observed from Fig. 8(a–o) that the maximum error is corresponding to zero error. Mean and standard deviations for each of the plot are also given in Fig. 8(a–o). It can be observed that the mean values of majority of events are close to zero. Slight difference may be due to the trade off between source parameters and model parameters used in this study.

In order to check the capability of synthetic ground motions to predict the Fourier spectrum, plots of Fourier spectrum based on actual and synthetic data are presented in Fig. 9(a–o). The entire spectra are corresponding to Fig. 7(a–o). Since, comparison in Fig. 7(a–o) is made till 2 s, Fig. 9(a–o) shows the comparison between Fourier spectrums from 0.5 s onwards. It can be observed from Fig. 9(a–o) that the Fourier spectrum based on actual and synthetic data is closely matching with each other for various

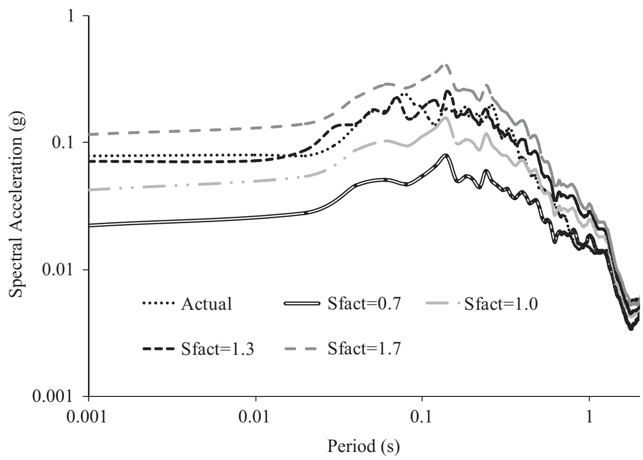

Fig. 5. Parametric study to establish the S_{fact} value in simulation for 1988 Manipur earthquake recorded at Harenjao.

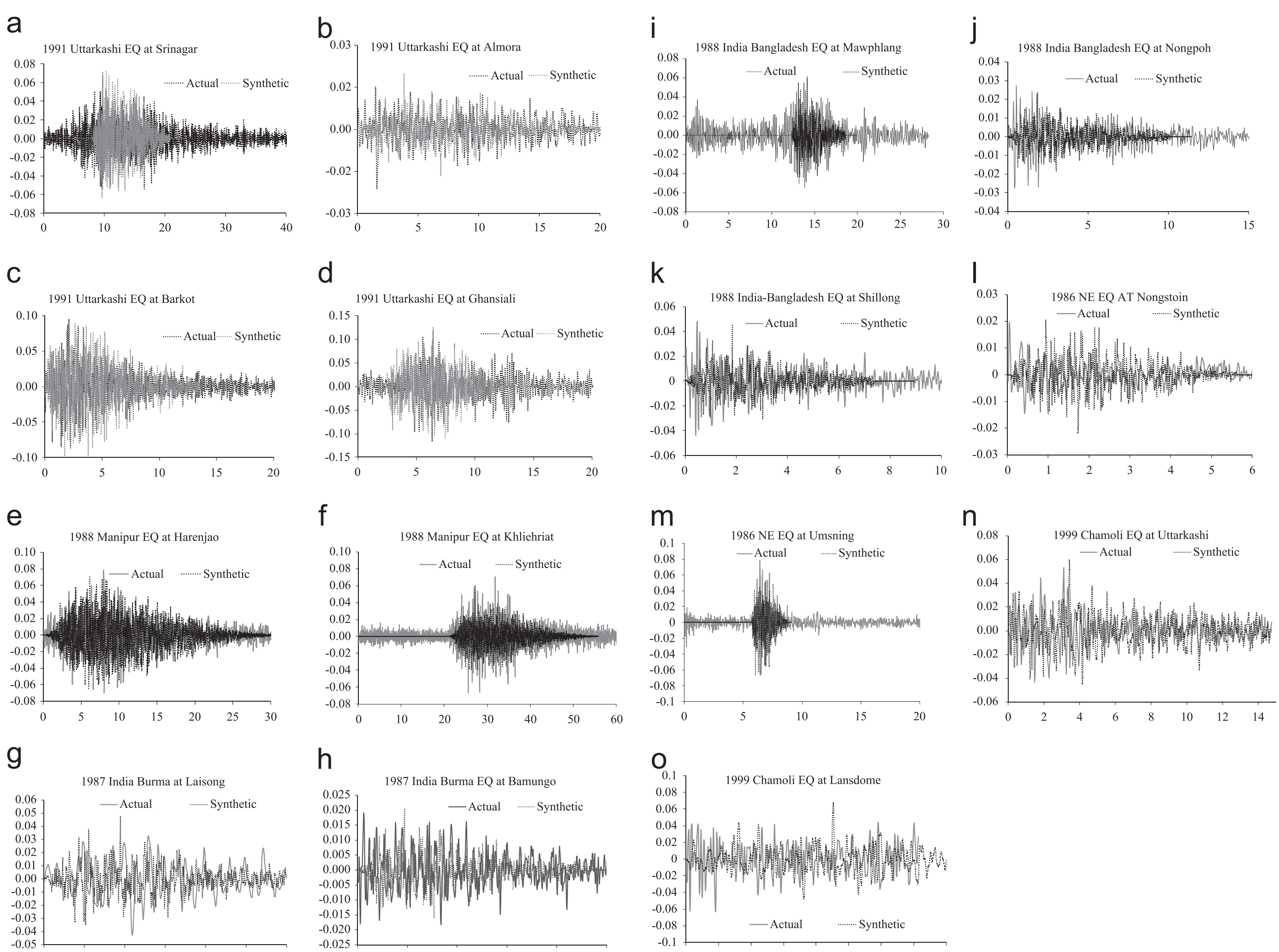

Fig. 6. (a–o) Comparison between recorded and simulated ground motions.

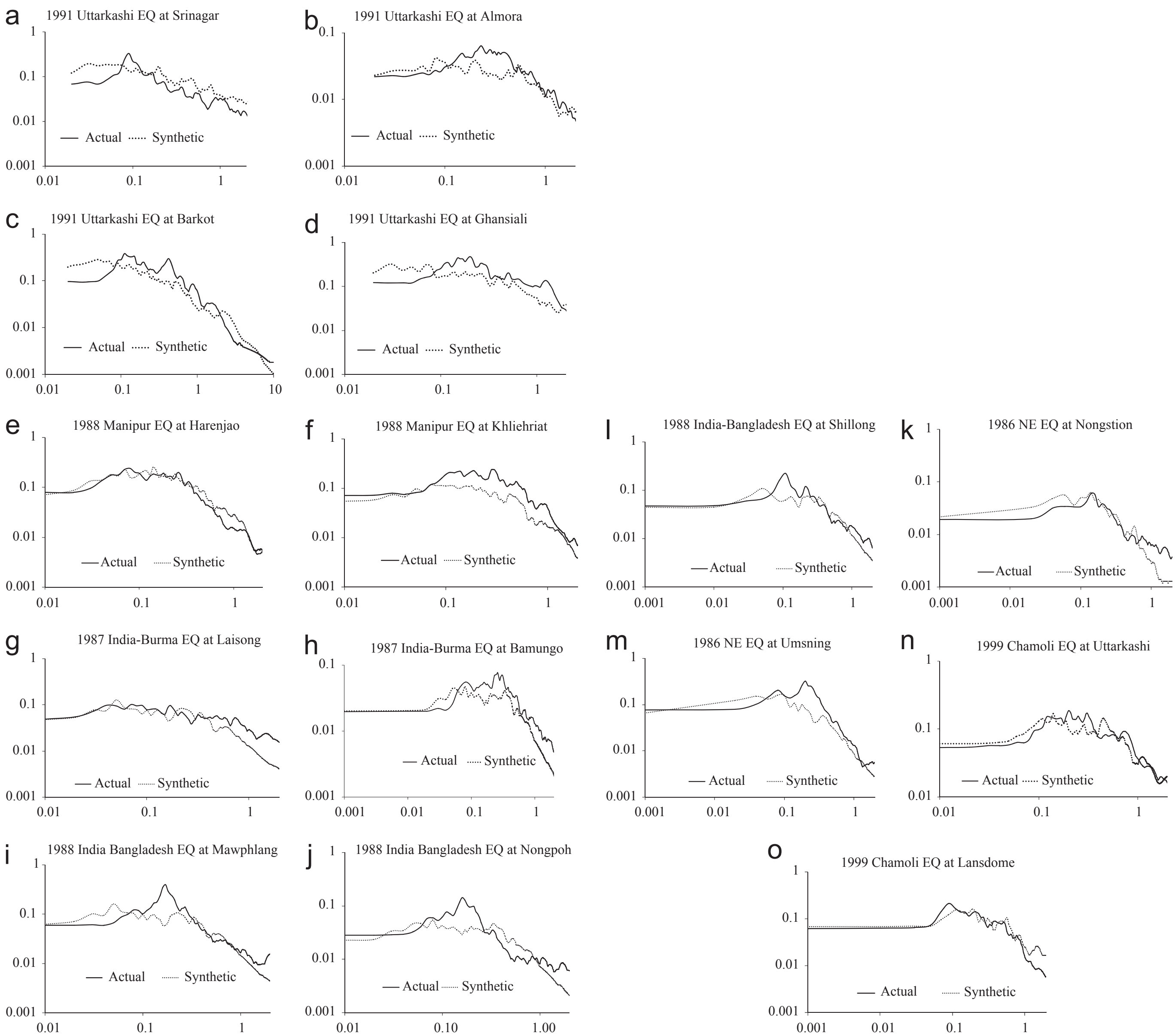

Fig. 7. (a–o) Comparison of response spectrum from recorded and simulated ground motions.

earthquakes with slight differences observed at many stations. This slight difference may be because of the selection in the ground motion parameters used for synthetic ground motion generation. However, Figs. 6–9(a–o) show enough evidence that the synthetic ground motion model is capable of predicting the actual data with utmost accuracy within the period of interest. The model parameters corresponding to synthetic ground motions with recorded data available are taken as reference model parameter to generate similar magnitude ground motion at unavailable locations. Even though all the above model parameters are region specific, the suitability of using all the above parameters in single study has not been attempted earlier. Thus, there may be a limitation with the available values due to strong trade off in the source parameters.

Using the reference model parameters discussed above, simulations at unavailable locations are carried out to fill the gap in the existing available data shown in Fig. 4. It can be observed from Fig. 4 that for each magnitude value (*Y*-axis) limited number of bedrock motions are available (solid square) and gap in terms of bedrock motion for each magnitude event exists. In order to fill this gap in the existing database at bedrock and enrich ground motion data, apparent stations (AS) are created for each event. The locations of AS are selected in such way that these stations should cover an epicentral distance up to 300 km and also capturing the source finiteness in the simulations. The apparent stations are established at 30 azimuths covering a range of 0-360° around the epicentre at an interval of 12°. Every next AS will be at a distance interval of 10 km with an azimuth difference of 12° around the epicentre from its successor station. Thus, the first station will be at 10 km radial distance from the epicentre with an azimuth of 12° angular shift keeping epicentre at the centre. The next station will be at 20 km from the epicenter with an azimuth of 24° from the epicentre. The same procedure was repeated to establish 30 AS such that the last station will be at 300 km from the epicentre with an angular shift of 360° from the epicentre. The concept of AS is first time adopted in India to simulate synthetic ground motions at unavailable locations to fill the gap in the recorded ground motion data for the application of GMPE development. Fig. 10 shows a pictorial representation of apparent stations (AS) concept. Using the validated model parameters for recorded events, synthetic ground motions at AS stations have been generated. If recorded data at bedrock is

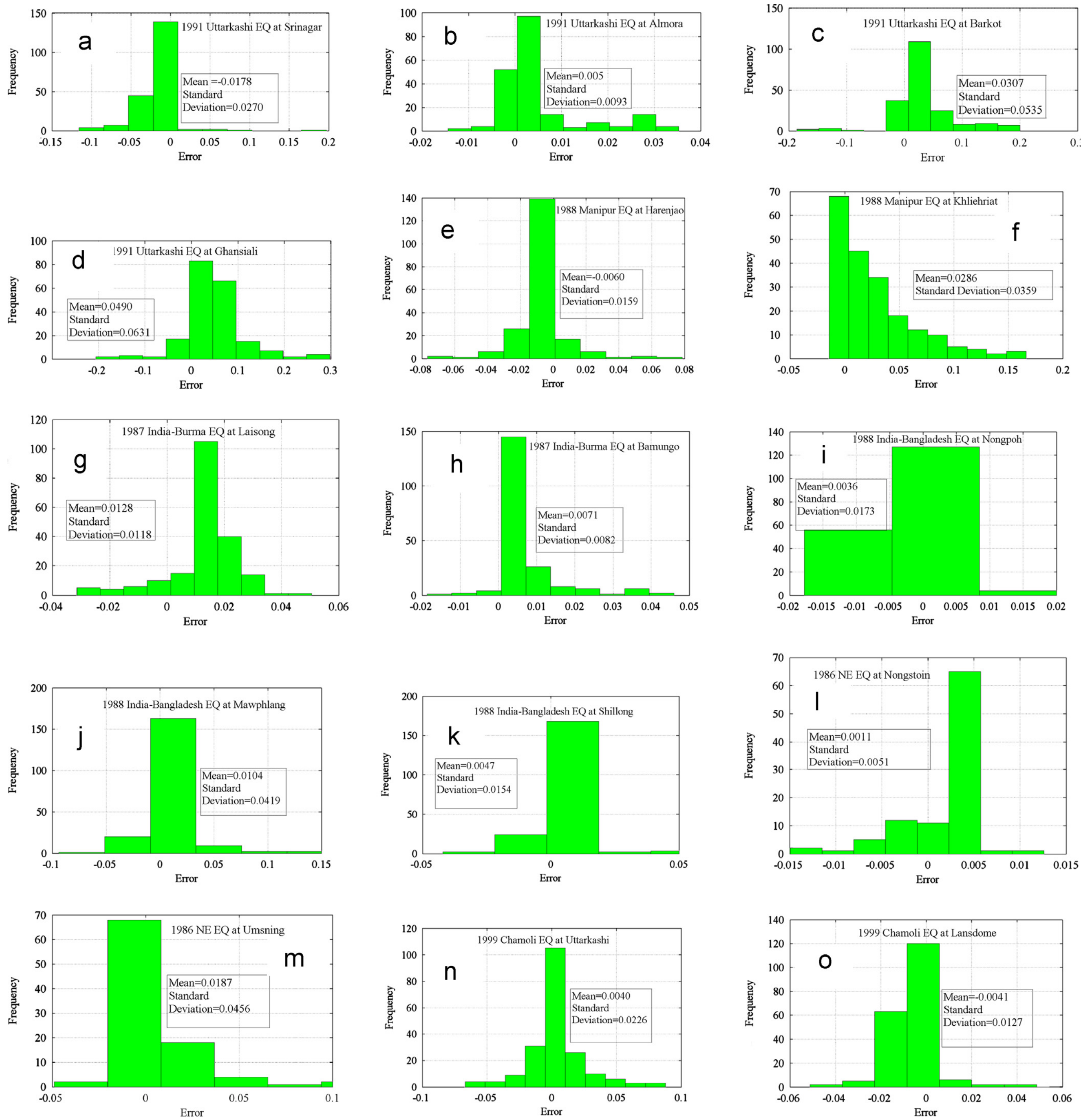

Fig. 8. (a–o) Error versus frequency plot for the response spectra shown in Fig. 6.

available for any distance range (solid squares in Fig. 4), synthetic ground motion for that distance range is avoided. Thus, synthetic ground motions are considered in the database only for locations where recorded ground motions at bedrock are not available. Combining the recorded and the synthetic ground motions yields a dataset consisting of bedrock ground motions for all the ranges of hypocentral distance.

7. Simulation of historic data

Simulation of ground motion corresponding to instrumented magnitudes has helped to enrich ground motion data up to the available instrumented magnitude of Mw 7.1. However, Himalayan region is also prone to greater earthquake magnitudes where no instrumented ground motion data are available. The study shows that about five greater earthquakes were reported in the Himalayan region for which detailed felt reports with isoseismal maps are available. These isoseismal maps provide MMI (Modified Mercalli Intensity) values at different locations. Typical isoseismal map with MMI values for Bihar–Nepal 1934 earthquake is shown in Fig. 11 (modified after [45]). These MMI values are converted to surface PGA values considering Murphy, O'brien [49] correlation as given in the following equation:

$$\log(a_H) = 0.25 I_{MM} + 0.25 \quad (1)$$

where, a_H is the Peak Ground Acceleration (PGA) in cm/s^2, I_{MM} is the MMI value at the location of interest. Singh et al. [69] and NDMA [54] have used this correlation to estimate Mw for the

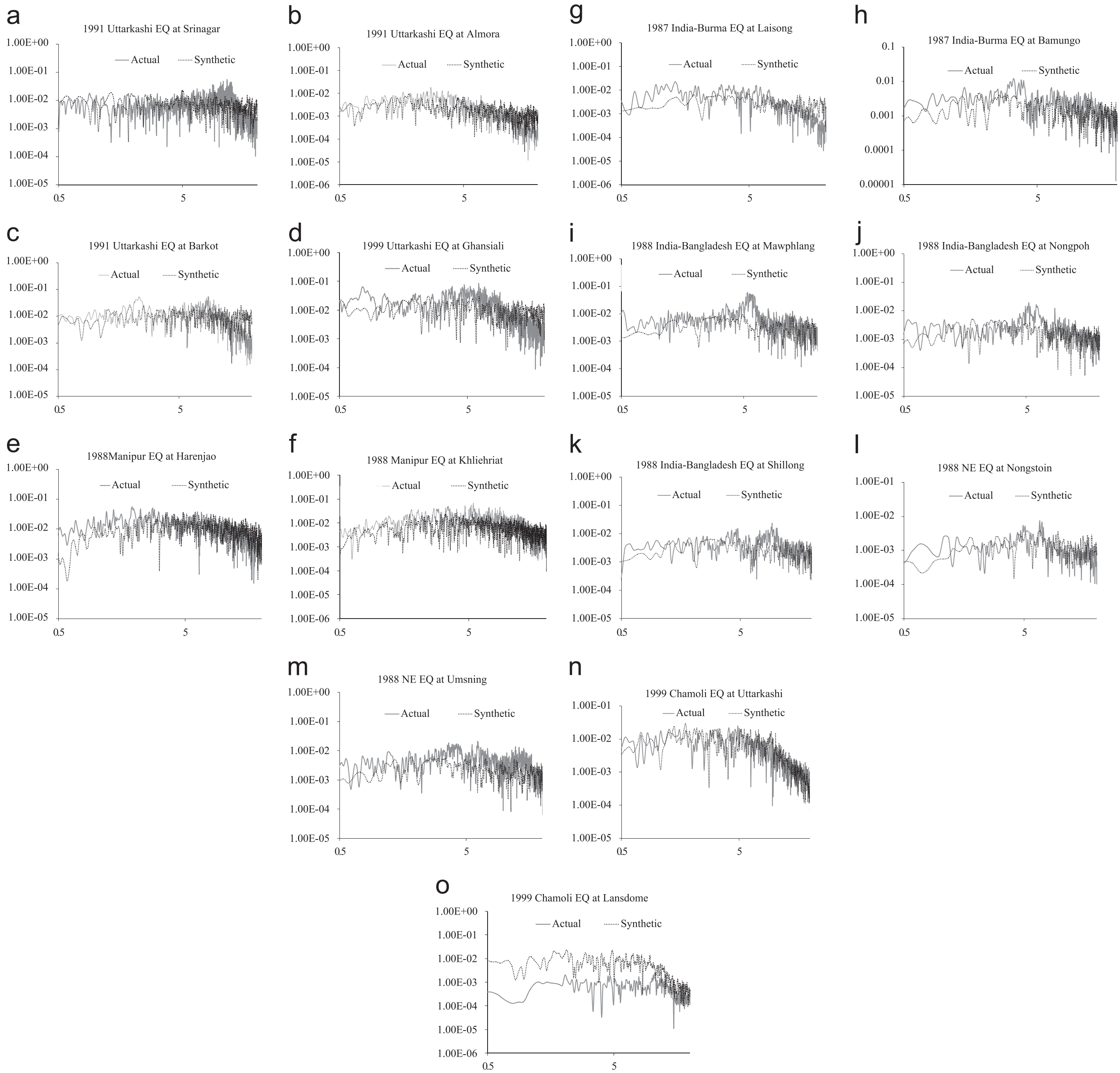

Fig. 9. (a–o) Comparison of Fourier amplitude spectrum for selected recorded and simulated ground motions.

development of attenuation relations for Himalayan region. Eq. (1) will give the surface level PGA value at selected locations. Historic earthquake ground motion data at bedrock are simulated using available model parameters given in Table 2 and selected model parameters during simulation of instrumented data. The model parameters for Shillong 1897, Bihar–Nepal 1934 and Assam 1950 earthquakes are obtained from Nath et al. [51]. Source parameters of Kangra 1905 earthquake are taken from Singh [68], while other model parameters were estimated as discussed in the previous section to generate synthetic ground motions for instrumented data. Bedrock ground motions for the Bihar–Nepal 1934 earthquake are simulated and compared with PGA from MMI values. Fig. 11 shows a typical isoseismal map for 1934 Bihar–Nepal earthquake with estimated PGA at the surface from MMI and simulated PGA at the bedrock at selected locations. It can be noted here that PGA obtained from MMI values are amplified surface PGA and simulated data PGA are on rock level without site effects. Difference in PGA values may be attributed to site effects i.e. amplification. The relative amplification from the ratio of surface PGA and rock PGA are estimated and shown in Fig. 11. This ratio varies from 1.0 to 2.0 which are considered as amplification due to local site effects. Since, the local soil strata details were not available on any site; such amplification cannot be analysed in detail. However these amplification values are comparable to previous studies by Raghukanth [57] and Anbazhagan et al. [7,5]. Raghukanth [57] has compared the bedrock PGA from synthetic data and surface PGA from isoseismal map and highlighted the ratio between the two PGA values were of the order of 1–2.5 due to local site effect. Anbazhagan et al. [7] found amplification in 1–2.5 for Himalayan region by carrying out site response analysis using SHAKE2000 and available borehole reports. The surface PGA for 1999 Chamoli earthquake is estimated using available isoseismal

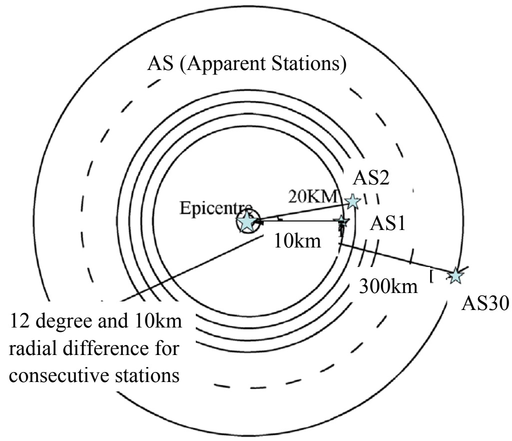

Fig. 10. Details of apparent stations distribution around the epicentre.

map while the bedrock motion are generated using FINSIM as discussed by Anbazhagan et al. [5]. Anbazhagan et al. [5] had highlighted that observed PGA from isoseismal map using Murphy, O'brien [49] was found to match well with the PGA obtained after site response study using synthetic ground motion. Relative amplification values estimated in this study are comparable with above values. Once the bedrock motions are verified for greater earthquakes, using model parameters for each of the events, synthetic ground motions are generated at all 30 AS for each event. The locations of AS are determined in the similar way given in the last section. Thus, the exercise has provided a dataset consisting of bedrock ground motions at all ranges of hypocentral distance for greater earthquakes.

A total of 420 (30 × 14) ground motions are available from the above database generated based on recorded events and historic events. Combining the datasets obtained for recorded earthquakes and the greater earthquakes will be used for further analyses. Fig. 12(a–d) shows the comparison of recorded PGA with the synthetic PGA for recorded events for four selected earthquakes. It can be seen from Fig. 12(a–d) that for recorded data at rock sites, the recorded and synthetic PGA values are closely matching for all the earthquakes. However for recorded data at soil sites, the synthetic data are giving lesser values of PGA which can be attributed to effect of local soils. Thus, the synthetic data are showing the PGA values at bedrock for all the locations. Similarly for historic earthquakes, comparisons between the PGA obtained from isoseismal maps and bedrock PGA from synthetic data are carried out as shown in Fig. 12(e and f). It can be seen from the figure that for all the locations, the PGA at bedrock is lesser than the surface obtained PGA values. Once, the comparison between the synthetic data with available data is done, the entire database consisting of the database developed for recorded earthquakes and the historic earthquakes can be used for further analyses.

8. Development of GMPE based on synthetic and recorded data

The dataset generated in the earlier sections consist of 14 earthquakes as listed in Table 2. For each earthquake synthetic ground motions are developed at 30 apparent stations at 10 km interval. Then, generated synthetic data are eliminated if recorded data are available for a particular distance. Thus, for every earthquake the database first considered is the recorded data and then synthetic data for unavailable distance ranges. A total of about 420 acceleration time histories consisting of 30 data from each earthquake listed in Table 2 and for 14 earthquakes are available for the Himalayan region. These data belongs to earthquake with Mw of 5.3–8.7 and up to a hypocenter distance of 300 km. These ground

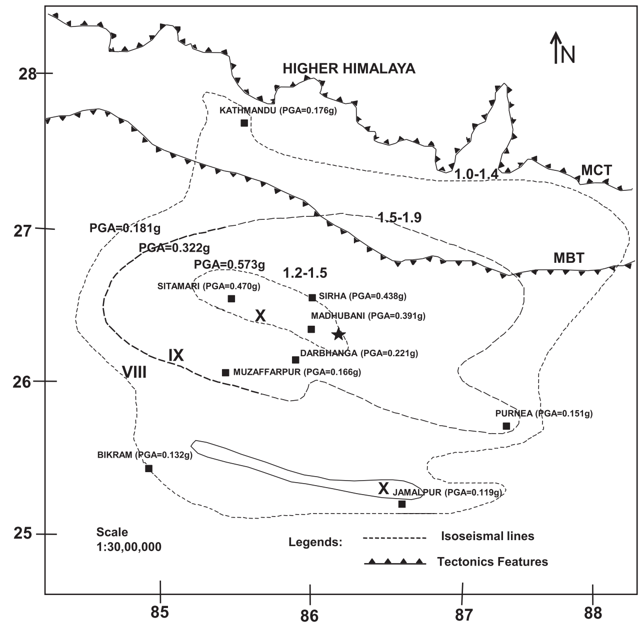

Fig. 11. Isoseismal map in MMI with converted peak ground acceleration (left in counter) for 1934 Bihar–Nepal earthquake along with ground motion simulated locations and respective PGA.

motion data are converted to spectral acceleration for 5% damping value. The data consist of Spectral Acceleration (SA) variation with respect to magnitude (Mw) and hypocentral distance (X). This dataset is analysed using two step-stratified regression similar to Sharma [65], Sharma and Bungum [63] and Fukushima and Tanaka [26]. As a first step of analysis, each event is analysed separately using a linear form of regression as given below:

$$\log(y) = -b\log(X) + c \tag{2}$$

where y is the SA in terms of g, $X = \sqrt{(R^2 + h^2)}$, where R is the closest distance to the rupture in km, h is the focal depth in km, b and c are the regression coefficients. The regression is performed separately for each event of y and X values. Table 3 lists the values of regression coefficients b and c for each event obtained after the linear regression along with standard error values given in brackets.

Based on first step analysis, the average value of decay parameter 'b' from all the events is estimated as 1.792 for zero periods. As a second step, a multi-regression analysis is performed for the whole set of data considering the following form of equation:

$$\log(y) = aM - b\log(X) + c \tag{3}$$

where y is SA in terms of g, M is moment magnitude of event, $X = \sqrt{(R^2 + h^2)}$, where R is the closest distance to the rupture in km, h is the focal depth in km and a, b and c are the regression coefficients of Eq. (3). Based on the multi-regression analysis of the whole set of data, the value of decay parameter 'b' obtained is 1.562 which is significantly less when compared to the average value of $b = 1.792$ obtained after linear regression analysis of Eq. (2). Such difference in 'b' value can cause large variation in ground motion prediction from the newly proposed relation. Thus to reassure the correct value of decay parameter b, a two step stratified regression suggested by Joyner and Boore [38] is followed in this study. This method was also applied by Fukushima and Tanaka [27] and Sharma [65] for developing GMPE for Japan and Himalayan region respectively. Following the same approach, the value of decay parameter 'b' for the entire data set was obtained as 1.796 which was very close to 1.792 as compared to 1.562. In the next step a nonlinear regression using a whole data

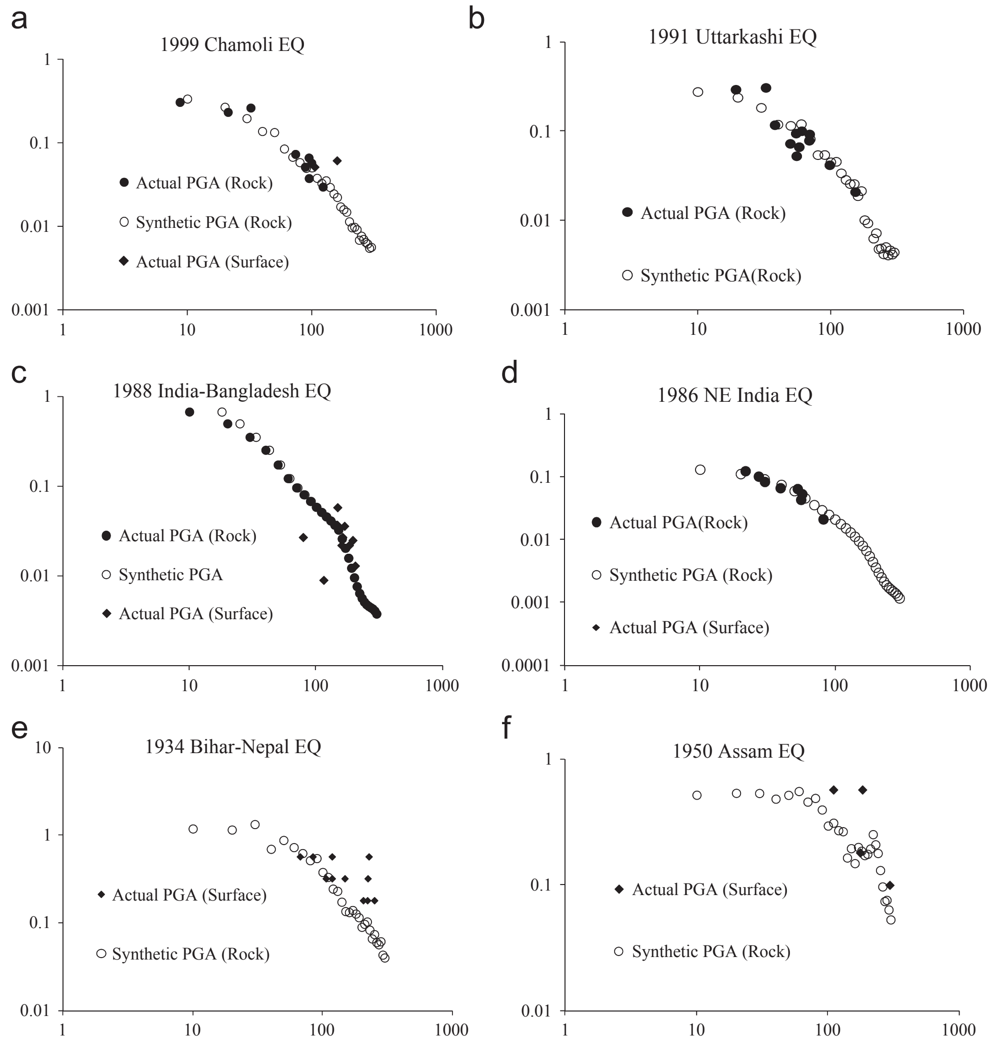

Fig. 12. (a–f) Comparison of simulated peak ground acceleration with recorded values at soil surface and rock level for selected earthquakes.

Table 3
Values of regression coefficients as per Eq. (3).

Name of the Earthquake (EQ)	b (Std. err.)	c (Std. err.)
1897 Shillong EQ	1.377 (0.075)	5.280 (0.161)
1905 Kangra EQ	1.293 (0.114)	4.754 (0.243)
1934 Bihar–Nepal EQ	1.441 (0.069)	5.330 (0.148)
1950 Assam EQ	0.968 (0.090)	4.410 (0.196)
1986 NE India EQ	2.513 (0.059)	6.356 (0.127)
1986 Dharmsala EQ	1.832 (0.108)	4.650 (0.228)
1987 India–Burma EQ	2.670 (0.0692)	6.808 (0.151)
1988 India–Bangladesh EQ	2.017 (0.008)	5.668 (0.175)
1991 Uttarkashi EQ	1.802 (0.097)	5.080 (0.213)
1999 Chamoli EQ	1.495 (0.110)	4.530 (0.250)
2005 Kashmir EQ	1.528 (0.097)	5.018 (0.207)
2005 Chamoli EQ	2.107 (0.053)	5.522 (0.112)
2007 Uttarkashi EQ	2.262 (0.080)	5.903 (0.170)

*Std. err. = standard error.

set was performed with decay parameter $b = 1.792$ and considering the following form of the regression equation:

$$\log(y) = c_1 + c_2 M - b \log(X + e^{c3M}) + (\sigma) \quad (4)$$

where y is SA in g, M is moment magnitude, $X = \sqrt{(R^2 + h^2)}$, where R is the closest distance to the rupture in km, h is the focal depth in km, b is a decay parameter as estimated above, c_1, c_2 and c_3 are regression coefficients and (σ) is the standard error term. The logarithm in the above equation is to base 10. The above form of nonlinear regression was first attempted for dataset corresponding to zero period ground motion. Based on the analysis, the values of coefficients given in Eq. (4) are found as; $c_1 = -1.283$, $c_2 = 0.544$, $c_3 = 0.381$, $b = 1.072$, $\sigma = \pm 0.283$. Further the analyses are performed to estimate the regression coefficients of Eq. (4) at other periods. Since, similarities between the recorded and the simulated response spectra are found up to 2 s (Fig. 7(a–o)), nonlinear regression analyses were performed up to a period of up to 2 s. The values of various coefficients of Eq. (4) for different time periods obtained after nonlinear regression analysis have been presented in Table 4. The values given in the brackets in Table 4 indicate the standard error associated with different coefficient values.

9. Validation of the newly proposed GMPE

A newly developed GMPE can be used to predict a ground motion for future earthquakes in the region; hence it needs to be validated. At the same time the data used for the validation should not be included while developing GMPE. Even though Himalayan region has experienced many small earthquakes to great earthquakes from historic time, but after 2007 only three moderate earthquakes are available to validate new developed GMPE. Recorded ground motions for three different events namely Pithoragarh earthquake

Table 4
Coefficients for spectral acceleration for different periods as per Eq. (4).

Period (s)	c_1 (Std. err.)	c_2 (Std. err.)	b	c_3 (Std. err.)	(σ)
0	−1.283 (0.093)	0.544 (0.015)	1.792	0.381 (0.030)	0.283
0.1	−1.475 (0.098)	0.544 (0.015)	1.585	0.322 (0.048)	0.307
0.2	−1.366 (0.107)	0.546 (0.017)	1.641	0.410 (0.032)	0.318
0.3	−1.982 (0.097)	0.542 (0.016)	1.385	0.367 (0.043)	0.298
0.4	−2.602 (0.096)	0.555 (0.015)	1.178	0.329 (0.061)	0.298
0.5	−2.980 (0.095)	0.606 (0.015)	1.206	0.350 (0.053)	0.292
0.6	−3.00 (0.10)	0.623 (0.016)	1.258	0.387 (0.044)	0.299
0.8	−3.812 (0.096)	0.670 (0.015)	1.080	0.365 (0.055)	0.296
1.0	−4.357 (0.099)	0.731 (0.016)	1.114	0.383 (0.051)	0.300
1.2	−4.750 (0.099)	0.766 (0.016)	1.082	0.390 (0.050)	0.298
1.4	−5.018 (0.099)	0.779 (0.016)	1.032	0.375 (0.057)	0.303
1.6	−5.219 (0.102)	0.824 (0.016)	1.123	0.399 (0.048)	0.306
1.8	−5.327 (0.105)	0.840 (0.017)	1.139	0.412 (0.046)	0.313
2.0	−4.920 (0.122)	0.953 (0.022)	1.617	0.581 (0.022)	0.310

*Std. err. = standard error.

2008 (Mw = 4.3), India–Nepal Border earthquake 2011 (Mw = 5.7) and Sikkim earthquake 2011 (Mw = 6.8) are used for the validation. The proposed GMPE based PGA values are compared with these three earthquake data and also with the predicted PGA values for each earthquake based on five highly ranked GMPEs by Nath and Thingbaijam (2011) for the region. It can be noted here that SHAR09 and AKBO10 GMPEs are applicable up to 100 km, CABO08 and IDR08 GMPEs are applicable up to 200 km and KAN06 GMPE is applicable to 425 km.

Even though the proposed GMPE is developed considering Mw of 5.3–8.7, in order to check its capability to predict lower magnitude Pithoragarh earthquake 2008 (Mw = 4.3) comparison has been made here. Fig. 13(a) shows predicted data based on new GMPE along with recorded PGA for Pithoragarh earthquake 2008 and PGA values from highly ranked GMPEs. PGA values from the GMPE proposed in this study match well with the recorded data at all the three rock sites. The proposed GMPE matches well up to 150 km with first ranked KAN06 GMPE and up to 200 km with second ranked CABO08 GMPE and fifth ranked IDR08 GMPE. The proposed GMPE predicts PGA values slightly more than KAN06 GMPE PGA values beyond 150 km. The PGA obtained from KAN06, CABO08 and IDR08 matches with recorded PGA values for this earthquake. The region specific GMPE by Sharma et al. [64] ranked at third position by Nath and Thingbaijam (2010) and PGA obtained from this GMPE are not comparable to recorded PGA values. It can be also noted from Fig. 13(a) that Sharma et al. [64] GMPE gives very high PGA values when compared to recorded data and other GMPEs. Fourth ranked AKBO10 GMPE gives PGA values close to recorded PGA and comparable to other GMPEs up to distances of 30 km. Beyond 30 km this GMPE gives lower PGA values in comparison to recorded PGA and other highly ranked GMPEs for all distances. The proposed GMPE is well matching with recorded data of lower magnitude Mw 4.3, even though no data less than Mw of 5.3 is included in GMPE development. Nepal–India border earthquake with an Mw of 5.7 occurred on 4th April 2011. This earthquake was recorded at many stations installed on bedrock in the Himalayan region. Detailed ground motions and station details can be obtained from PESMOS. The comparison between proposed PGA and recorded PGA at the rock level at various stations is given in Fig. 13(b). It can be observed from Fig. 13 (b) that PGA values based on the proposed GMPE match well with recorded values up to 300 km. The PGA obtained from KAN06 and CABO08 matches with recorded PGA values up to 200 km, beyond 200 km KAN06 under-predicts when compared to recorded and proposed GMPE. PGA values from and IDR08 GMPE is slightly lower than recorded values and proposed GMPE predictions. PGA values are over-predicted by SHAR09 GMPE and are under

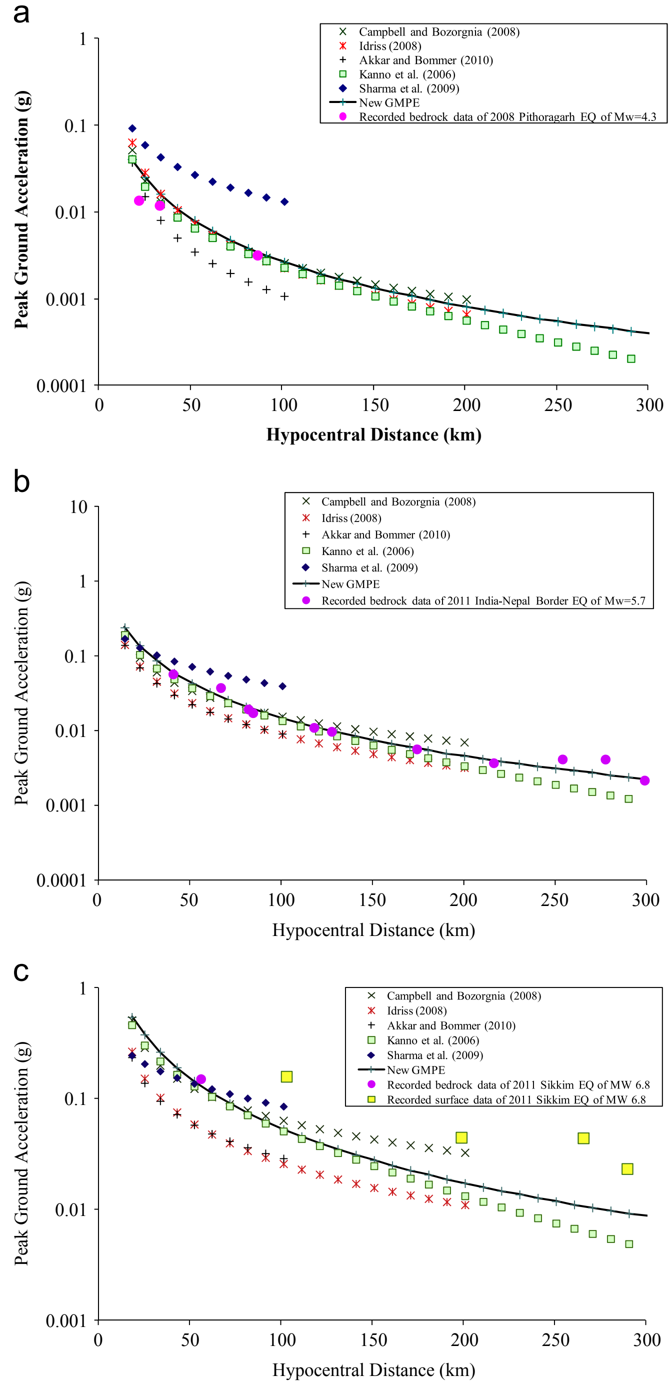

Fig. 13. (a) Comparison of new GMPE with first five highly ranked GMPEs and with recorded earthquake data for 2008 Pithoragarh earthquake of 4.3 in Mw. (b) Comparison of new GMPE with first five highly ranked GMPEs and recorded earthquake data for 2011 Nepal–India Border EQ with Mw of 5.7. (c) Comparison of new GMPE with first five highly ranked GMPEs and recorded earthquake data for 2011 Sikkim EQ with Mw of 6.8.

predicted by AKBO10 GMPE for applicable distance range of 100 km, when compared to PGA records of 2011 Nepal–India Border EQ and proposed GMPE. Moreover, these two GMPEs are not following prediction value of other three highly ranked GMPEs and GMPE proposed in this study. Fig. 13(c) shows the comparison of recorded data with different GMPEs for Sikkim earthquake 2011. In this case, only one recorded data from rock site and four data from soil sites (site class C as per [47]) were available within 300 km radial distance from the epicentre. Comparison between the predicted PGA based on proposed GMPE and recorded data for rock site shows that both the values are close to each other. However, soil sites recorded PGA is found to be many folds higher than predicted PGA. This difference between two values may be due to local site effects, which needs to be understood for these soil sites. Regional GMPE by Sharma et al. [64] predicts PGA values close to recorded data and matches with proposed relation up to 100 km for this earthquake. PGA values from CABO08 GMPE match with recorded PGA and proposed GMPE up to distance of 150 km, beyond this the GMPE overestimates for this earthquake. Similarly, PGA values from KAN06 GMPE match with recorded PGA and proposed GMPE up to distance of 200 km, beyond this the GMPE underestimates similar to other earthquakes. PGA values estimated from IDR08 and AKBO10 GMPEs are not matching with recorded PGA, and with other highly ranked GMPEs.

In addition, capability of new GMPE to predict spectral accelerations is verified by comparing the response spectra from these three earthquakes at selected locations from rock site data. Fig. 14 (a–c) shows the comparison of predicted spectral acceleration using new GMPE with response spectra from recorded data. Since, immediately after zero period, next period taken for the regression is 0.1 s, the constant value in spectral acceleration below 0.01 s and 0 s cannot be observed from Fig. 14(a–c). Upper and lower bound of predicted response spectra in Fig. 14(a–c) indicates $\pm$ one standard deviation with respect to mean predicted response spectra values. Fig. 14(a–c) shows that up to a period of 0.06 s, the response spectra based on recorded data match well with mean predicted response spectra. Beyond 0.1 s, the recorded response spectra matched well with mean predicted response spectra except for 2011 Sikkim earthquake. Since only one bedrock motion for 2011 Sikkim earthquake is available within 300 km hypocentral distance, it is not possible to compare the predicted response spectra with more number of data. Since, similarities between recorded and synthetic response spectra were obtained up to 2 s, comparison made in this section are limited to 2 s. This section shows that the proposed GMPE is capable predicting PGA and spectral accelerations from small magnitude of 4.3–8.7 even though data used was 5.3–8.3.

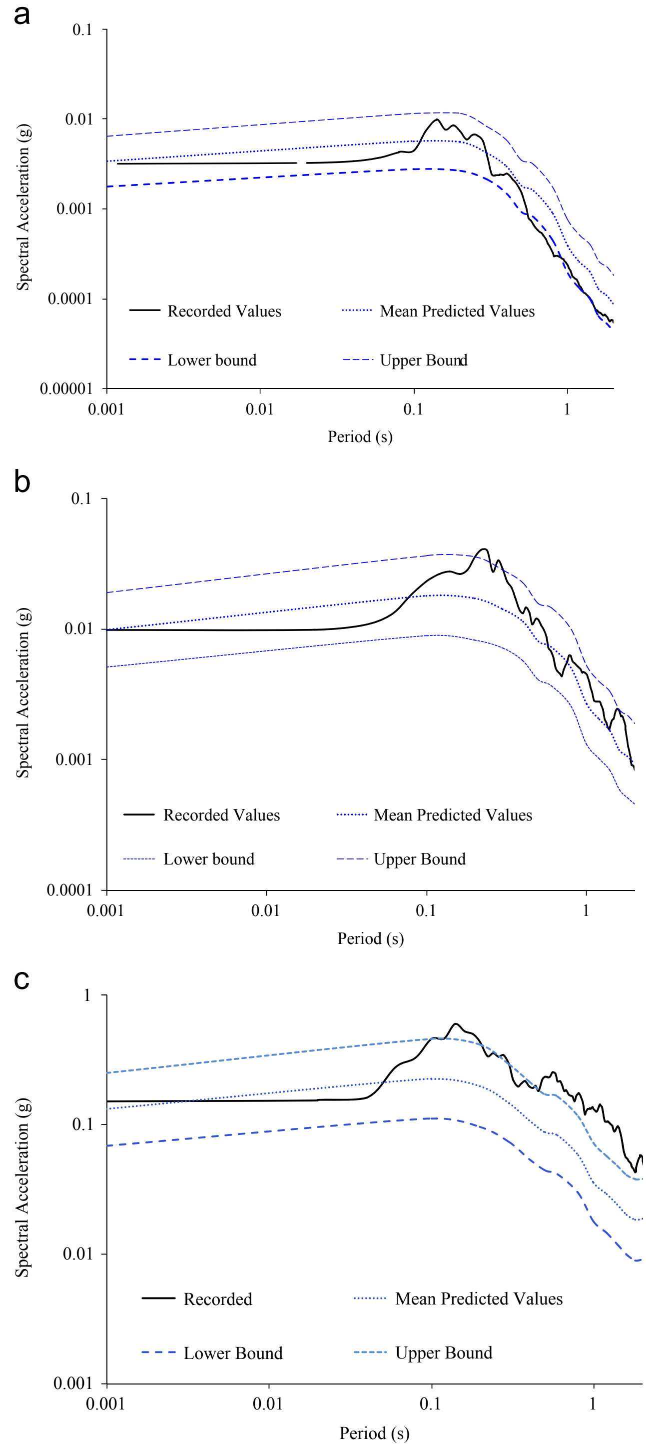

Fig. 14. (a) Comparison between proposed response spectrum in this study and response spectrum from the recorded 2008 Pithoragarh EQ at Champawat. (b) Comparison between proposed response spectrum in this study and response spectrum from the recorded 2011 Nepal–India Border EQ at Almora. (c) Comparison between proposed response spectrum in this study and response spectrum from the recorded 2011 Sikkim EQ at Gangtok.

10. Himalayan GMPEs and quantitative analysis

The Himalaya region has about 11 GMPEs developed in India considering region specific data as shown in Table 1. Of these, Singh et al. [69] and Sharma [65] GMPEs do not contain a standard error term, hence these cannot be used for the probabilistic seismic hazard analysis. Baruah et al. [11] GMPE is valid only for magnitude (Mw) less than 5, which may not be significant in engineering requirement. Remaining eight region specific GMPEs (Sl no 3–6 and 8–11 in Table 1) are available to predict PGA values. Among the three available earthquake recorded data, Nepal–India 2011 earthquake has wide range of rock level PGA records. This earthquake PGA values are used to check prediction capabilities of eight region specific GMPEs. Predicated PGA values from eight GMPEs for Nepal–India 2011 earthquake of Mw of 5.7 and recorded PGA at rock site stations are shown in Fig. 15. GMPEs given by Iyenger and Ghosh [35], Sharma and Bungum [63], Das et al. [23] and Sharma et al. [64] are over predicting PGA values for entire valid distances when compared to recorded values and proposed GMPE. GMPEs given by Nath et al. [52] are under predicting and Nath et al. [51] is over predicting up to 50 km. Beyond 50 km both GMPEs predicting are matching with recorded values up to 100 km and are not valid beyond 100 km. PGA predicted by Gupta [28] GMPE matches well with recorded data from 150 km to 230 km and beyond 230 km this GMPE is under predicting. It can be also noted here that this GMPE is not valid below 150 km. NDMA [54] GMPE predicts PGA values close to the recorded and proposed GMPE up to 100 km and beyond 100 km this GMPE is under predicting when compared to recorded data and proposed GMPE. In summary, none of the region specific GMPEs are capable of predicting PGA value for the magnitude (Mw) of 5.7 close to recorded PGA values for the entire distance range up to 300 km. It can be observed from Fig. 15 that the proposed GMPE is predicting the PGA values close to the recorded

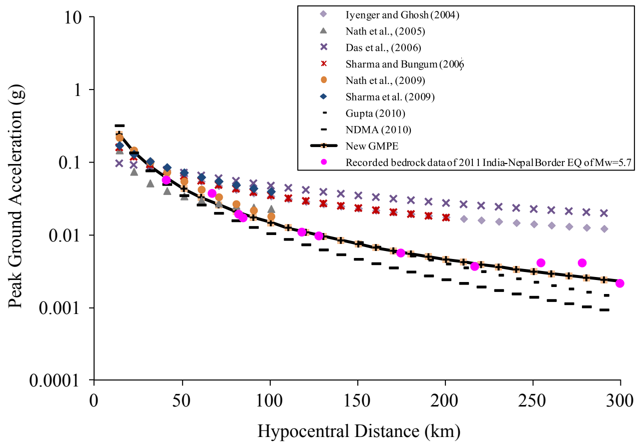

Fig. 15. Comparison of PGA predicted by various GMPEs with the recorded PGA during 2011 Nepal–India earthquake.

PGA for the entire distance range. The newly proposed GMPE is capable of predicting PGA values close to recorded data in the region for the distances of up to 300 km when compared to the region specific GMPEs and the highly ranked GMPEs for the region.

Among eight regional GMPEs useful for seismic hazard analysis, only Iyenger and Ghosh [35], Das et al. [23] and NDMA [54] are capable of predicting PGA values up to 300 km. Of these three, Iyenger and Ghosh [35] GMPE can only predict spectral acceleration at zero period i.e. PGA and cannot be used to get spectrum. Hence Das et al. [23] and NDMA [54] GMPEs are used along with proposed GMPE for quantitative analysis. Quantitative analysis of estimating the goodness of fit in terms of percent residual is used to check predictive capability of proposed GMPE models. Goodness of fit describes quantitatively how closely a prediction is matching well with the observations, which will determine the worthiness of the proposed relation to forecast PGA and spectral accelerations. Percent residual is the estimation showing the percent by which the predicted data are varying with respect to recorded data. Nepal–India 2011 earthquake recorded PGA values and Das et al. [23], NDMA [54] and proposed GMPE are considered for the quantitative analysis. Percent residual is estimated for the two regional GMPEs for the locations where recorded PGA is available and compared with percent residual of the proposed GMPE. Fig. 16(a) shows percent residual for Das et al. [23] GMPE and proposed GMPE considering Nepal–India 2011 earthquake records. It can be seen from Fig. 16 that GMPE by Das et al. [23] yields more than 40% residual as minimum and increasing with the increase in the hypocentral distance. At the same time newly proposed GMPE percent residual is close to zero for entire distance range. The proposed GMPE is capable of predicting hazard values closer to recorded values with lower percent residual. Percent residual of NDMA [54] GMPE and proposed GMPE is shown in Fig. 16(b). GMPE given by NDMA [54] shows residual in the range of 10–50% up to hypocentral distance of 100 km and proposed GMPE has residual value of less than 10%. For higher distances, the residual obtained for NDMA [54] increasing with increase in distance and reaches up to 75%. The residual based on the proposed GMPE in this study shows a narrow band within 30% for almost all the hypocentral distances. Thus limited region specific GMPEs are available to predict hazard values for entire range of hypocentral distance of 300 km. Available existing GMPE are predicting PGA values with higher percent of residual.

In order to test the capability of proposed GMPE to predict spectral acceleration, percent residual for selected record and shown in Fig. 17. It can be observed from Fig. 17 that percent residual of proposed GMPE is within $\pm 30\%$ for period up to 2 s. The proposed GMPE not only predict PGA close to recorded values

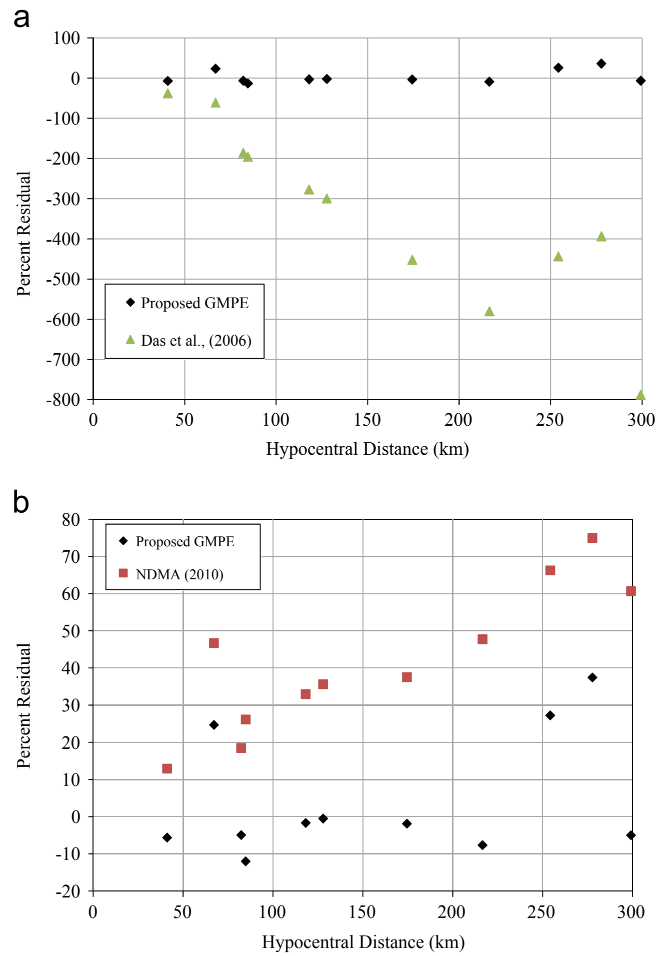

Fig. 16. (a) Plot of percent residual between recorded PGA and predicted PGA from Das et al. [23] and newly proposed GMPE for 2011 Nepal–India Border EQ. (b) Plot of percent residual between recorded PGA and predicted PGA from NDMA [54] and newly proposed GMPE for 2011 Nepal–India Border EQ.

but also is capable of predicting spectral acceleration up to 2 s. Quantitative analysis carried out in this section shows that none of the region specific GMPEs are capable of predicting PGA and spectral acceleration with less percent residual values for entire distance and spectral period for the recent earthquake of Mw 5.7. The predicted PGA and spectral acceleration by the proposed GMPE closely match with three earthquake records and also show lesser percent residual for the entire distance and period range. The proposed GMPE is capable of predicting PGA and spectral values better than any of the region specific GMPE.

11. Conclusion

A new GMPE for Himalayan region is presented here considering earthquakes of magnitude (Mw) from 5.3 to 8.7 reported at different places in Himalayan region up to 2007. FINSIM model was used to generate additional ground motions to fill the existing gap in recorded data using established regional model parameters. Synthetic ground motions were found well in agreement with the recorded ground motions and response spectrum for moderate earthquake. PGA from simulated ground motion for historic earthquakes were less than 1.0–2.5 times with that of surface PGA arrived from MMI values which was found comparable with other region specific amplification studies. Concept of apparent stations is used in this study to generate additional synthetic ground motions for distances where recorded data are unavailable.

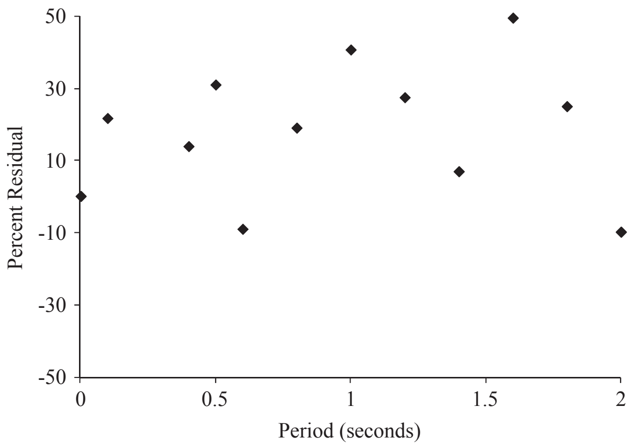

Fig. 17. Plot of percent residual between response spectra based on recorded data and newly proposed GMPE for 2011 Nepal–India Border EQ.

Regression analysis was performed on combined dataset of recorded and synthetic data at bedrock. Based on regression analysis, a new ground motion prediction equation for PGA and SA was developed for Himalayan region. Newly proposed GMPE for Himalayan is given below:

$$\log(y) = c_1 + c_2M - b\log(X + e^{c_3M}) + \log(\sigma)$$

Comparison of the newly proposed relation with recorded data for events occurred after 2007 showed that the proposed relation predicts values in accordance with recorded data. The performance of the proposed GMPE was also found to be comparable to highly ranked GMPEs for Himalayan region. Also, the spectral acceleration arrived from the proposed relation for recorded earthquake Mw of 4.3, 5.7 and 6.8 matches very well with actual response spectrum. Proposed relation is the first relation for the region, which is valid for all ranges of magnitudes of engineering interest and up to hypocenter distance of 300 km. Quantitative analysis of estimating the goodness of fit in terms of percent residual between predicted and recorded PGA and spectral acceleration showed that none of region specific GMPEs were capable of predicting values with low percent residuals. Newly proposed GMPE is capable of predicting PGA and spectral acceleration with lesser percent residual for entire distance and period range.

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