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SITE-SPECIFIC EMPIRICAL CORRELATION BETWEEN PHA AND MMI VALUES FOR CHAMOLI, INDIA FOR THE SELECTION OF GMPEs

A. Kumar (1), T G Sitharam (2), P S Kumar (3)

(1)Associate Professor, Indian Institute of Technology Guwahati, India. abhiak@iitg.ac.in
(2)Director, Indian Institute of Technology Guwahati, India. tgs@iitg.ac.in
(3)Junior Research Fellow, Indian Institute of Technology Guwahati, India. premkumars@iitg.ac.in

Abstract

With limited availability of ground motion records, development of region/ site-specific ground motion prediction equation (GMPE) is still a challenging task. Further, in case an existing GMPE is adopted from other regions for seismic hazard analysis, the appropriateness of selected GMPE for the study area is a matter of debate. Log-likelihood (LLH) based approaches have made it possible to understand the suitability of selected GMPE for the region under study. This is done by comparing the bedrock ground motion proposed by selected GMPE and the one observed during regional earthquake (EQ) record or intensity values. It has to be highlighted here that in such comparison, correlation between bedrock motion and surface experienced intensity plays a vital role and is a regional characteristic. It may not be wrong to say that even though many of the seismic hazard studies use multiple GMPEs in logic-tree, their weights and ranks are still estimated based on limited available correlations between PHA and MMI, developed for other region. Hence, whether such an approach will really take regional subsoil response into account is debatable. In this present work, citing large-scale damages witnessed during 1999 Chamoli EQ, regional empirical correlations between PHA/PGA-MMI for Chamoli region are proposed. While ground motions are synthesised using regional synthetic ground motion model parameters obtained from regional records, intensity values are obtained from available isoseismal map for the above EQ. In the light on ongoing strain accumulation and past damaging EQs found in the north-western Himalaya, it cannot be denied that any major to great EQ is likely to occur in the region which may lead to devastation that can be manifold than the one witnessed during 1999 Chamoli EQ. In such case, proposed correlations will be very useful for selecting GMPEs and assigning their weights/ ranks while attempting seismic hazard analysis of the region.

Keywords: Northwest Himalaya; GMPE; logic-tree; log-likelihood; Seismic hazard.

1 Introduction

Places located in seismically active regions witness repeated EQs, at frequent intervals. On the other hand, places, which are not seismically very active, often experience moderate to significant induced effects from distant EQs. Thus, collectively, whether it is seismic activity of a region or potential of a region to experience induced effects, it can be said that almost every place on earth is prone to moderate to very high seismic hazard. As a result, during an EQ, while locations within epicentral region witness sufficient EQ generated ground motion, distant locations experience amplified ground motion by the local soil resulting in induced effects. This can be understood from the fact that the regions located in close proximity of highly active seismic zones are classified under high to very high seismic zones. Hence, it can be said that the witnessed seismic hazard at a site/ region is a collective effect of regional seismic activity as well as subsoil's capability to alter bedrock ground motions. In the last couple of decades, population agglomeration and subsequent advancement in infrastructure have posed newer challenges to EQ experts. The assessment of regional seismic hazard, in order to develop massive structures is of paramount importance. The developed infrastructure should be able to withstand anticipated ground motions during its design life, without undergoing complete collapse.

The Indian subcontinent has a widely distributed seismic activity starting from Indian-Eurasian subduction zone running almost 2500km from the northern to the eastern part of the country. Further, the eastern part of India has complex tectonic setting due to the combined effect of Indian-Eurasian collision and Indian-Burmese collision zones, followed by rotations and active regional sources. As a result, while the Himalayas are the major sources of seismic activity from Kashmir to Arunachal Pradesh, regional sources also have significant contribution in governing seismic activity of north east India. Other parts of India consist of Indo-Gangetic plains, Peninsular India and islands of Andaman & Nicobar, each having varying seismic activity. In terms of human settlement, the forelands of the Himalayas have always been a higher priority possibly because of the presence of most fertile lands, job avenues, political reasons and may more. As a result, forelands, which cover the states of Uttar Pradesh, Punjab, Haryana, Uttarakhand, Delhi, Himachal Pradesh, Bihar etc. are some of the most densely populated regions on the country. With Government of India's vision of "collective efforts inclusive growth" (*sabka saath sabka vikaas*), numerous development schemes including development in terms of infrastructure and targets to provide connectivity, shelter and electricity to every individual even located in most remote locations of the country are underway.

It is a well known fact that in many of the developing countries, the money which can be utilized for implementing development schemes goes towards restoration works after a natural disaster hits the country. EQ, unlike any other natural disasters such as tsunami, fire etc., which are terrain specific, can occur almost everywhere on earth and is one of the most deadliest form of natural disasters witnessed globally. In this direction as well, Government of India has brought out schemes where quantification of seismic hazard of region/ city can be attempted under seismic microzonation project. While assessing seismic hazard of a region, in addition to past EQ and seismic source informations, sound knowledge about the selection GMPE is equally important. The soundness of a seismic hazard study depends upon the effectiveness of selected GMPE in forecasting ground motion characteristics as close to the reality as possible. While the development of a GMPE requires regional ground motion records, in the absence of regional records, GMPE developed in similar tectonic regions can also be adopted.

In India, ground motion recording started in 1980. 1986 Dharmsala EQ was the first EQ for which ground motions were recorded in India. Keeping in mind the seismic activity of the Himalayas and possibility of seismic gap between rupture locations of 1905 Kangra EQ and 1934 Bihar-Nepal EQ (known as Central Seismic Gap after Khattri et al. [1], regions in close proximity to the Himalayan belt are under constant threat to EQs and induced damages. Keeping in mind the dense population and poor construction practice, it will not be wrong to state that in case of future EQ, damages will be manifold in comparison to the past, even in case of same magnitude EQ. Thus, in order to minimize such damages during future EQ, numerous important cities (Amritsar, Chandigarh, Kolkata, Delhi etc.) located within close proximity to the Himalayas have been studied so far to determine possible seismic hazard values. A careful observation of such seismic hazard studies indicates that most of such studies used one regional GMPE or GMPEs developed for other region. Further, in case multiple GMPEs were used based on logic-tree approach, their weights were assigned with no justification. It must be highlighted that logic-tree for GMPE was proposed keeping in mind that each applicable GMPE is developed based on limited set of input data and thus can always have error with respect to true value in terms of seismic hazard for a site. Thus, using multiple GMPEs, such error in seismic hazard values can be minimised. Citing this reason, though numerous existing studies used multiple GMPEs (Chennai, Mumbai, Lucknow, Kolkata, Sikkim), the appropriateness of selected GMPEs for the regions under studies were not tested. As a result, though multiple GMPEs were used, since the suitability of GMPEs for the region were not tested, proposed seismic hazard values are debatable.

LLH method proposed by Scherbaum el al. [2] provided an effective tool to check the appropriateness of selected GMPEs in capturing regional ground motion characteristics by means of LLH value that was obtained based on intensity measures. However, utilization of LLH methodology requires regional correlation between bedrock ground motion characteristics and felt intensity values. In the absence of sufficient regional ground motion records, development of such correlation is difficult and hence LLH cannot be adopted for the selection of GMPEs. In the present work, four correlations are proposed between ground motion characteristics and Modified Mercalli Intensity (MMI) for Chamoli region. Detailed discussion can be found in the later sections.

2 1999 Chamoli EQ

On March 29, 1999, at 00:36:13.4 hours, region of Garhwal Himalayas was rocked by an EQ (mb=6.8). The epicentre was located at 30.408ºN and 79.416ºE near Uttarkashi. The focal depth for the event was estimated to be 21km [3]. Generated ground motions caused significant shaking in regions of Chamoli, Gopeshwar and Rudraprayag. With Alaknanda valley been the worst affected area, felt a MMI of VIII. In addition, regions of Devaldhar and Mandal Valley, and Chamoli town were also reported to have experienced MMI of VIII during the EQ. Shaking during the EQ was felt till Nepal in east, Pune in southwest, Punjab, Himachal Pradesh and Haryana in north-west as well as Uttar Pradesh and Bihar in the east. The event took about 64 lives and caused heavy loss to the properties. Based on damages, Mandakini valley were assigned MMI of VIII [4,5]. In addition, regions of Makku, Kansili, Siroli and Dobalco experienced several ground fissures as well as landslides during the EQ.

Major tectonic units of the Garwal Himalayas consist of the Main Boundary Thrust (MBT), the Main Central Thrust (MCT) and the Main Frontal Thrust (MFT) separating the Himalayan belt and the Indo-Gangetic basin. It must be mentioned here that the governing seismic activity of the Himalayas is due to the northward movement of Indian plate subducting under the Eurasian plate. While the rate of movement is 5cm/year, the rise in the Himalayas is taking place at a rate of 2cm/year clearly indicating that a significant portion of strain energy, as a result of convergence, is getting accumulated along the Himalayan belt triggering EQs at frequent intervals. Further, the region of Uttarakhand, where 1999 Chamoli EQ had happened, lies within Central Seismic Gap. Considering the damage scenarios experienced during 1999 Chamoli EQ and since then a manifold increase in population density along with poor construction practice, attempting seismic hazard assessment is the need of the hour towards minimizing future EQ induced damages and is the motivation for the present work.

3 Dataset

As highlighted earlier, keeping in mind the ongoing seismic activity and the damage scenario witnessed during 1999 Chamoli EQ, detailed seismic hazard study is very essential. Effective seismic hazard study requires appropriate GMPE for the analysis. Further, in order to select appropriate GMPE for the study area, correlation in terms of felt intensity (such as MMI) and the ground motion predicted by a particular GMPE can be used. This requires correlation between Peak Horizontal Acceleration (PHA) and MMI, or/ and Peak Ground Acceleration (PGA) and MMI. Based on the reported damages and ground shaking scenario, Sarkar et al. [6] developed isoseismal map of 1999 Chamoli EQ, which has been considered in the present work as shown in

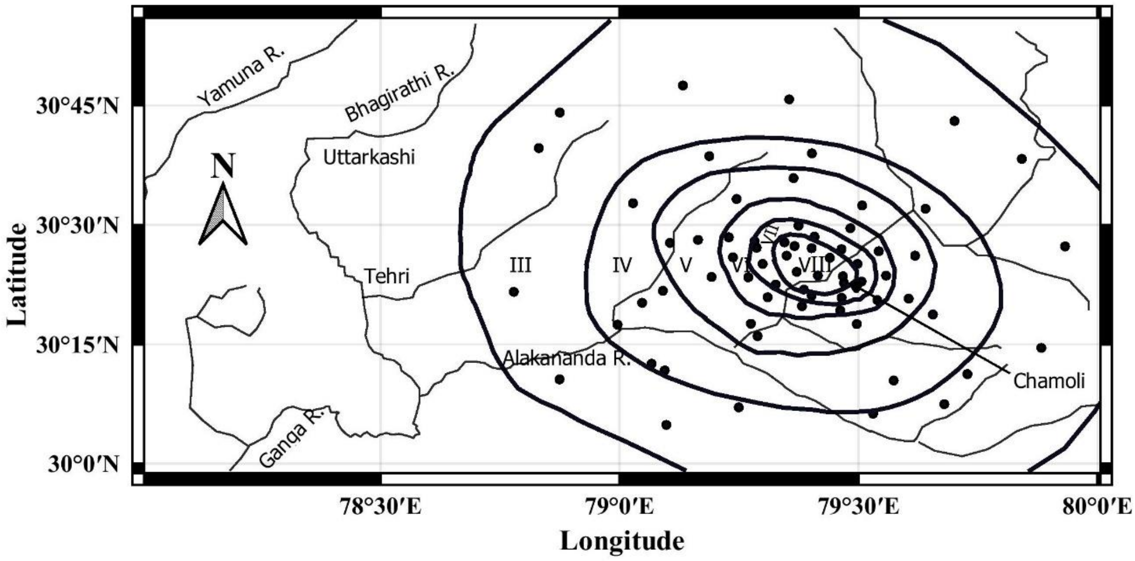

Fig. 1– Isoseismal map of 1999 Chamoli earthquake (modified after Sarkar et al. [6]). (Note: 65 locations considered for the present study are shown as solid dots)

Fig. 1. In order to develop the correlations, a total of 65 random locations within the isoseismal map are selected as shown by solid dots in Fig. 1. Firstly, MMI values are considered. Above 65 locations are selected such that in each isoseism, 10 to 20 locations fall, which are distributed around the epicenter. This way, from isoseism corresponding to MMI VIII to III, a total of 65 locations are selected and MMI at each location, following isoseismal map by Sarkar et al. [6] is observed for the work.

Further to develop the correlation, PHA/ PGA values at above 65 locations are needed. Ground motion records for 1999 Chamoli EQ are available at three recording stations namely; Barkot, Ghansiali and Barkot. However, as per Harinarayan and Kumar [7], Barkot, Ghansiali and Almora belong to NEHRP site class (SC) C suggesting that the ground motions recorded at these stations have sufficient local site component and cannot be considered as PHA or PGA for SC A condition for this work. For this reason, synthetic ground motions are generated at each of the 65 locations as discussed in the next section.

4 Synthetic ground motions

In the absence of regional ground motion records, use of synthetic ground motions for seismic hazard and for the development of GMPE have been utilised effectively across the globe [8–11]. Brune [12] point source model was used in several studies to model ground motion. A major drawback of the point source model is that it is unable to capture directivity and rupture propagation path effect accurately, which controls the amplitude, frequency and duration of simulated ground motion. This issue can be addressed by using a finite fault model. In finite fault model, the entire rupture area is divided into several sub-faults and each sub-fault is modelled as a single point source model rather than modelling the entire event as a single point source. The main event is obtained by adding the contribution from each sub-fault [13]. Numerous studies have used the finite fault models based on different source and propagation path models [14–16]. Beresnev and Atkinson [17] introduced the finite fault simulation (FINSIM) model based on the shear dislocation theory of Aki and Richard [18]. The source and propagation paths were incorporated using time functions depicting the real physical process. Later, Motazedian and Atkinson [19] modified FINSIM and developed EXSIM (Extended Finite-Fault Simulation) based on the concept of dynamic corner frequency (f_0). EXSIM code based on the EXSIM model, developed by Motazedian and Atkinson [19] is used in this work to develop synthetic ground motion. EXSIM interprets f_0 as a time-dependent parameter and the rupture history defines the frequency content of the simulated time series of each sub-fault. Rupture starts with a high value of f_0 and advances to lower f_0 as the ruptured area develops. The rupture process is modelled such that the slip occurs on a part of the fault (sub-fault) at any one instance and other sub-faults remain inactive during this time. A sub-fault undergoing rupture controls its f_0 while the amplitude of ground motion is constrained by the number of sub-faults in the calculations of f_0 [19]. The acceleration spectrum for the shear-wave part of the accelerogram of the jth sub-fault and ith recording station $(U_{ij}(f))$ can be expressed as [19];

$$U_{ij}(f) = \left\{CH_{ij}M_{0j}(2\pi f)^2)/[1+[\frac{f}{(f_{0j})}]^2]\right\}\left\{e^{(^{-\pi f R_{ij}}/_{Q_s\beta_s})}Gr\right\}\{e^{(-\pi\kappa f)}\}\{D_i\} \tag{1}$$

Where, $C = R^{\theta}FV/(4\pi\rho{\beta_s}^3)$ (2)

Further, term $e^{(-\pi\kappa f)}$ in eq. 1 represents the near-surface high-cut filter such that κ controls the linear decay of spectral amplitude of the S wave part of the accelerogram at higher frequencies. Further, in eq. 1, the term $\left\{e^{(^{-\pi f R_{ij}}/_{Q_s\beta_s})}Gr\right\}$ represents the path attenuation factor and the term $\left\{CM_{0j}(2\pi f)^2)/[1+\left(^f/_{f_{0j}}\right)^2]\right\}$

Table 1 – List of modelling parameters used for simulation of ground motion records

Parameters	Value	Reference
Fault dimension	15km×12km	Rajput et al. [20]
Stress drop	65bar	Kumar et al. [21]
Crustal density (ρ)	2.71g/cc	Nath et al. [22]
Crustal shear-wave velocity (β_s)	3.5km/s	Mukhopadhyay and Kayal, [23]
Kappa	0.05	Chopra et al. [24]
Quality factor (Qs)	$Q_s = (155)f^{(0.927)}$	Banerjee and Kumar [25]
Geometric spreading	$Gs[f,R] = \begin{bmatrix} ^1/_{\sqrt{R}} & R \le 100\text{ km} \\ ^1/_{\sqrt{100R}} & R > 100\text{ km} \end{bmatrix}$	Singh et al. [26]
Rupture propagation speed	$0.8\,\beta_s$	Atkinson and Boore [27]
Site component	Average HVSR based amplitude for site class A [D as per eq. 1]	Harinarayan and Kumar [7]

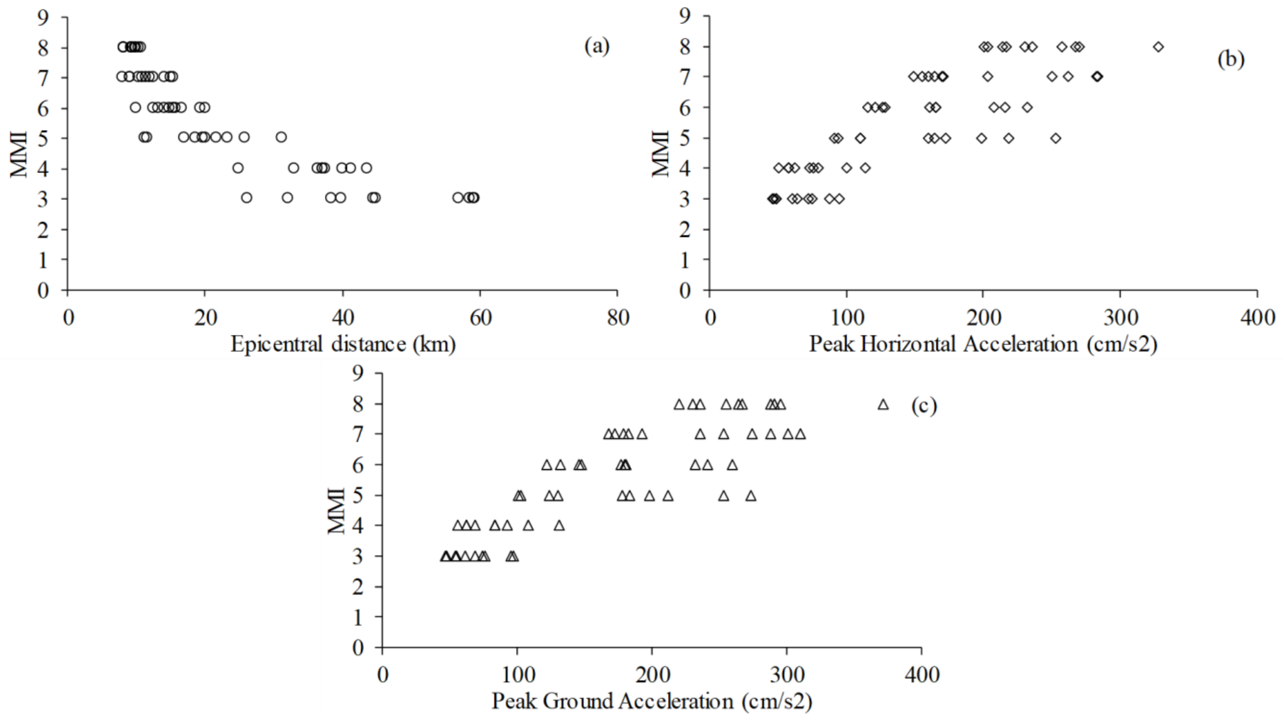

Fig. 2– Distribution of MMI versus; a) epicentral distance; b) PHA; c) PGA used as database for the present analysis

represents the source factor. D_i term in eq. 1 represents the site component. Term H_{ij} represents a factor for scaling to preserve the spectral level of sub-faults at higher frequency [19].

As discussed earlier, though ground motion records for 1999 Chamoli EQ are available, these were not recorded for bedrock or SC A condition and hence cannot be used directly for developing the present correlations. For the work, synthetic ground motions are generated following eq. 1 and considering values of various model parameters for Chamoli region as summarised in Table 1. It must be mentioned that ground motions are synthetically generated at same locations where MMI values are considered, as discussed in the last section. Further, for each location, two sets of synthetic ground motions are generated. While one ground motion is corresponding to bedrock condition and its peak value is considered as PHA, another ground motion is generated corresponding to SC A condition and its peak value is considered as PGA. This way based on generated synthetic ground motions, 65 PHA and 65 PGA values are obtained at 65 locations with known MMI values. It should be mentioned here that these 65 sets of MMI-PHA-PGA are corresponding to 1999 Chamoli EQ. A summary of data in terms of MMI variation with epicentral distance, PHA and PGA, which are used for development MMI correlation with PHA/PGA and epicentral distance (r) is shown in Figure 2. Another set of correlations of MMI with PHA/ PGA and hypocentral distance (R) are also developed considering focal depth of 21km, as highlighted earlier. Based on non-linear regression analyses and following functional form used by Nath and Thingbaijam [28], four sets of empirical correlations are developed as given below;

$$MMI = 21.407 - 2.556\ \log_{10}(PHA) - 8.182\log_{10}(r) \tag{3}$$

$$MMI = 17.745 - 1.396\ \log_{10}(PGA) - 7.193\log_{10}(r) \tag{4}$$

$$MMI = 18.790 - 0.137\ \log_{10}(PHA) - 9.148\log_{10}(R) \tag{5}$$

$$MMI = 16.236 + 0.482\log_{10}(PGA) - 8.287\log_{10}(R) \tag{6}$$

5 Use of proposed correlations

While a GMPE is a crucial part of seismic hazard analysis, such correlation is usually developed based on limited set of ground motion records. Thus, GMPE based on limited dataset can have uncertainty in terms of predicting ground motions for future EQ in the same region or may be in a different region with similar tectonic setting. To minimize such error, one can use multiple number of GMPEs found applicable or developed for the same region. With each GMPE developed based on different dataset and might be following different functional form, seismic hazard collectively based on multiple GMPEs can be more accurate than the one developed based on single GMPE. Further, for selecting such multiple GMPEs, either one can select a GMPE arbitrarily from the pool of available GMPEs and assigning weights based on individual's judgement or each GMPE can be tested for its suitability with respect to available ground motion/ intensity characteristics and based on closeness to true measures, its relative weight can be estimated. Efficacy test quantitatively assesses the appropriateness of a GMPE and thus assigns ranks in case multiple GMPEs are to be used. In efficacy test, one compares the observed EQs characteristics in the region with the one predicted by each GMPE and thus depending upon the closeness of predicted values with observed values, normalize weights and ranks are assigned to various GMPEs. This way, checking the appropriateness of GMPEs and assigning weights to each selected GMPE becomes more data specific rather than a subjective decision to make [2]. Nath and Thingbaijam [28] used efficacy test and based on LLH method by Delavaud et al. [29] not only identified GMPEs for various parts of India including the tectonically active regions of the Himalayas, North east India, Peninsular India and as well as for different subduction zones but also ranked each of the GMPEs found applicable, for future use. Referring to Nath and Thingbaijam [28], Anbazhagan et al. [30] proposed another GMPE stating that existing GMPEs had limitation in terms of magnitude and distance range of application while using in seismic hazard studies. Later, seismic hazard study of the Shillong Plateau (SP) by Baro et al. [31] firstly found GMPEs which are applicable for the SP and then estimated weights of appropriate GMPEs based on LLH method by Devalaud et al. [29]. Scherbaum et al. [2] proposed Kullback–Leibler divergence which is a measure of appropriateness with which a selected GMPE can predict or capture true ground motion variation. While estimating LLH using Scherbaum et al. [2], PHA/ PGA obtained from a GMPE needs to be converted to intensity value and then standard deviation as well as mean of selected GMPE model can be determined. To do so, in addition to the availability of GMPE for the region, regional correlation between MMI and PHA/ PGA must be available. For seismic hazard analysis, while selecting GMPEs for LLH approach, one can refer to existing literature but while examining the suitability of selected GMPEs, in most of the cases, regional correlations between MMI and PHA/ PGA are not available. Nath and Thinbaijam [28] developed correlation between microseismic intensity and PGA collectively based on data from subduction zone, active region, intraplate regions. It must be mentioned here that MMI as well as PHA/ PGA are regional characteristics and thus correlations based on collective dataset from different regions, to be used for regional specific seismic hazard studies is a matter of debate. For this reason, current work proposed suitable correlations between MMI and PHA/ PGA for Chamoli region, which can be used in future seismic hazard studies while checking the appropriateness of various GMPEs as well as for assigning weights to each of them. This way, not only GMPE but weights can be assigned based on regional characteristics.

6 Conclusion

Taking into account the extent and type of damages, witnessed during moderate to major EQs, role of seismic hazard studies cannot be neglected. While attempting regional seismic hazard studies, appropriate GMPEs, either developed for the region or developed for similar tectonic region are adopted. Since, each developed GMPE is based on limited ground motion data, there is always error between predicted ground motion and actual ground motion. By using logic-tree in GMPE, above error can be minimized as different GMPEs deal with governing factors in different ways. While using multiple GMPEs, appropriateness of each selected GMPE and accordingly its weight plays a controlling role in predicting seismic hazard values. Rather than going for arbitrary assignment of weights of GMPE, by means of existing methodology, suitability of GMPE for the region under study as well as relative weights of all suitable GMPEs can be assessed. However, this requires additional correlation with which felt intensities and PHA/ PGA are correlated. Though for a majority of regions, suitable GMPEs are documented in literature, regional correlations are not available. In the present work, 1999 Chamoli EQ is considered for the study. Firstly, MMI values for 65 random locations are considered. Further, two sets of ground motions for each of the 65 locations are generated using finite source model. While one of the ground motions gives bedrock motion (subsequently PHA), other set of motions gives surface motion for SC A condition (subsequently PGA). These two sets of ground motions are generated considering regional ground motion parameters. Further, referring to existing GMPEs correlating EQ characteristics in terms of ground motions either at bedrock or SC A condition, two sets of ground motions are generated in this work. Further, while some GMPEs correlate ground motion characteristics in terms of r, others correlate ground motion characteristics in terms of R. Hence, further proposed GMPEs are developed based on r and R as dependent variable. This way, four empirical correlations are proposed in the current work.

Keeping in mind the seismic activity of Chamoli region, its location in the central seismic gapand chances of great EQ in the near future the proposed correlations are very useful in selecting GMPEs for seismic hazard studies.

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