UNCERTINITY OF GROUND MOTION ATTENUATION RELATION FOR PREDICTING EARTHQUAKE FORCE

PREPARED BY:

ADITYA AKASH

MASTER OF CIVIL ENGINEERING, 2ND YR
REGISTRATION NO: 160044 OF 2021-2022
EXAMINATION ROLL NO: M4CIV23021B
CLASSES ROLL NO: 002110402032
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A Thesis is submitted for the Partial Fulfilment of the Continuous Assessment of the Course of Master of Civil Engineering of Jadavpur University

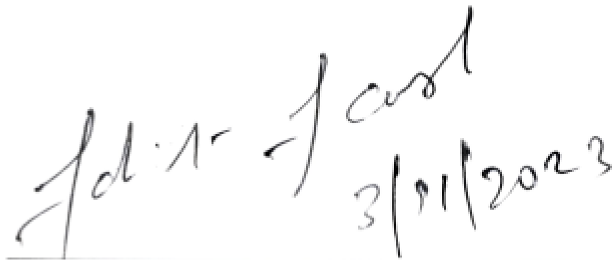
UNDER THE GUIDANCE OF

Dr. AMIT SHIULY

FACULTY OF ENGINEERING & TECHNOLOGY
CIVIL ENGINEERING DEPARTMENT
(STRUCTURAL ENGINEERING)
KOLKATA – 700 032, INDIA

DECLARATION

This thesis titled "**UNCERTINITY OF GROUND MOTION ATTENUATION RELATION FOR PREDICTING OF EARTHQUAKE FORCE**" is prepared and submitted for the partial fulfillment of the continuous assessment of Master of Engineering in Structural Engineering course of Jadavpur University.



Aditya Akash
Class: M.C.E-2nd yr.
Structural Engg
Roll No: 002110402032
Exam Roll No: M4CIV23021B
Registration No.: 160044 of 2021-2022

Date:
Place: Civil Engineering Department
Jadavpur University, Kolkata

JADAVPUR UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING
KOLKATA – 700032

RECOMMENDATION CERTIFICATE

It is here by certified that this Thesis titled "**UNCERTINITY OF GROUND MOTION ATTENUATION RELATION FOR PREDICTING OF EARTHQUAKE FORCE**" is prepared and submitted for the partial fulfillment of the continuous assessment of **Master of Civil Engineering in Structural Engineering** course of **Jadavpur University** by **Aditya Akash**, a student of thesaid course for the session 2021-2023 under my super supervision and guidance. It is also declared that no part of thesis of said work has been presented or published elsewhere.

Dr. AMIT SHIULY
(Thesis Supervisor)
Department of Civil Engineering
Jadavpur University

Countersigned by:

3/11/23

Head of the Department
Department of Civil Engineering
Jadavpur University

3/11/23

Dean
Faculty of Engineering and Technology
Jadavpur University

DEAN
Faculty of Engineering & Technology
JADAVPUR UNIVERSITY
KOLKATA-700 032

JADAVPUR UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING
KOLKATA – 700032

CERTIFICATE OF APPROVAL*

This is to certify that this thesis is hereby approved as an original work conducted and presented satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is implied that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose for which it is submitted.

Final Examination for evaluation of thesis

1)………………………………………………

2)………………………………………………

3)………………………………………………

(Signature of Examiners)

*Only in case the thesis is approved.

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Aditya Akash
Class: M.C.E-2nd yr.
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Date:
Place: Civil Engineering Department
Jadavpur University, Kolkata

“Engineering is the art

of directing the great sources

of power in

nature for the use and convenience

of humankind”

-Thomas Tredgold

ABSTRACT

Several Ground Motion Prediction Model (GMM) were developed in Himalayan region in the past by several researchers. In the present studya comprehensive review the existing GMMs for Himalayan region were carried out. Here an attempt has been madeto identify and collect the seismo-tectonic setting of the region and source of seismic data.Further, applicability of these generated GMMs were inspected thoroughly using available seismic records of Indo Himalayan region. For this purpose, predicted peak ground acceleration (PGA) and Peak Spectral Acceleration (PSA) obtained by using the GMMs for different magnitude and distance are compared with recorded data by computing Root Mean Square Error (RMSE) and Chi-square value. Moreover, Log-likelihood (LLH) scoring method has been applied and proper weights of the GMMs have been proposed.RMSE is employed to quantify the model's goodness of fit, LLH measures the model's ability to capture the distribution of observed data, and chi-square statistics assess the agreement between observed and predicted values.

Further, GMMs have been developedto predict the PGAwith the help of different machine learning technique like ANN, ANFIS, FUZZY, GA and RANDOM FOREST. Here also above mentioned statistical analysis were performed in order to analyse their performance. The proposed machine learning-based ground attenuation relation has the potential to significantly improve seismic hazard assessments and engineering design, leading to safer and more resilient structures in earthquake-prone regions.The incorporation of these statistical measures allows us to rigorously assess the appropriateness of our model.

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1. INTRODUCTION

1.1. GENERAL

There are about 12000-14000 earthquakes recorded every year around the globe as per the IRIS (Incorporated Research Institute for Seismology) [1] . Out of which most of the earthquakes occur is of low or very low magnitude which causes no or negligible harm to humanity. However, there are few earthquakes of magnitude of 7 or more which causes huge destruction of lives, infrastructures and the global economy.

There is no way to avoid earthquake from occurring as it is a natural phenomenon and human have no control over it. In order to reduce the damage and destruction due to earthquake, design of earthquake resistant structure necessary. It is important to note that the structure should be economic as well. Otherwise, uneconomical earthquake resistant structure won't be possible for everyone to afford. Thus, a prediction of earthquake force is very important. The earthquake force can be estimated through seismic hazard analysis which requires ground motion predicting model (GMM) on the basis of past earthquake data [2][3][4][5].

India has experienced several earthquakes of high magnitude with huge damages to property and lives. Bhuj earthquake 2001 of 6.9 intensity on Richter scale, alone took 18,602 lives and 1,66,734 people were injured. 21 district was affected out of which 6 was majorly affected [6]. Nepal 2015 of magnitude 7.8, it was so big that 5 countries (Nepal, Ganges plain in northern India, north-western Bangladesh, western Bhutan and southern part of Tibet plateau in China) felt the shock [7]. Uttarkashi Himalayan earthquake 1991 was largest earthquake recorded in Himalayan region till 1991 having magnitude 6.8 and caused huge damages to the Garhwal region [8]. Shillong earthquake 1897 having magnitude 8.1 and great Assam earthquake 1950 of magnitude 8.6 has changed the topography and course of river flowing in that region. Assam oil industry also incurred huge loss due to Assam earthquake 1950

[9][10].

Indo Himalayan region which is almost 59% of India, susceptible to moderate to high earthquake [11]. Major cities like Delhi, Kolkata, Patna, Ahmedabad, Lucknow etc. which is economic hub of the country and densely populated with various other small cities like Dehradun, Itanagar, Shillong, Shimla, etc. are very much vulnerable to seismic hazard. Thus, quantitative estimation of hazard due to earthquake in a city of Indo Himalayan region is very important. This quantitative estimation can be carried out through detailed deterministic as well as probabilistic seismic hazard analysis (PSHA) [12]. The seismic hazard analysis for the many cities has been conducted by several researchers like, for Delhi [3][4][5][16], Kolkata [7][8][9][10], Patna [11][12], Dehradun [23], Shillong[24], North-east India [15][16] etc. Thus, for conducting the hazard analysis GMM is very important.

Strong motion data from 5 earthquakes (Dharamsala earthquake 1986 (M= 5.7), Meghalaya earthquake 1986 (M= 5.7), Burma-India earthquake 1987(M= 5.7). Tripura-Assam eartquake 1988 (M=5.8), Gauhati earthquake 1988(M= 7.2)) of different region of India has been used by Singh et al. (1996) [27] to develop GMM for predicting PGA and PGV using least-square regression. Sharma (1998) [28] conducted a study, wherein he analyzed five earthquake records to develop a Ground Motion Model (GMM) using a two-step stratified regression approach and the research yielded a residual sum of squares for the proposed equation, which was recorded as 0.14. Due to lack of data of Indian region, Zargos region of Iran's data were considered by Sharma et. al. (2009) [29] for generation of GMM which was developed on the basis of 16 earthquake records and suggested different coefficients for predicting spectral acceleration at different time period. In 2010 NDMA published report on Development of Probabilistic Seismic Hazard Map of India where GMM was also suggested [30] in which coefficients of the equation for predicting spectral accelerations at different time period were obtained from the simulated database of 80,000 samples by a two-step stratified regression.

Anbazhagan et. al. [31] in 2013 used recorded as well as simulated data for evaluating GMM by finite fault simulation mechanism and simulated data were compared with the recorded one. Different coefficient for the developed equation were proposed for predicting spectral acceleration at different time period. Due to insufficient strong motion data, Raghukanth and Kavita in 2014 [32] developed GMM on the basis of 80000 data considering the stochastic finite fault simulation model of region specific seismo-tectonic parameters from the past earthquake simulation method for Andaman region, Indo-Gangetic region, Indo-Burmese region and the Himalayan region. Under the Mission Mode Project by Govt. of India, Nation-wide strong motion network deployment was done. Using strong data from from 24 earthquakes of these network GMM was developed based on two-step stratified regression model developed for North-Eastern Himalayan region by Kumar et al. in 2017[10]. Further, Kumar et. al. (2019) [33] developed GMM using data set of 116 records from 9 earthquakes with magnitude from 5 to 6.8 from UP arrays of National Strong Motion Instrumentation Network and Earthquake Early Warning System of India. Ramkrishnan et al. (2019) proposed new GMM for the North and Central Himalayas using recorded strong motion data[34] of magnitude ranging 4.1 to 7.8 for North and Central Himalayas using multiple regression for hypocentral distance upto 1580km. Based on non-linear multiple regression model, Ramkrishnan et al. in 2020 proposed GMM for North-East India [35] on the basis of 204 recordings of 24 earthquakes from 1986 to 2013 were cosidered for magnitude ranging from 4.2 to 6.9. Harinarayan and Kumar in 2020 proposed GMM for magnitude range of 3.5 to 7.8 using synthetic ground motion for different site class [36] by regression. Huang et. al. [37] developed ground motion prediction model using artificial intelligence technique for North India where recorded data from Kangra and UP array were used, which are available in PESMOS website. Shiuly et. al. (2021) [38] developed GMM using Artificial Neural Network (ANN) and Genetic Algorithm(GA) for the Himalayan region[38]. In order to validate their model they used Chi-square method to compare between ANN and GA model. Ground Motion Model with the help of machine learning technique is not studied much for the Indian region. Few paper published that is based on one or two technique only. Comprehensive comparison between different model using different model is not done. Different modern machine learning (ML) based GMM can capture the nature of empirical GMMs using minimum earthquake data and without a need for nonlinear regression having large numbers of coefficients [39]. As reported by Khosravikia and Clayton [40] and Dhanya, J. and Raghukanth[41], that these ML based GMM perform better than conventional polynomial multiple regression.

Furthermore, the GMM were developed in order to predict the PGA for given magnitude and distance. Only NDMA [30], Anbazhagan et. al. [31], Raghukanth and Kavita in 2014 [32], Harinarayan and Kumar [36], Harbindu et al. [42] has developed GMM for predicting spectral acceleration at different time period for a particular distance and magnitude. In addition to that, no GMM is developed on the rupture type, considering other distances (like Joyner Boore distance).

1.2.NEED FOR PRESENT STUDY

However, the conventional approach remains valuable in cases where the available data is limited. This limitation often arises from the fact that the model relies on predefined equations that are rooted in fundamental physical principles. In addition to that, some physically sound features are obtained in all alternatives, inspiring the use of these tools in ground motion estimation. However, the ML tools like ANN, FIS, ANFIS, RF, GA are not able to yield mathematical equations that can be directly used by others. This is the prominent drawback of the ML methods while the equations are necessary for future engineering analysis. Present literature review on GMM for India indicates that there is a need of nonparametric local GMM for the Indian earthquake dataset by designing and applying a web-based application model for end users. The suggested ML-based GMM could be further studied in future research for India and more homogeneous real datasets. Other limitations of the GMM are the lack of reflection of spatial correlation and additional input parameters to consider near-field effects in the ground motion records. Thus, to improve GMM in India, modern ML methods should be used.

It is to be noted that all the GMM was based on limited numbers of data. Further, almost all the GMM model were developed on the basis of linear and nonlinear regression model. Except Shiuly et al. (2021) [38] developed GMM on the basis of machine learning methods. Further, applicability of the GMM for purpose of seismic hazard was not stated. It is evident that analysis using different scoring method will yield accuracy of the GMM. Most of the GMM were developed on rock site.Also Ground Motion Model with the help of machine learning technique is not studied much for the Indian region. Few paper published that is based on one or two technique only. Comprehensive comparison between different model using different ML Technique is not done yet.

1.3. OBJECTIVE AND SCOPE OF WORK

Therefore, in the present study first an effort has been made to review the developed GMMs for Indo Himalayan region thoroughly. For this purpose,

1. the seismo-tectonic settings, availability of seismic data, seismic hazard analysis carried out in this region, has been briefly discussed.
2. Further, the available GMMs were reviewed immensely. Furthermore, applicability of these developed GMMs were examined in detailed using available earthquake records in Indo Himalayan region.

3. Predicted PGA and PSA obtained by using the GMMs for different magnitude and distance are compared with actual ground motion by comparing Root Mean Square Error (RMSE) and Chi-square value for each GMM.
4. Further, Log-likelihood (LLH) scoring method has been introduced and proper weights for the GMMs have been suggested.

Secondly an effort has been made to develop GMMs using different technique like ANN, GA (geometric algorithm), Fuzzy Logic, ANFIS, Random tree and Regression for Himalayan region. There is various factor which is responsible for PGA due to seismic activity but to avoid complexity only two factor magnitude and hypo-central distances has been taken into consideration.

1. Data for Indo-Himalayan region were downloaded from PESMOS website. 234 data from 79 different earthquakes (table no. 1) of this region were considered for the study. 211(about 90%) of data were separated for the purpose of training the models. And about 10% (23) kept aside for testing purpose to check the appropriateness of result.
2. With the help of different machine learning technique model were trained using training data which were kept aside.
3. After training, result was obtained for the testing data for the comparison between actual and predicted value.Chi-square value and RMSE (root mean square error) of different model have been calculated for the comparison of accuracy of Model developed by different technique.

1.4. ORGANIZATION OF THE REPORT

The dissertation has been organized in four chapters. The table and Figures have been presented in a sequence as they appear in the chapters.

In **Chapter 1**a brief introduction about earthquake and seismic activity and GMMs (ground motion model) developed by the previous researcher is been discussed. The present need for the study and the scope of the work also has been discussed here. Organization of full report is also mentioned.

In **Chapter 2** review of several GMMs developed by the previous researcher has been done. Detailed of seismo-tectonic setting of Indo-Himalayans region are explained. For the comparison PGA and PSA plotted for data downloaded from PESMOS website. And appropriateness of resultis also discussed.

In **Chapter 3** various machine learning method has been explained and using that method GMMs are developed for prediction of PGA.

In **Chapter 4** summarizes the whole work. Major conclusion drawn from the study. Limitation and recommendation of further study were also discussed.

A list of references is also provided at the end.

2 LITERATURE REVIEW

2.1. GENERAL

Various researcher has tried to develop Ground Motion Prediction Equations(GMPEs) for the Himalayan region using different method as mentioned in chapter 1. GMPEs were developed using limited amount of data and even we cannot be sure about their correctness and appropriateness. We have seen in chapter 1 that some researcher used different region data which has seismo-tectonic similarities with Himalayan region for GMPE creation. Today due to technological advancement we now have data more in number and more accurate one. So it becomes important to analyze the GMPEs proposed by the researcher in the past as per the recent data available. So in this chapter effort has been made to do the same.

2.2 SEISMO TECTONIC OF HIMALAYAN REGION

On the basis of geological and tectonic features, Indian subcontinent can be divided into: - 1. Region between Kirthar and Sulaiman mountain ranges in north west 2. In north the Himalayan mountain 3. ArakanYoma region in east [43]. Himalayan mountain extends from west to east in the north. ArakanYoma region extend north to south into the island of Andaman and Nicobar, Sumatra and Java islands. Himalayan region is one of most active seismic region of the world [33] due to frequent seismic events in this region. These seismic events occur in Himalaya region as it is situated between Indian and Eurasian plate. About 250 Million year ago, India was an Island situated off the Australian coast. Further, around 200 million years ago when Pangaea broke, the Indian plate started advancing northward towards Eurasian plate. After that, nearly 40 to 50 million years ago Indian and Eurasian plate collided and this lead to the formation of immense mountain ranges between these huge landmasses [44].Due to constant pressure of the Eurasian plate on the Indian plate, strained energy accumulating and it keeps releasing itself from time to time in the form of seismic events. Occurrence of these seismic events is due to accumulation of strained energy under the Himalayas is a normal and relentless process. It is important to mentioned that, Geological survey of India has developed seismo-tectonic map for India in which all the known major and minor fault of India has been compiled in the form of atlas with the title "Seismo-tectonic Atlas of India and its Environs" in 2000 [45]. Map is in 1:1 Million scale and about 67 active faults are present in country of which 15 are major present in Himalayan belt as per the map. Seismo-tectonic setting of Himalaya region is presented in Fig. 1.

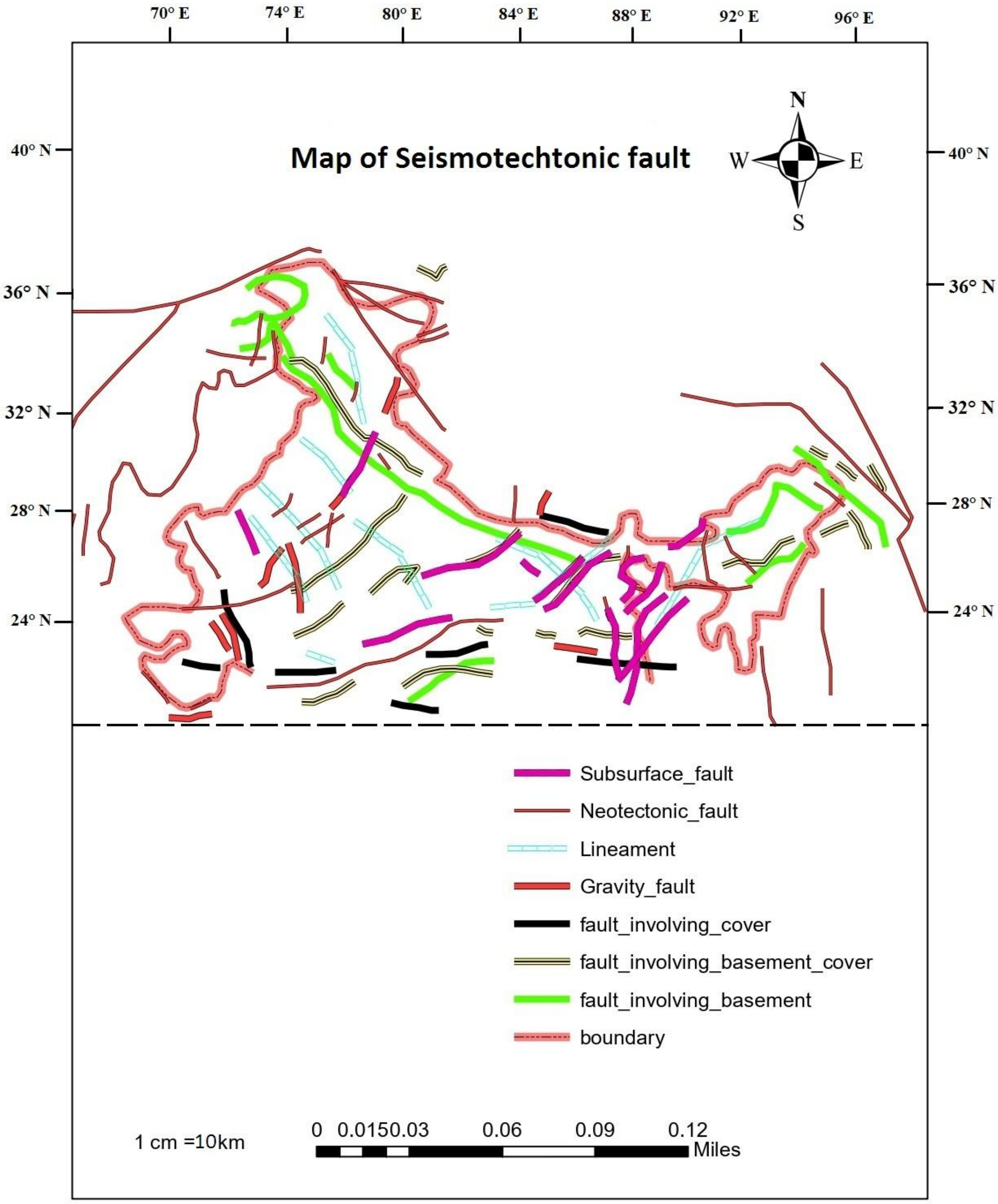


Fig1. Map of Seismo-tectonic fault of Himalayan region

It is to be mentioned that, all the major faults of India have potential for generating large seismic events. Fault zone which may be responding to crustal deformation in the Himalayan collision zone are known to be site of large earthquakes like MCT (main central thrust), MBT (main boundary thrust), HFT (Himalayan frontal thrust); in the North-East Indian region Mishmi thrust, Lohit thrust, Kopili fault; and in the western Indian region Allah Bund fault, Kutch Mainland fault, Katrol Hill fault and Bhuj fault [46][47]. However, it is to be mentioned that, after the great earthquake of 12 June 1897(M 8.7) in N-E India, investigation of surface rupture started [48] and probably this was the first active fault studies in India. Based on detailed geological and geomorphological investigations, two faults were recognized. First was Chedrang fault and second was Bordwar fault. Chedrang fault extends over 18km with up throw up to 10m in crystalline rocks. Geomorphic features which indicated Chedrang fault is a series of waterfalls alternating with pools along the stream. Bordwar fault extends up to 7 miles followed by broken trees and cracks in the ground. Ordinary sign of Bordwar fault was not detected as there is probability that displacement due to this seismic events must have returned to its original position due to post earthquake.

Further, Nakata in 1972 first reported the active faulting in the Himalayan foothill[49]. Faults that were reported along HFT (Himalayan Frontal Thrust) are Chandigarh fault, Pinjore Garden fault and Barsar thrust based on the observed geomorphic features such as vertical dislocation, wrapping and back tilting of the fluvial and alluvial fan deposits of Late Pleistocene-Holocene age[50]. The study on the trench along the Chandigarh fault revealed the total displacement of 3.5m due to large (Mw =7) prehistoric earthquake (1300-1400 AD) along the HFT[51]. In NW Himalaya two new parallel NNW-SSE striking active fault scarps named as Hajipur faults along the north-western end of the Janauri anticline in the foothill zone have been identified[52]. Paleo seismological investigation of Kashmir Himalaya indicate the occurrence of a major earthquake during 1555 AD [53]. This caused ground fissures and rupture which extends 100km. Based on the landform evidence like lakes, trenches, gorges fault scraps, uplifted terrain, terraces, etc. investigation of the neo-tectonic activity along the Main Boundary Thrust(MBT) in southern Kumaun Himalaya has done [54].

Studies found major faults in NE Himalayan region like Dauki fault, Dudhnoi fault, Kopili fault, Oldham fault, Sylhet fault, etc.[55]. Trench investigation made in the meizoseismal area of 1950 Assam great earthquake reveal two past seismic events in 1548AD and 1697AD [56]. Gorubathan, Matiali and Chalsa thrusts are the active faults that identified after studying Neora-Jaldhaka Valley of Darjeeling-Sikkim Sub-Himalayan foothill region [57]. Gorubathan thrust, where unequivocal surface rupture is present, in addition to that the Matiali and Chalsa faults are blind thrusts. Many active faults were reported in the Arunachal Himalaya also. Compressed meandering is commonly observed in the frontal streams and rivers of the Sub-Himalaya along the Kimin section, indicating the interruption by faults along their stream channels. Sudden widening and narrowing of river due to tectonic event is also commonly seen here which are related to neotectonic event in Sub Himalayas [58].

Allah Bund fault generated after the earthquake of 16 June 1819 (Mw 7.8) in Gujarat. This is one of the spectacular evidence of faulting among the Indian fault. The plain of Rann of Kutch got up-heaved and rupture along 80km long segment [59]. Killari earthquake (Mw 6.3) 1993 deformed the ground surface in a 100m wide zone [60][61]. Bhuj earthquake of 2001(Mw 7.3) created rupture along a 0.5km segment of the Kutch mainland fault [62]. Further, Muzaffarabad earthquake 2005(Mw 7.6) produced coseismic rupture along NW-SE of length 80km [63].

Now a day due to technological advancement it is easy to locate active fault in Himalayan region with accuracy with the help of technique like GPS, GPR, InSARetc.. Many near surface fault has been located with the help of GPR. To estimate important data like slip rate and strain accumulation the GPS based geodetic survey has been used in major faults of country [46]. GPS based geodetic survey were also used in investigation of several large earthquakes like 2001 Bhuj, 2004 Andaman Sumatra, 2005 Kashmir, 2011 Sikkim and their relationship to active faulting. A slip of 16mm was measured towards N 46° E during Bhuj 2001 earthquake [64]. The coseismic horizontal displacement of 1.6m (Harewak Island) to 6.6m (Car Nicobar) in WSW to SE direction was found out by GPS-Based geodetic survey done after 2004 Andaman Sumatra earthquake. This survey also found vertical displacement of 1-2m on east coast of Andaman and Nicobar Island and uplift of 0.5-1.0m in North and Little Andaman [65][66][67]. The maximum offset during 2005 Kashmir Earthquake was predicted to be 26cm at a site 44km from the epicentre and 19cm at 85km east of epicentre [68] by the GPS-Based geodetic survey done after Kashmir 2005 earthquake. Moreover, work is going on to identify active fault in the India Himalaya region.

2.3 SEISMIC DATA OF INDO HIMALAYAN REGION

Himalayan is one of the most seismically active region of the world [31]. It is due to major fault line in Himalayan region like MCT, MBT, MFT, etc. which resulted due to the collision of the Indian and Eurasian plate [46][69]. There is no proper estimation for ground motion parameter is available for Indian region as earthquake data was almost non-existent before 1986. First strong motion data for Indian region was from Koyna dam region in peninsular India in 1967 [70].

During 1985 to 1991, 135 SMA-1 type strong motion accelerographs were deployed by the Earthquake Engineering department of IIT-Roorkee in three major region of Himalayas, North-west Himalayas, Central Himalayas and North-east Himalayas covering its major tectonic features. Kangra array in North-west Himalayas, UP array in Central Himalayas and Shillong array in North-east Himalayas. Kangra array consists of 50 accelerographs, spread across North-west Himalayas elevation between 470m to 2700m. In UP array (also known as Garwal-Kumaon array), 40 accelerographs are installed which extends from North-west

Himalayas to Central Himalayas. 45 accelerographs are installed in Shillong array, which covers parts of Meghalaya and Assam slate [71].

More accelerographs were installed by IIT-Roorkee later in 2005, about 280 accelerographs covering more areas like North-east and southern alluvial plains of the Himalayas and the Delhi region [72]. The Earthquake Engineering department of IIT-Roorkee is managing the data recorded from all these accelerographs and made these data available in website (pesmos.in). Dataset consists of all the necessary details which can be used for study, like coordinates, magnitude, average shear velocity, peak ground motion acceleration, velocity, station, location of station whether it is in rock sites or soil.

In this paper 234 numbers of data from 79 earthquakes is taken into consideration having moment magnitude ranging from 3.9 to 8 and hypo-central distance ranging from 20.6 Km to 1480.4 Km which was downloaded from the PESMOS website (Table 1) [73]. It is to be mentioned that only moment magnitude has been considered. In the present study, body wave magnitude or surface wave magnitude has been converted to equivalent moment magnitude according to Das et al. [74]. Further, only rock site data i.e. Vs-30 greater than 700m/s has been considered in the present investigation. It is to be noted that the data consist of three direction component of motion. The geometric mean of the PGA for two horizontal direction motions of a particular site has been considered as PGA in the present study. In order to determine spectral acceleration for a particular time period of a recording site, same method has been followed.

Table No.:- 1 Some of the recorded earthquakes in Indo Himalayan region [75][76].

PLACE	DATE	TIME	M	LALTITUDE	LONGITUDE	DEPTH(KM)
NE India, India	10-09-1986	07:50:26	4.5	25.385	92.077	43
India-Burma Border, India	18-05-1987	01:53:51	5.9	25.271	94.202	49

PLACE	DATE	TIME	M	LALTITUDE	LONGITUDE	DEPTH(KM)
India-Burma Border, India	06-02-1988	14:50:45	5.8	24.688	91.57	15
India-Burma Border, India	06-08-1988	00:36:25	7.2	25.149	95.127	90
India-Burma Border, India	09-01-1990	18:51:29	6.1	24.753	95.241	119
Uttarkashi, India	19-10-1991	21:23:15	7	30.78	78.774	10
Uttarkashi, India	20-10-1991	21:23:15	8	30.78	78.774	10
India-Burma Border, India	06-05-1995	01:59:07	6.4	24.987	95.294	117
Xizang-India Border, India	26-03-1996	08:30:25	4.8	30.651	79.102	47
India-Burma Border	08-05-1997	02:53:15	6	24.894	92.25	34
Chamoli, India	28-03-1999	19:05:11	6.6	30.512	79.403	15
Chamoli-Uttarakhand	14-12-2005	07:09:48	5.2	30.9	79.3	25.7
UTTARKASHI-UTTARANCHAL	22-07-2007	23:02:12	5	31.2	78.2	33
DELHI-HARYANA-BORDER-REGION	25-11-2007	23:12:20	4.3	28.6	77	20.3
Andaman	10-08-2008	08:20:34	6	11.1	91.6	10
PITHORAGARH	19-08-2008	10:54:26	4.3	30.1	80.1	15
INDIA(UTTARAKHAND)-TIBET-BORDER-REGION	04-09-2008	12:53:21	5.1	30.1	80.4	10
HINDUKUS-AFGHANISTAN	06-09-2008	05:47:33	5.8	36.7	70.6	160
KULLU-HIMACHAL-PRADESH	21-10-2008	15:09:06	4.5	31.5	77.3	10
HINDUKUSH-REGION-AFGHANISTAN	03-01-2009	20:23:19	6.4	36.5	70.8	188
Chamoli-Uttarakhand	15-05-2009	18:39:22	4.1	30.5	79.3	15
MYANMAR-INDIA(MANIPUR)BORDER	11-08-2009	21:43:39	5.6	24.4	94.8	22
MYANMAR-India-Manipuir-Border	03-09-2009	19:51:08	5.9	24.3	94.6	100
UTTARKASHI-UTTARAKHAND	21-09-2009	09:43:47	4.7	30.9	79.1	13
BHUTAN	21-09-2009	08:53:04	6.2	27.3	91.5	8
BAGESHWAR-UTTRAKHAND	03-10-2009	05:20:54	4.3	30	79.9	15
KOKRAJHAR-ASSAM	29-10-2009	19:56:58	4.2	26.6	90	10

PLACE	DATE	TIME	M	LALTITUDE	LONGITUDE	DEPTH(KM)
BHUTAN	29-10-2009	17:00:35	5.2	27.3	91.4	5
HINDUKUSH-REGION-AFGHANISTAN	29-10-2009	17:44:30	6	36.4	70.8	190
CHINA-INDIA(J&K)-BORDER	06-12-2009	04:33:15	5.3	35.8	77.3	60
BAGESWAR-UTTARAKHAND	22-02-2010	17:23:43	4.7	30	80.1	2
TIBET	26-02-2010	04:42:33	5.4	28.5	86.7	28
HIMACHAL-PUNJAB-(HOSHIAPUR)-BORDER	14-03-2010	06:53:21	4.6	31.7	76.1	29
Himachal	28-05-2010	07:25:06	4.8	31.2	77.9	43
INDIA-NEPAL	06-07-2010	19:08:20	5.1	29.8	80.4	10
Almora-UTTARAKHAND	10-07-2010	03:16:20	4.1	29.9	79.6	10
Hindukush	17-09-2010	19:21:09	6.5	36.5	70.8	167
Southwestern-Pakistan	18-01-2011	20:23:27	7.4	28.9	64	5
UTTARKASHI-UTTARAKHAND	09-02-2011	19:17:12	5	30.9	78.2	10
Hindukush-Region-Afganistan	21-03-2011	09:48:59	5.7	36.5	70.9	166
NEPAL-INDIA-BORDER-REGION	04-04-2011	11:31:40	5.7	29.6	80.8	10
INDIA-NEPAL	04-05-2011	20:57:15	5	30.2	80.4	10
India(Sikkim)-Nepal-Border	03-06-2011	00:53:21	4.9	27.5	88	26
Chamoli-Uttarakhand	20-06-2011	06:27:18	4.6	30.5	79.4	12
J&K-Border	28-07-2011	18:42:34	4.4	33.3	76	21
DELHI-HARYANA(SONIPAT)-Haryana	07-09-2011	17:58:18	4.2	28.6	77	8
INDIA-(Sikkim)-NEPAL-BORDER	18-09-2011	21:51:52	4.2	27.6	88.4	28
INDIA-(Sikkim)-NEPAL-BORDER	18-09-2011	13:54:17	4.5	27.5	88.4	9
INDIA-(Sikkim)-NEPAL-BORDER	18-09-2011	13:11:59	5	27.6	88.5	16
INDIA-(Sikkim)-NEPAL-BORDER	18-09-2011	12:40:47	6.8	27.6	88.2	10
WESTERN-NEPAL	26-02-2012	23:08:42	4.3	29.6	80.8	10
HARYANA-DELHI-BORDER-REGION	05-03-2012	07:41:05	4.9	28.7	76.6	14

PLACE	DATE	TIME	M	LALTITUDE	LONGITUDE	DEPTH(KM)
Chamoli-Uttarakhand	10-05-2012	22:00:40	3.9	30.2	79.4	5
NEPAL-INDIA-BORDER-REGION	28-07-2012	05:48:06	4.5	29.7	80.7	10
NEPAL	23-08-2012	16:30:19	5	28.4	82.7	10
CHAMBA-DISTT-HIMACHAL	02-10-2012	03:45:28	4.5	32.4	76.4	10
CHAMBA-DISTT-HIMACHAL	02-10-2012	08:34:52	4.9	32.3	76.3	10
CHAMBA-KANGRA-DISTT-BORDER	06-11-2012	12:21:12	4.1	32.3	76.2	5
CHAMBA-KANGRA-DISTT-BORDER	11-11-2012	20:23:12	4	32.3	76.2	5
WESTERN-NEPAL	11-11-2012	18:39:13	5	29.2	81.5	10
UTTARKASHI-UTTARAKHAND	27-11-2012	12:15:15	4.8	30.9	78.4	12
WESTERN-NEPAL	02-01-2013	17:42:15	4.8	29.4	81.1	10
NEPAL	09-01-2013	07:44:20	5	29.75	81.74	34
NEPAL	29-01-2013	19:42:52	4	30	81.6	7
UTTARKASHI-UTTARAKHAND	11-02-2013	10:48:55	4.3	31	78.4	5
IRAN-PAKISTAN-BORDER-REGION	16-04-2013	10:44:11	7.8	28	62.1	46
JK-HP-BORDER	01-05-2013	06:57:12	5.8	33.1	75.8	15
LAHUL-SPITI-HIMACHAL-PRADESH	04-06-2013	17:34:44	4.8	32.7	76.7	18
CHAMBA-HIMACHAL-PRADESH	05-06-2013	22:04:00	4.5	32.8	76.3	10
J&K-HIMACHAL-BORDER	09-07-2013	13:49:13	5.1	32.9	78.4	10
KANGRA-HIMACHAL-PRADESH	13-07-2013	17:49:33	4.5	32.2	76.3	10
LAHUL-SPITI-HIMACHAL-PRADESH	15-07-2013	17:49:11	4.4	32.6	76.7	10
JK-HP-BORDER	02-08-2013	21:37:40	5.2	33.4	75.9	20
JK-HP-BORDER	02-08-2013	02:32:05	5.4	33.5	75.5	28
HIMACHAL-PUNJAB-(HOSHIAPUR)-BORDER	29-08-2013	10:13:21	4.7	31.4	76.1	10

PLACE	DATE	TIME	M	LALTITUDE	LONGITUDE	DEPTH(KM)
INDIA-CHINA-BORDER-REGION	20-10-2013	19:45:05	5.5	35.8	77.5	80
UTTARKASHI-UTTARAKHAND	25-12-2013	02:56:52	4	31.2	78.3	10
KANGRA-(H.P.)	17-06-2014	17:31:08	4.1	32.2	76.1	10
NEPAL	25-04-2015	11:25.9	7.8	27.98N	84.62E	1.32

2.4 USE OF ATTENUATION RELATIONSHIP FOR SEISMIC HAZARD ANALYSIS IN HIMALAYAN REGION

Seismic risk can be minimised through earthquake resistant design of structure. However, for making structure earthquake resistant estimation of earthquake force is very important which can be assessed through seismic hazard analysis. The Seismic Hazard Analysis is the process of quantitative evaluation of Earthquake Hazard [77]. There are two approach to Seismic Hazard Analysis, Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA).

DSHA is straight forward approach [12]. And does not require any information on the likelihood of occurrence of earthquake. In this analysis particular earthquake scenario is assumed which is called as Maximum Credible Earthquake (MCE). MCE is the largest possible earthquake that is capable of taking place on a particular tectonic framework. Structure made as per this analysis is safest but uneconomical, that is why it is applied to only those structure whose failure could lead to catastrophic consequences, such as Nuclear Power Plant and Large Dam.

PSHA is new concept as compared to DSHA. Where it is assumed that all the possible case of earthquake magnitude and distance combination. All the uncertainties are identified, quantified and combined using probability and presented in lucid manner, which can yield complete picture of seismic hazard. Design using PSHA is economical but calculation is time consuming and complex. Due to its economical nature it is used most widely in structural design.

Himalayan region is one of the world's earthquake prone zone. There are several important metro cities like Delhi, Kolkata and various important cities like Ahmedabad, Lucknow, Shimla, Dehradun, Amritsar, Patna, Guwahati etc. are situated in this area. Future earthquake may cause damage and destruction of the cities. Thus, making earthquake resistant design of structure may mitigate the problem. It is important to note that, for making earthquake resistant design of structure in India IS 1893-2016 [78] is generally used where India is divided into four seismic zones. Nevertheless, for precise and accurate earthquake resistant design of important structure site specific hazard analysis is required for any region [79][80][81]. However, for this reason hazard analysis is very much necessary which requires effective GMMs. It is to be mentioned that in recent past several researchers have carried out both DSHA and PSHA of important locations in this area by using various GMMs. In several locations seismic hazard analysis has been conducted like Delhi [15][82][16][13], Haryana [83], Chandigarh [77], Jammu [84][85], Kashmir [86][87][88][89], Dehradun [23], Guwahati [26], Shillong[24], Kolkata [20][90][17][19][91], Shimla [92][93], Ahmedabad [94], Kutch [95], Gujarat [96], Lucknow [97], Kanpur [98], Patna [22][21], Sitamarhi[99], Tripura [100], Imphal[101], Dhaka [102], North-East India [25][103], Sikkim [104][105][106]. These are tabulated in Table 2. It is important to note that several hazard analysis has been performed using the GMMs developed using Indian earthquake records [32][35][28][38][27]. However, many hazard analyses were conducted by utilising the GMMs which were developed for other regions in the world [107][108][109][110][111]. It is important to note that some hazard analysis was conducted by considering several GMMs by providing a suitable weight each of them [13][21][85][89][104].

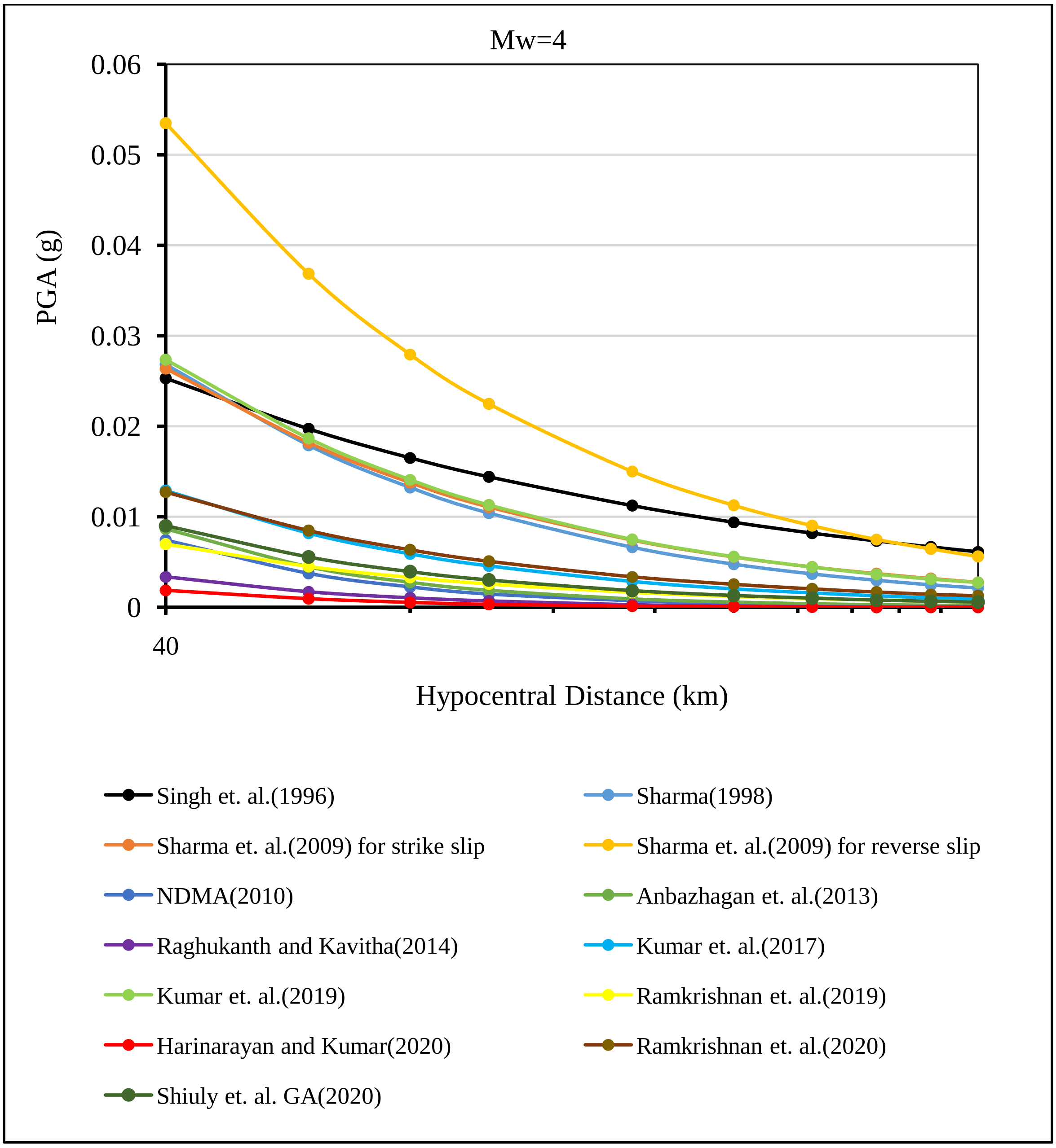
Table No.: - 2 Hazard analysis conducted for different locations in Indo-Himalayan region.

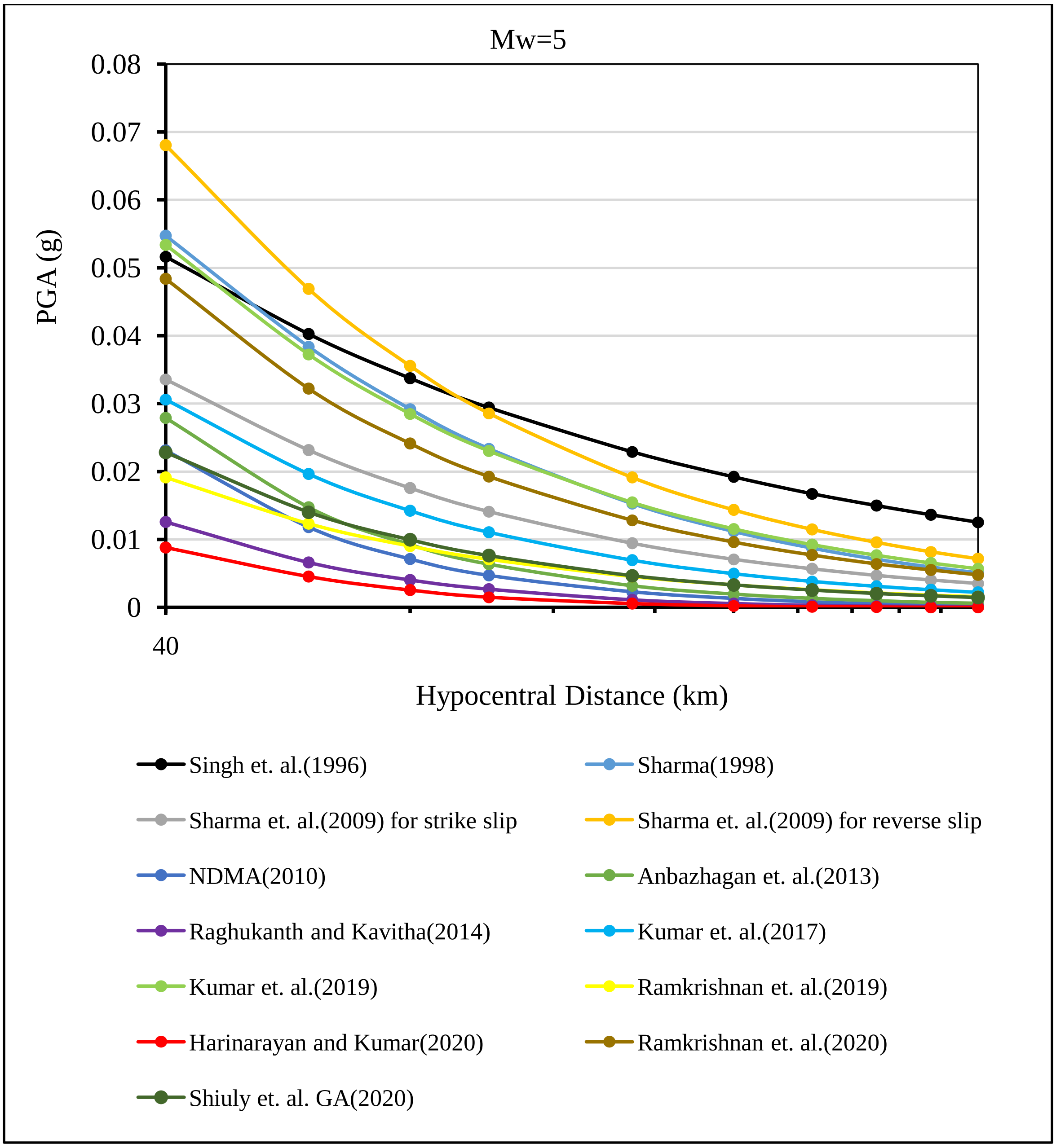
Region	Type of hazard analysis	Author with year	Equation used
Delhi	PSHA	M. L. Sharma, Wason, and Dimri 2003[15]	Abrahamson, Norman A. and Litehiser 1989 [112]
Delhi	PSHA	Iyengar and Ghosh 2004[82]	M. L. Sharma 1998[28]
Delhi	PSHA and DSHA	Kolathayar 2021[13]	Kanno 2006[113] Mukat Lal Sharma et al. 2009[29]Boore and Atkinson 2008[109]Ghasemi et al. 2009[114]S. Akkar and Bommer 2010[107], NDMA 2010[30], P. Anbazhagan, Kumar, and Sitharam 2013[31], Ramkrishnan, Kolathayar, and Sitharam 2021[115], Atkinson and Boore 2006[116] (updated by Sankar Kumar Nath et al. 2019[117]) and Kenneth W. Campbell and Yousef Bozorgnia 2003[118] (updated by Sankar Kumar Nath et al. 2019[117],
Delhi	DSHA	Divakar, Prakash, and Kolathayar 2018[16]	S. Akkar and Bommer 2010[107]
Haryana	PSHA	Puri and Jain 2019[83]	N. A. Abrahamson and Silva 1997[108]
Chandigarh	PSHA	Puri and Jain 2018[77]	N. A. Abrahamson and Silva 1997[108]
Jammu	DSHA and PSHA	Ansari et al. 2022b[84]	NDMA11[119]Raghukanth and Kavitha 2014[32]Idriss 2014[120]Mukat Lal Sharma et al. 2009[29]
Jammu	DSHA	Ansari et al. 2022a[85]	Mukat Lal Sharma et al. 2009[29] NDMA 2011[119], Raghukanth and Kavitha 2014[32]K. S. Rao and Rathod 2014[121]
Kashmir	PSHA	Zahoor et al. 2023[86]	Idriss 2008[122] NDMA 2011[119]Raghukanth and Kavitha 2014[32]
Kashmir	PSHA	Chandra et al. 2018[87]	Kanai 1961[123]
Kashmir	PSHA	Shah et al. 2022[88]	Boore and Atkinson 2008[109]Sinan Akkar and Bommer 2007[124]
Kashmir	PSHA	Sana 2019[89]	Boore and Atkinson 2008[109]Kenneth W. Campbell and Bozorgnia 2008[125] and Mukat Lal Sharma et al. 2009[29]
Dehradun	PSHA	M. L. Sharma and Lindholm 2012[23]	Ambraseys et al. 2005[126], SADIGH et al. 1997[127] and Mukat Lal Sharma et al. 2009[29]
Guwahati	DSHA	Sankar Kumar Nath, Thingbaijam, and Raj 2008[26]	Motazedian 2005[128]
Shillong	PSHA	Baro, Kumar, and Ismail-Zadeh 2020[24]	Baro, Kumar, and Ismail-Zadeh 2020[24]G. R. Toro, Abrahamson, and Schneider 1997[110], NDMA 2010[30]
Kolkata	PSHA	Shiuly, Sahu, and Mandal 2015[20]	Raghukanth 2005[129]
Kolkata	DSHA	Shiuly and Narayan 2012[17]	Litehiser 1989[130]
Kolkata	PSHA	Mohanty and Walling 2008[19]	G. R. Toro, Abrahamson, and Schneider 1997[110]
Shimla	PSHA	Shaligram Patil et al. 2014[92]	Boore and Atkinson 2008[109]
Shimla	PSHA	Muthuganeisan and Raghukanth 2016[93]	Muthuganeisan and Raghukanth 2016[131]
Ahmedabad	DSHA	S. Rao et al. 2012[94]	Iyengar and Kanth 2004[132]Mandal et al. 2009[133]

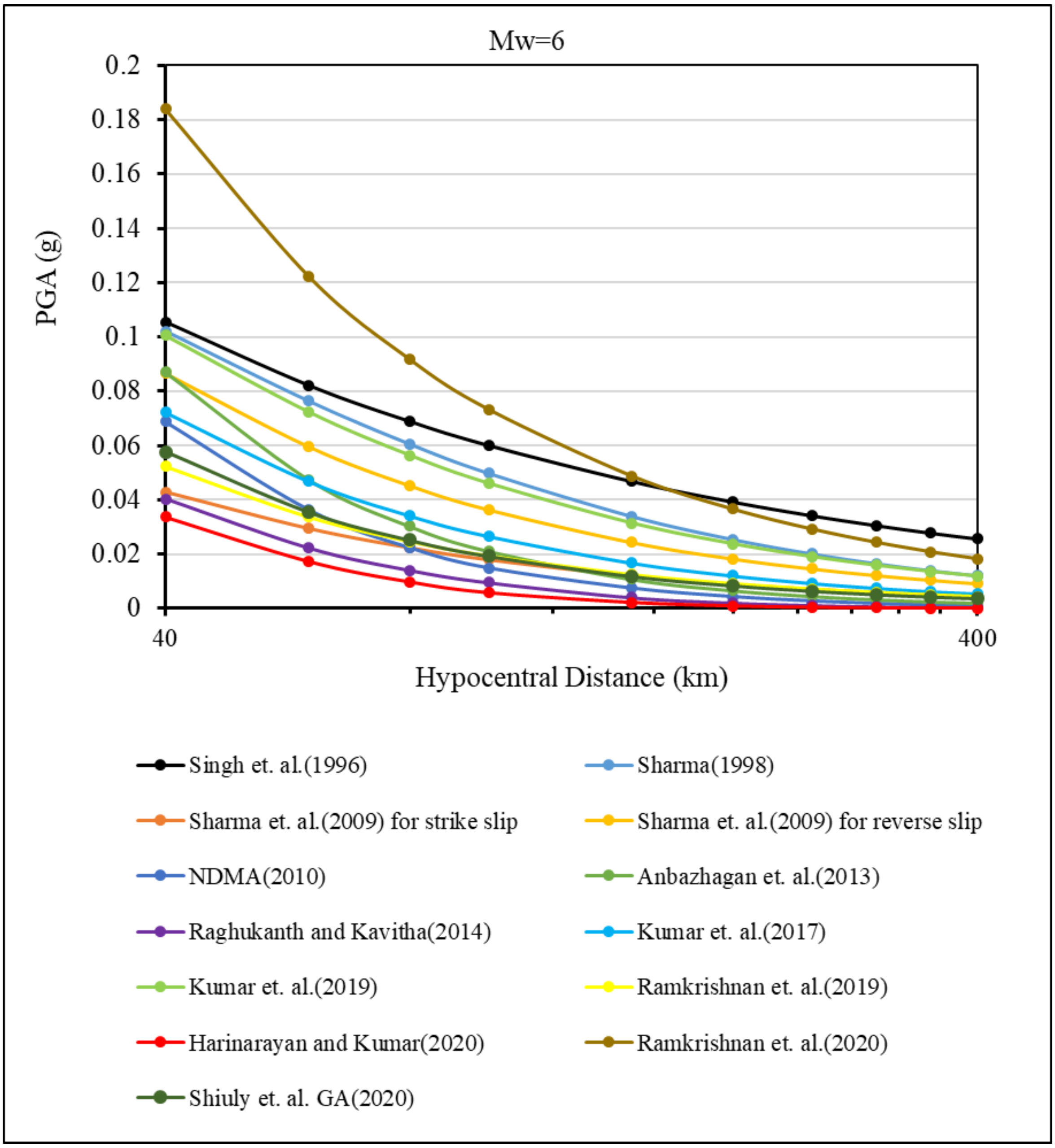
Region	Type of hazard analysis	Author with year	Equation used
Lucknow	PSHA and DSHA	A. Kumar, Anbazhagan, and Sitharam 2013[97]	Kanno 2006[113], NDMA 2010[30], P. Anbazhagan, Kumar, and Sitharam 2013[31]
Patna	PSHA	Panjamani Anbazhagan et al. 2019[22]	P. Anbazhagan, Kumar, and Sitharam 2013[31] National Disaster Management Authority (2010)[30], Kanno 2006[113]Boore and Atkinson 2008[109]
Patna	PSHA and DSHA	P. Anbazhagan, Bajaj, and Patel 2015[21]	Singh, Aman, and Prasad 1996a[70] M. L. Sharma 1998[28] Sankar Kumar Nath et al. 2005[134] S. Das, Gupta, and Gupta 2006[135] Baruah et al. 2009[136] I. D. Gupta 2010[137] P. Anbazhagan, Kumar, and Sitharam 2013[31] P. Anbazhagan et al. 2013[138] Litehiser 1989[130]Youngs et al. 1997[111]K. W. Campbell 1997[139]Spudich et al. 1999[140]Atkinson 2003[141]Ambraseys et al. 2005[126]S. K. Nath et al. 2009[142]Kanno 2006[113]Zhao 2006b[143]Mukat Lal Sharma et al. 2009[29]Idriss 2008[122]Boore and Atkinson 2008[109]Norman A Abrahamson 2007[144]Kenneth W. Campbell and Bozorgnia 2008[125] S. K. Nath et al. 2009[142] S. Akkar and Bommer 2010[107] NDMA 2010[30]
Sitamarhi	PSHA	Paul et al. 2021[99]	Jain et al. 2000[145]Boore et al. 2014[146] Bajaj and Anbazhagan 2019[147]
Tripura	PSHA	Sinha and Selvan 2022[100]	N. Abrahamson and Silva 2008[148]Kanno 2006[113]B.-J. Chiou and Youngs 2008[149]Kenneth W. Campbell and Bozorgnia 2008[125]I. D. Gupta 2010[137]Youngs et al. 1997[111]Atkinson 2003[141]
Imphal	PSHA	Pallav, Raghukanth, and Singh 2012[101]	Boore and Atkinson 2008[109]Atkinson 2003[141]
Dhaka	PSHA	Rahman, Siddiqua, and Kamal 2017[102]	Norman A. Abrahamson, Silva, and Kamai 2014[150]Stewart et al. 2016[151]Kenneth W. Campbell and Bozorgnia 2014[152]B. S.-J. Chiou and Youngs 2014[153]Idriss 2014[120]
N-E India	PSHA	Das, Sharma, and Wason 2016[25]	I. D. Gupta 2010[137] Boore and Atkinson 2008[109]
N-E India	PSHA	Borah and Kumar 2023[103]	NDMA 2010[30] P. Anbazhagan, Kumar, and Sitharam 2013[31]
Sikkim	PSHA	S. Kumar et al. 2022[104]	Atkinson and Boore 2006[154]Zhao 2006a[155]N. Abrahamson and Silva 2008[148]Boore and Atkinson 2008[109]Kenneth W. Campbell and Bozorgnia 2008[125]B.-J. Chiou and Youngs 2008[149]S. Akkar and Bommer 2010[107]
Sikkim	DSHA	Yadav and Kumar 2022[105]	Litehiser 1989[130]
Sikkim	DSHA and PSHA	G. N. S. N. Rao and Satyam 2022[106]	P. Anbazhagan, Kumar, and Sitharam 2013[31]

2.5 PAST GROUND MOTION ATTENUATION RELATIONSHIP FOR HIMALAYAN REGION

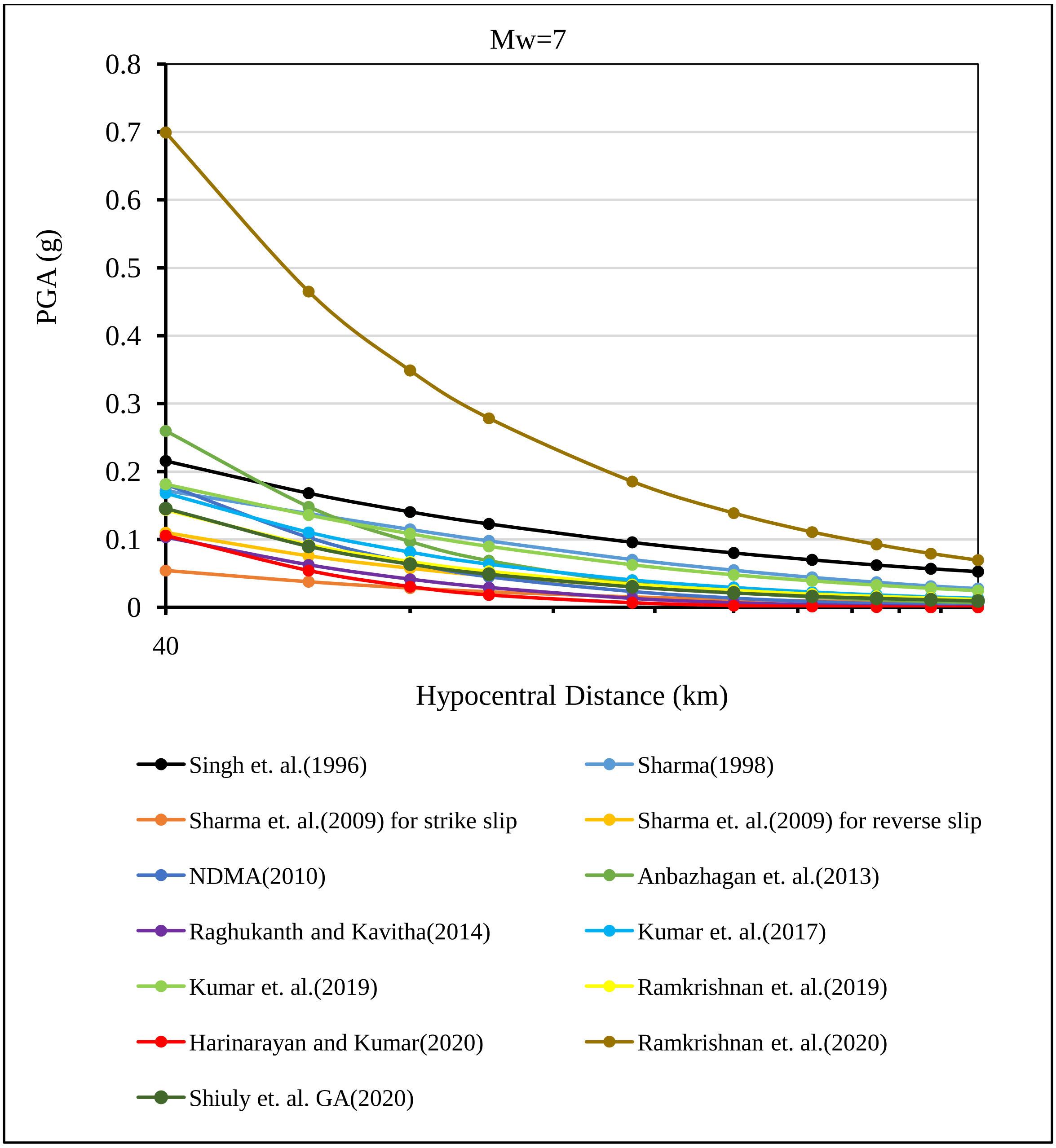
On the basis of past earthquakes records in India Himalayan region, several GMMs have been developed in past. It is to be noted that, though the Himalayan region is one of the seismically active region in the world, but due to lack of recorded earthquake data, the development of GMMs are very much challenging. Singh et al. [70]in 1996 proosed GMM considering 5 earthquakes and 86 number of record. In 1998 Sharma [28]suggested the GMM considering 66 numbers of records from 5 numbers of earthquakes from 1986-1991. Later, Sharma et al.[29]in 2009 proposed GMM for strike slip and reverse fault considering 201 numbers of earthquake records. NDMA [30] also stated GMMs for seismic hazard analysis in 2010. In 2013 Anbazhagan et al. [31]presented GMM considering 14 numbers of earthquake records. Raghukanth and Kavitha [32]also suggested GMM in 2014 considering 236 records from 62 earthquakes. In 2017, Kumar et al. [10] also proposed GMMS on the basis of 218 records from 24 earthquakes. In other study, Kumar et al. [33]in 2019 evaluated GMMs using 116 records of 9 earthquakes. Ramkrishnan et al. [34] suggested GMM in 2019 considering 278 numbers of records of 33 numbers of earthquakes from 1991 to 2016. Further, in 2020 using 2000 numbers of synthetc data Harinarayan and Kumar [36]determined GMM. Ramkrishnan et al. presented [35] GMM using 204 earthqukae records from 24 earthquakes. Shiuly et al. [38]in 2020 suggested attenuation relation using ANN and genetic algorithm.The developed GMMs are presented in Table 3. Most of the GMMs were developed on the basis of multiple regression analysis which yields equations. These equations are very much useful for any researcher for conducting both DSHA and PSHA. Only Shiuly et al. proposed attenuation relation on the basis of artificial intelligence, which is very difficult to use by other researchers. It is important to note that almost in all the GMMs predict PGA using distance and magnitude. However, they are silent about effect of fault mechanism (except [29][36]). Further, almost all the GMMs predict PGA. However, Sharma 2009 [29] proposed the GMMs which yields spectral accelerations and depends on fault condition. In addition to that Anbazhagan et al. 2013 [31], Raghukanth and Kavitha 2014 [32], Harinarayan and Kumar 2020 [36] proposed GMMs which predict spectral acceleration values at different time periods. Further, as soil plays as important role in ground motion, thus, all the GMMs were proposed for the rock site. These equations are helpful to carry out seismic hazard analysis of any place of Indio-Himalayan region. In the present study total 13 numbers of GMMs are studied thoroughly and are plotted for different magnitude which are presented in Fig. 2. Table 3 provides a comprehensive summary of all available models, along with their respective information and limitations.




Mw=5
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
PGA (g)
40
Hypocentral Distance (km)
Singh et. al.(1996)
Sharma(1998)
Sharma et. al.(2009) for strike slip
Sharma et. al.(2009) for reverse slip
NDMA(2010)
Anbazhagan et. al.(2013)
Raghukanth and Kavitha(2014)
Kumar et. al.(2017)
Kumar et. al.(2019)
Ramkrishnan et. al.(2019)
Harinarayan and Kumar(2020)
Ramkrishnan et. al.(2020)
Shiuly et. al. GA(2020)



Mw=6
PGA (g)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
40
400
Hypocentral Distance (km)
Singh et. al.(1996)
Sharma(1998)
Sharma et. al.(2009) for strike slip
Sharma et. al.(2009) for reverse slip
NDMA(2010)
Anbazhagan et. al.(2013)
Raghukanth and Kavitha(2014)
Kumar et. al.(2017)
Kumar et. al.(2019)
Ramkrishnan et. al.(2019)
Harinarayan and Kumar(2020)
Ramkrishnan et. al.(2020)
Shiuly et. al. GA(2020)


Mw=7
PGA (g)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
40
Hypocentral Distance (km)
Singh et. al.(1996)
Sharma(1998)
Sharma et. al.(2009) for strike slip
Sharma et. al.(2009) for reverse slip
NDMA(2010)
Anbazhagan et. al.(2013)
Raghukanth and Kavitha(2014)
Kumar et. al.(2017)
Kumar et. al.(2019)
Ramkrishnan et. al.(2019)
Harinarayan and Kumar(2020)
Ramkrishnan et. al.(2020)
Shiuly et. al. GA(2020)

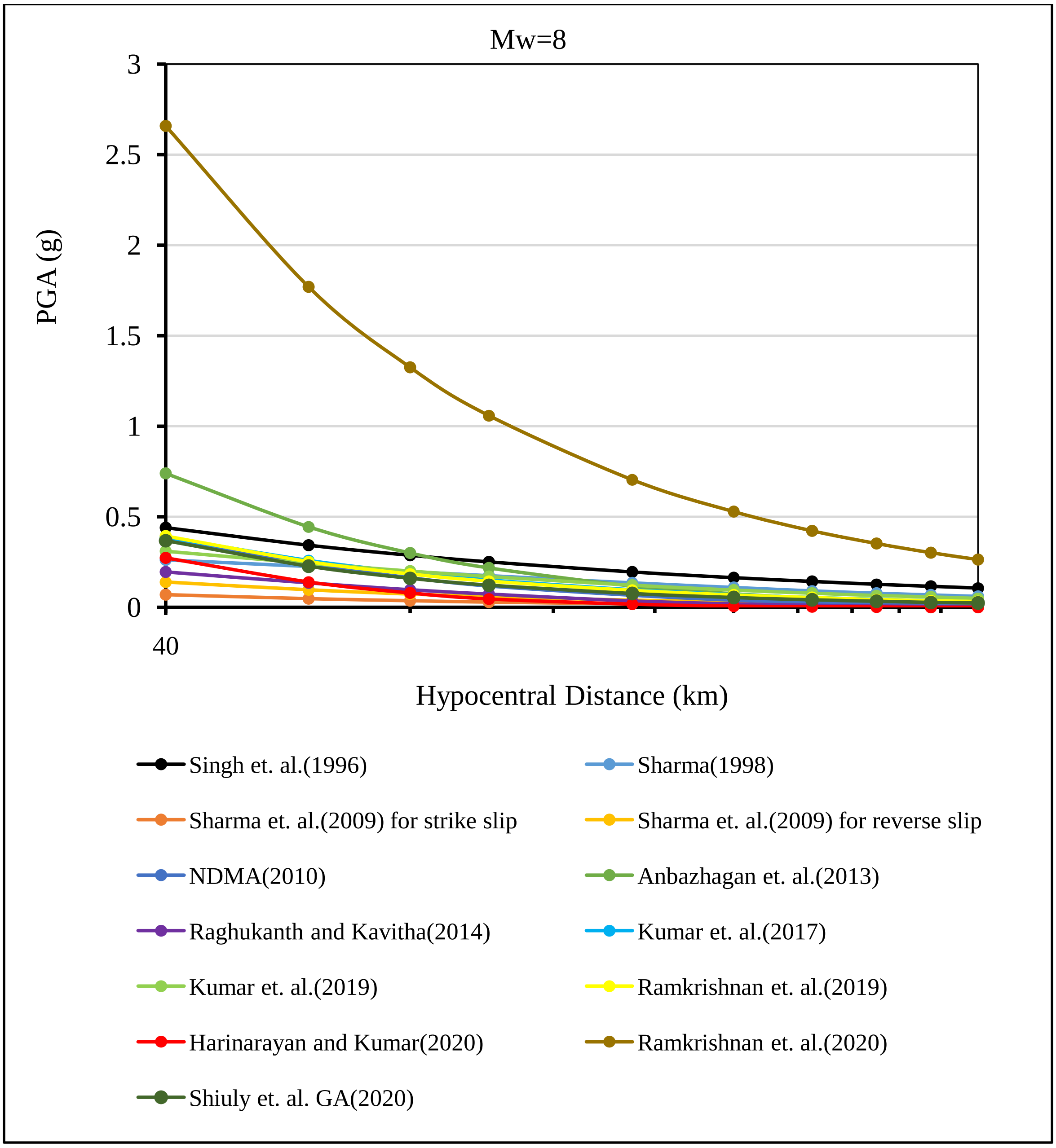


Fig. 2GMM for PGA at different magnitudes.

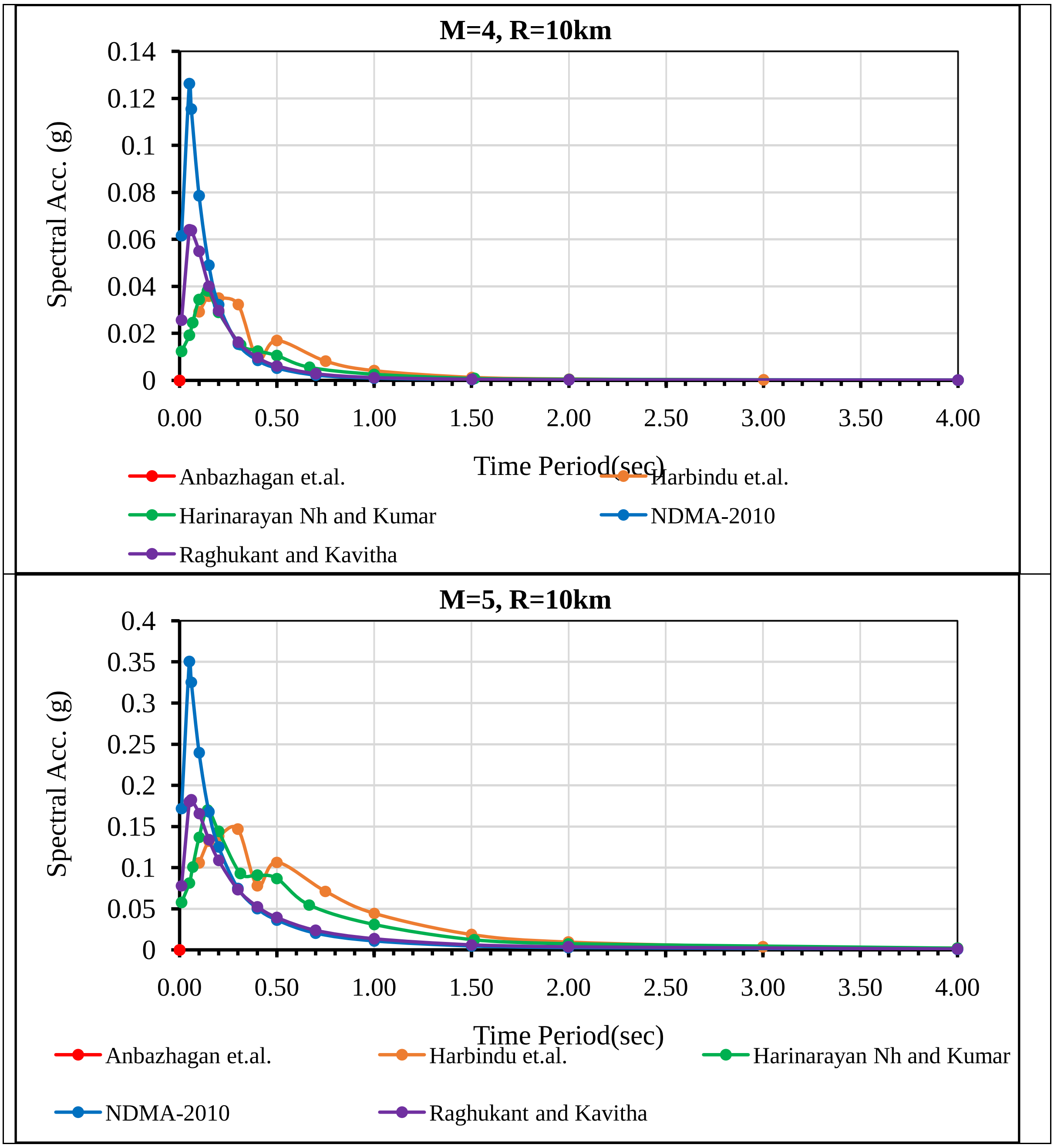
Table No.: - 3 Different ground motion attenuation relationship developed in Indo-Himalayan region.

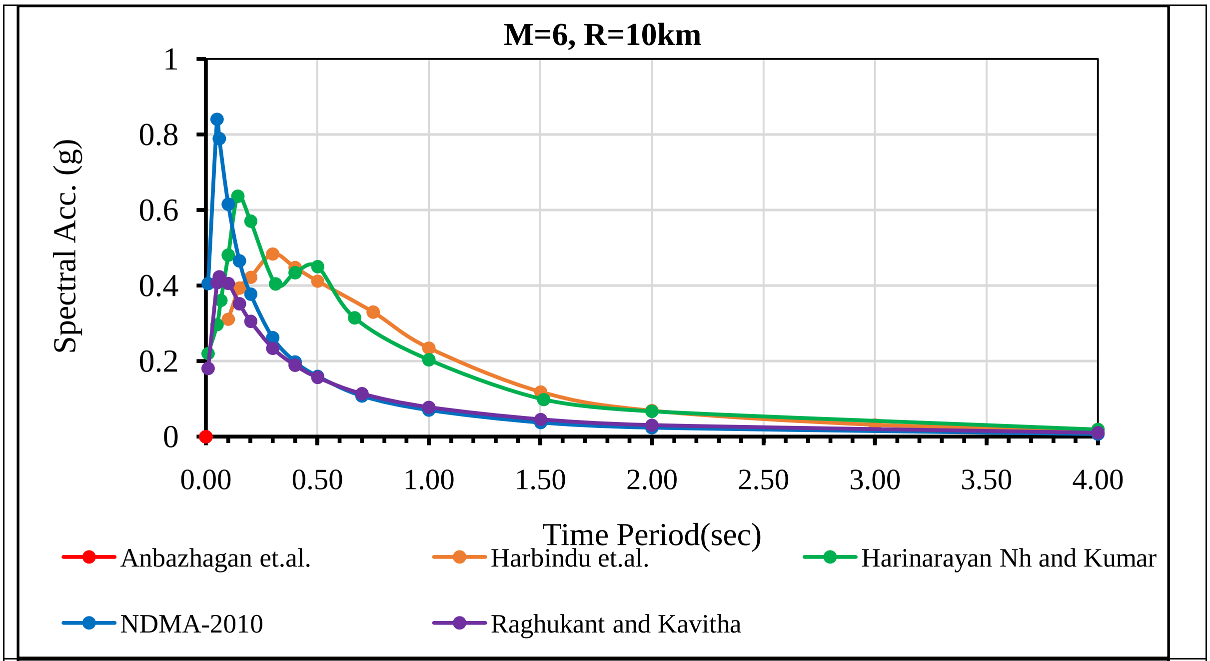
Serial Number	**Author**	**Earthquake consider from year**	**Earthquake consider to year**	**Number of earthquake**	**Number of earthquake records**	**Equation proposed**	**Method used**	**Standard error**	**Summary details**
1	**Singh, Aman, and Prasad 1996a**[70]	1986	1988	5	86	$\log(a\ in\ \frac{cm}{s^2}) = 1.14 + 0.31M - 0.615\log R$ $\log(v\ in\ \frac{cm}{s}) = 0.571 + 0.41M - 0.768\log R$	regression	0.066	Strong motion data from 5 earthquakes (Dharamsala earthquake 1986 (M= 5.7), Meghalaya earthquake 1986 (M= 5.7), Burma-India earthquake 1987(M= 5.7). Tripura-Assam earthquake 1988 (M=5.8), Guwahati earthquake 1988(M= 7.2)) of different region of India has been used
2	**M. L. Sharma 1998**[28]	1986	1991	5	66	$\log A = -1.072 + 0.3903M - 1.21\log(X + e^{0.5873M})$	regression	0.14	Analysed five earthquake records. Two-step stratified regression approach
3	**Mukat Lal Sharma et al. 2009**[29]	1984	2006	16	201	$\log A = 1.0170 + 0.1046M - 1.007\log(\sqrt{R^2 + 15^2}) - 0.0735 - 0.3068$ (for strike slip)	regression	0.0409	16 earthquakes were considered. Indian region, Zargos region of Iran's data of 16 earthquake records Proposed different coefficients for predicting spectral acceleration at different time period

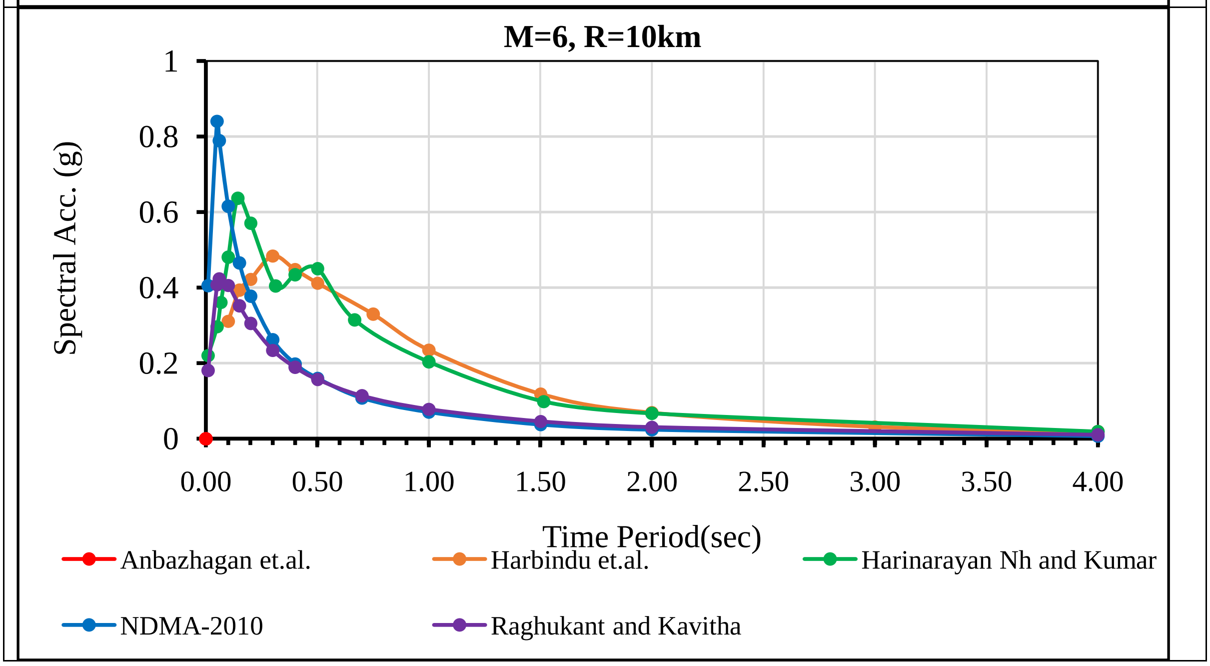
						$\log A = 1.0170 + 0.1046M - 1.007\log(\sqrt{R^2 + 15^2}) -$ 0.0735 (for reverse mechanism)			
4	**NDMA 2010**[30]					$\log\left(\frac{S_a}{g}\right) = -3.7438 + 1.0892M + 0.0098M^2 - 0.0046R - 1.4817\ln(R + 0.0124e^{0.995M} + 0.1249(\log R)f_0$ $f_0 = \max(\ln\left(\frac{R}{100}\right), 0)$	Two-step stratified regression	0.4094	coefficients of the equation for predicting spectral accelerations at different time period were proposed using the simulated database of 80,000
5	**P. Anbazhagan, Kumar, and Sitharam 2013**[31]	1897	2007	14		$\log(S_a/g) = -1.283 + 0.544M - 1.792\log(R + e^{0.381M})$	regression	0.283	used recorded as well as simulated data for evaluating GMM by finite fault simulation mechanism simulated data were compared with the recorded one. Different coefficient for the developed equation were proposed for predicting spectral acceleration at different time period.
6	**Raghukanth and Kavitha 2014** [32]	2005	2012	62	236	$\log(S_a/g) = -6.0157 + 1.6199M - 0.0244M^2 - 0.0045R - \ln(R + 0.0588e^{0.8588M} + 0.0943(\log R)f_0$ $f_0 = \max(\ln\left(\frac{R}{100}\right), 0)$	regression	0.3843	on the basis of 80000 simulated data considering the stochastic finite fault simulation model of region specific seismo-tectonic parameters from the past earthquake simulation method for Andaman region, Indo-Gangetic region, Indo-Burmese region and the Himalayan region
7	**Harbindu et al. (2014)**					$\log PSA = C_1 + C_2(M-6) + +C_3(M-6)^2 - \log(R) - C_4R)$	regression	0.0784	Simulated data on the basis of 1991 Uttarkashi earthquake (M_w=6.8) and 1999 Chamoli earthquake (M_w=6.4) For Garhwal Himalaya region Magnitude 3.5 to 6.8

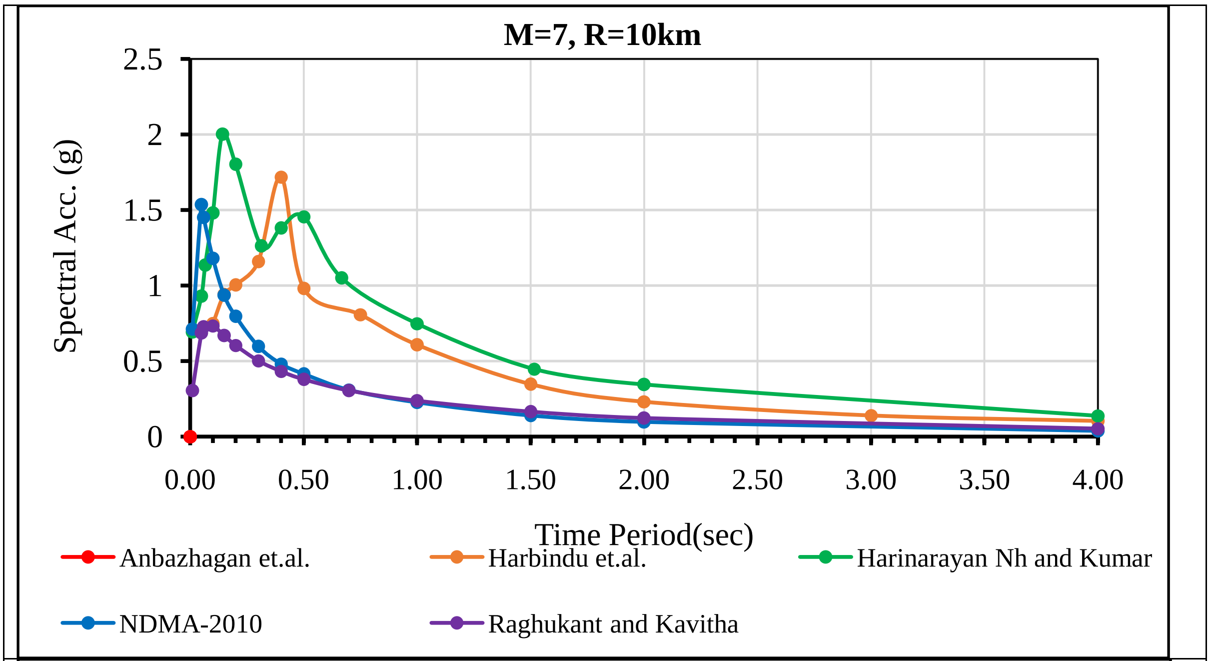
									Distance 10 to 250km
8	**Kumar et al. 2017**[10]	1986	2011	24	218	$\log A = -1.497 + 0.3882M - 1.19\log(R + e^{0.2876M})$	regression	0.1451	strong data from from 24 earthquakes two-step stratified regression model developed for North-Eastern Himalayan region
9	**P. Kumar et al. 2019**[33]	1991	2017	9	116	$\log A = -1.091 + 0.3245M - 1.0632\log(R + e^{0.4561M})$	regression	0.281	using data set of 116 records from 9 earthquakes with magnitude from 5 to 6.8 from UP arrays of National Strong Motion Instrumentation Network and Earthquake Early Warning System of India
10	**Ramkrishnan, Sreevalsa, and Sitharam 2019**[34]	1991	2016	33	278	$\log A = -2.135 + 0.437M - 1.099\log(R + e^{-0.080M})$	Multiple regression	0.549	for the North and Central Himalayas using recorded strong motion data magnitude ranging 4.1 to 7.8 for North and Central Himalayas hypocentral distance upto 1580km
11	**Harinarayan and Kumar 2020**[36]	1991	2015	15	20000	$\log\left(\frac{S_a}{g}\right) = -10.9 + 2.44M + 0.0996M^2 - 0.0178R - 0.768\ln(R - 0.000000118e^{-M}) + 0.102\,(\ln R)\,f_0$ $f_0 = \max(\ln\left(\frac{R}{100}\right), 0)$	regression using Synthetic ground motion data	0.323	for magnitude range of 3.5 to 7.8 using synthetic ground motion for different site class
12	**Ramkrishnan, Sreevalsa, and Sitharam 2020**[35]	1986	2013	24	204	$\log A = -2.607 + 0.580M - 1.004\log(R + e^{-1.332M})$	Non-linear regression models	0477	for the North and Central Himalayas using recorded strong motion data magnitude ranging 4.1 to 7.8 for North and Central Himalayas
13	**Shiuly, Roy, and Sahu 2020**[38]	1986	2013	25	147	$A = [\cos((R * M) + M) + \tan^{-1}(M) * M^2] + [M + ((5.644959 - \cos(M))^{0.5}]^2 + [\frac{M}{\left(\frac{5.700379}{2M}\right) + R + 5.700379}]$	Genetic algorithm		using Artificial Neural Network (ANN) and Genetic Algorithm(GA) for the Himalayan region

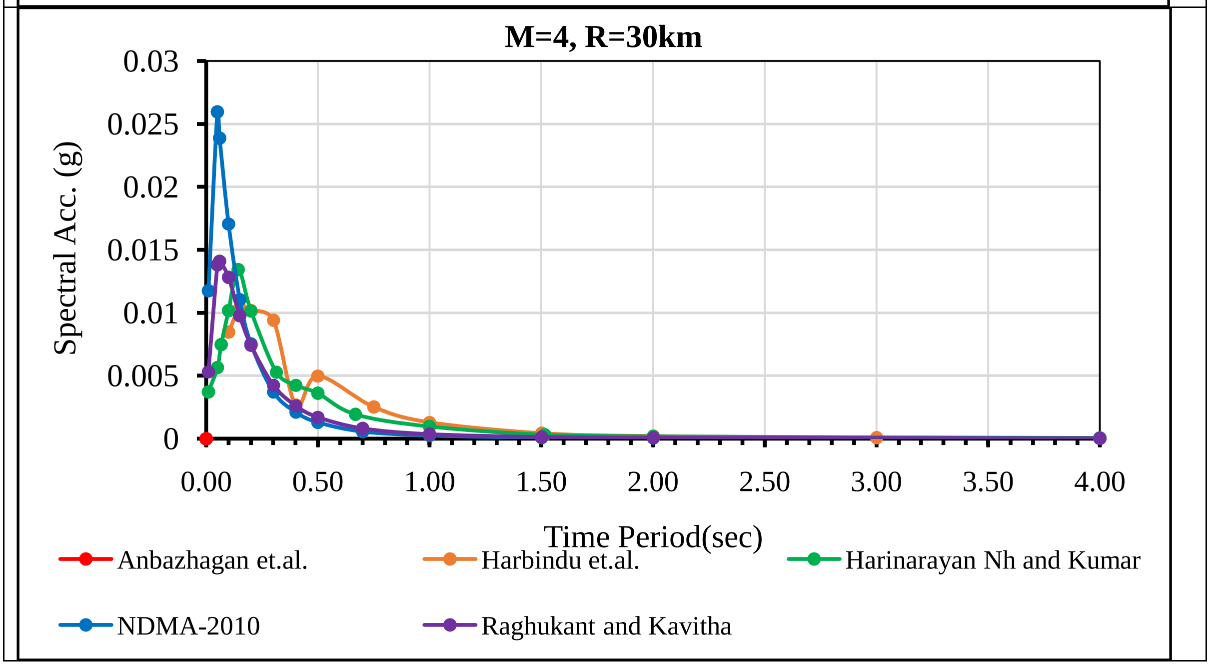
Among these GMMs, only NDMA [30], Anbazhagan et. al. [31], Raghukanth and Kavita in 2014 [32], Harinarayan and Kumar [36], Harbindu et al. [42] and NDMA have formulated GMM to predict spectral acceleration for various time periods at different distance and magnitude. The plot of spectral ordinates at different time period are presented in Fig. 3.

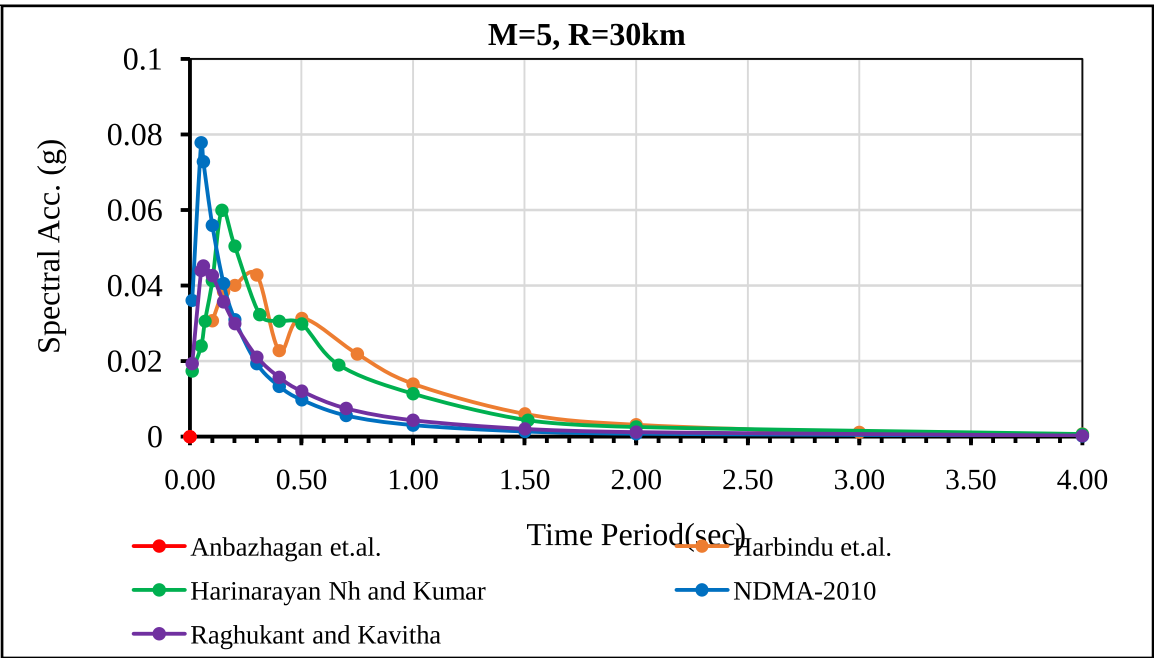


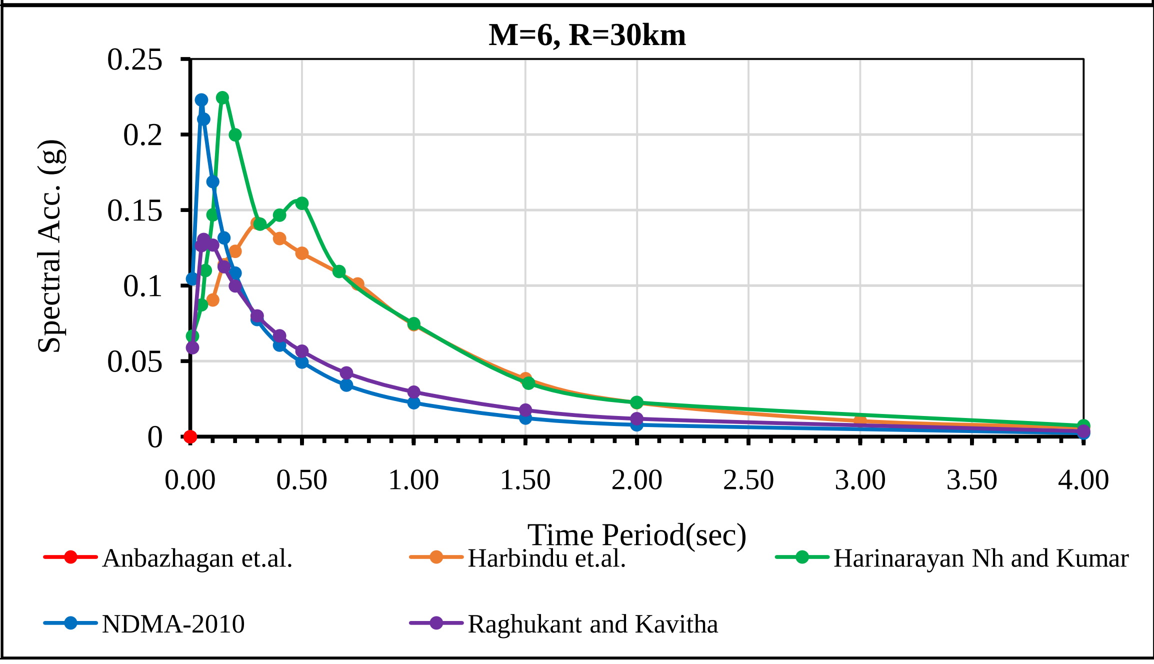

M=6, R=10km
Spectral Acc. (g)
1
0.8
0.6
0.4
0.2
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

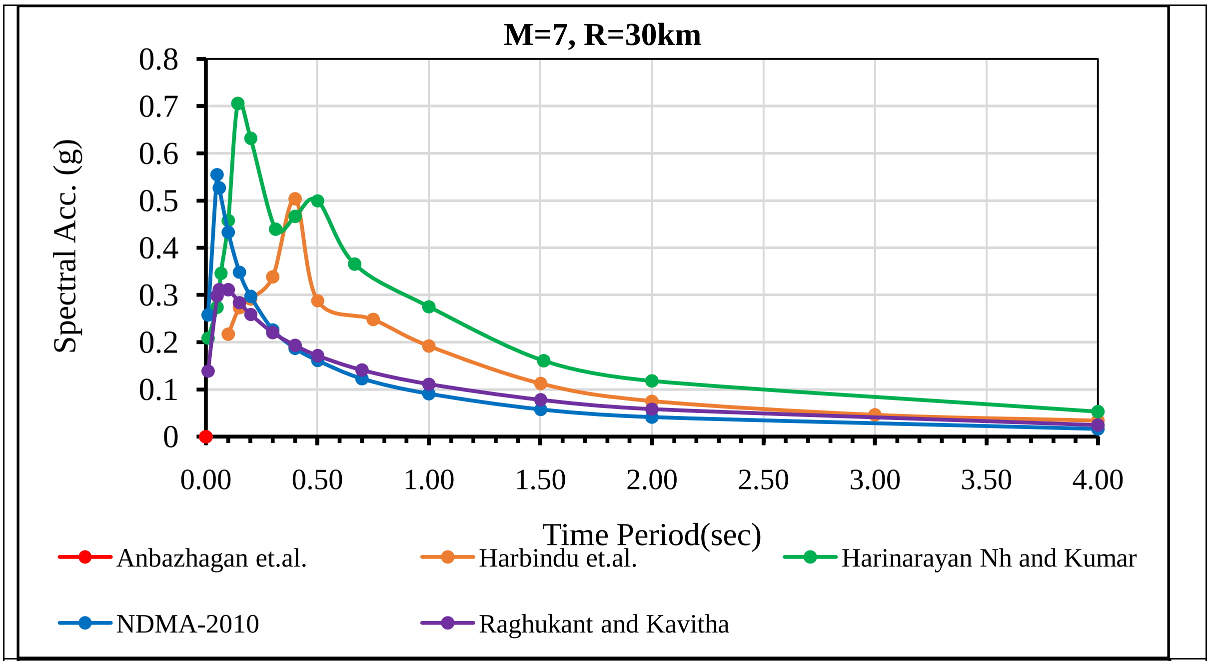

M=6, R=10km
Spectral Acc. (g)
1
0.8
0.6
0.4
0.2
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha


M=7, R=10km
Spectral Acc. (g)
2.5
2
1.5
1
0.5
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

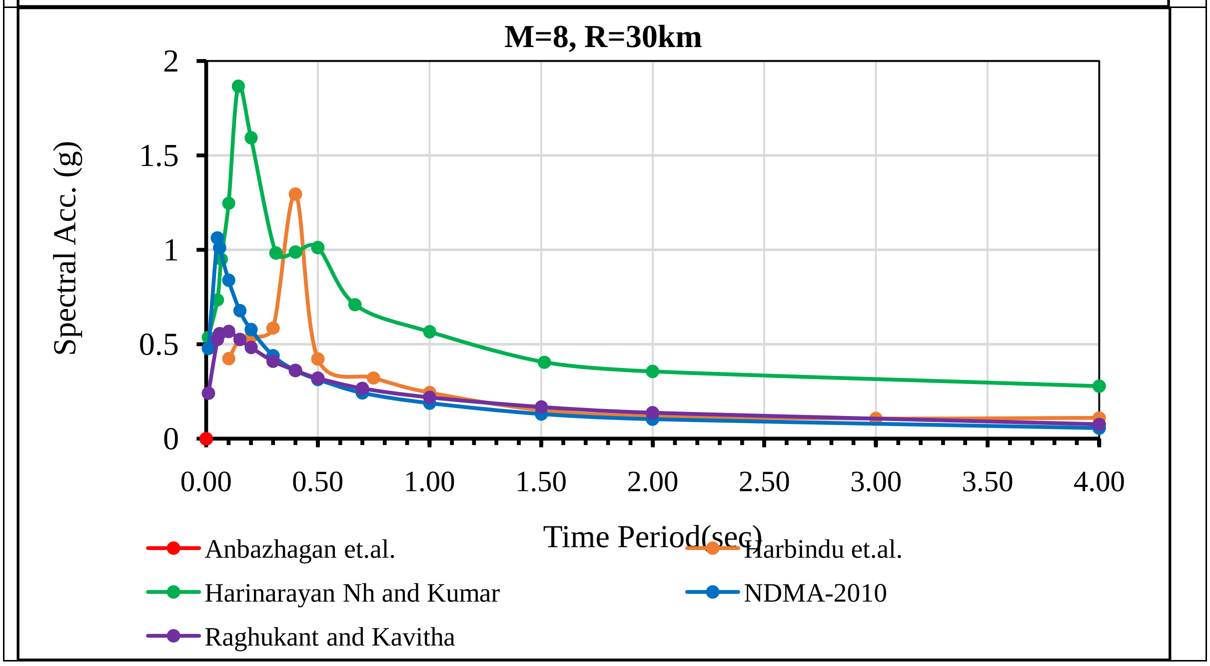

M=4, R=30km
Spectral Acc. (g)
0.03
0.025
0.02
0.015
0.01
0.005
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha


M=5, R=30km
Spectral Acc. (g)
0.1
0.08
0.06
0.04
0.02
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

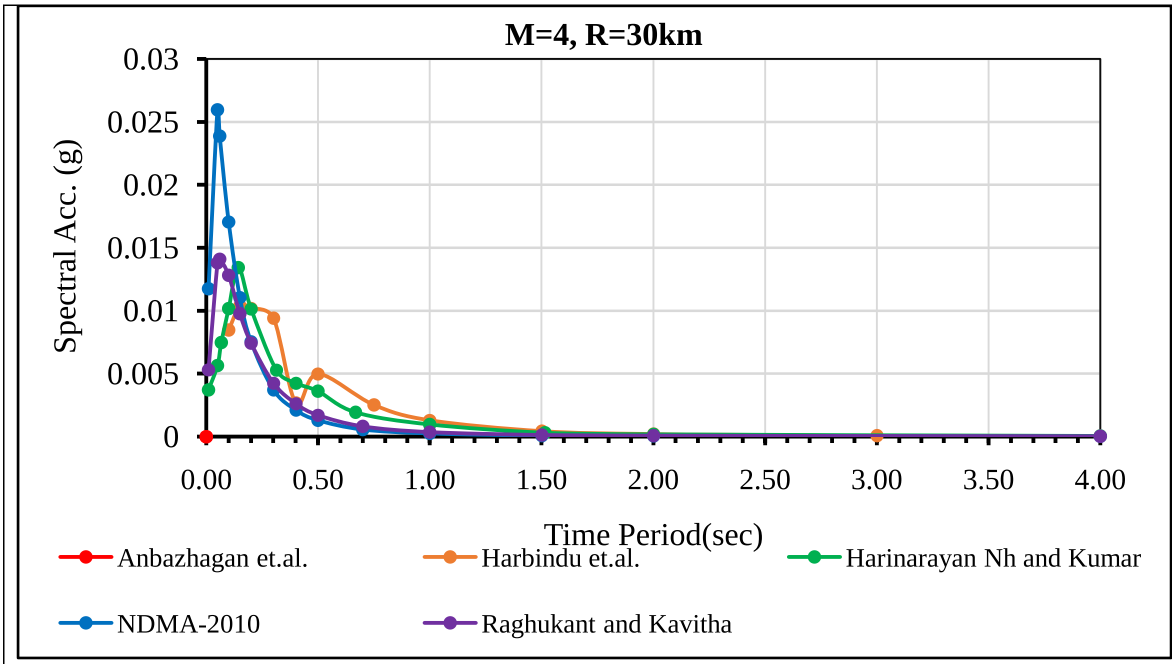

M=6, R=30km
Spectral Acc. (g)
0.25
0.2
0.15
0.1
0.05
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

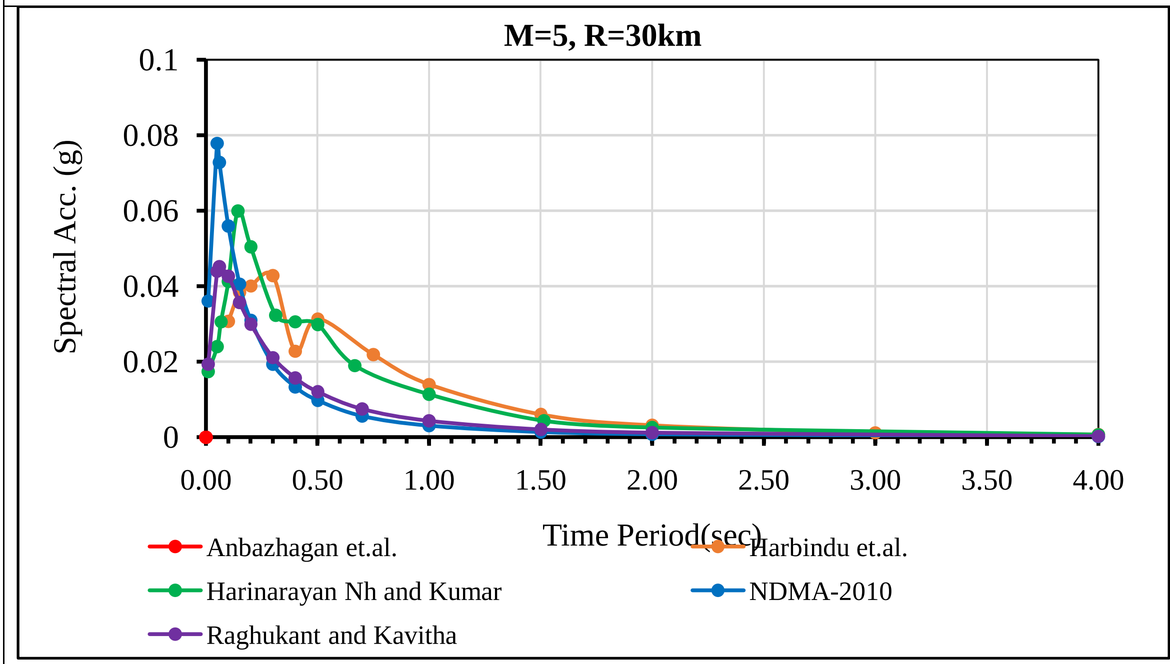


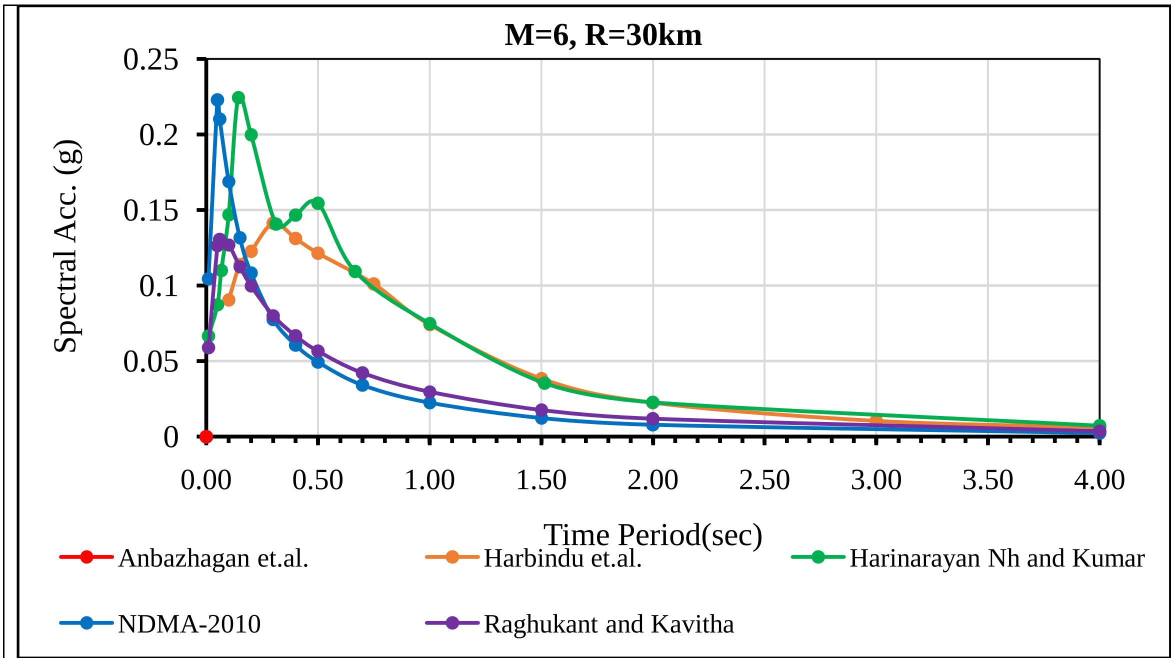
M=7, R=30km
Spectral Acc. (g)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha



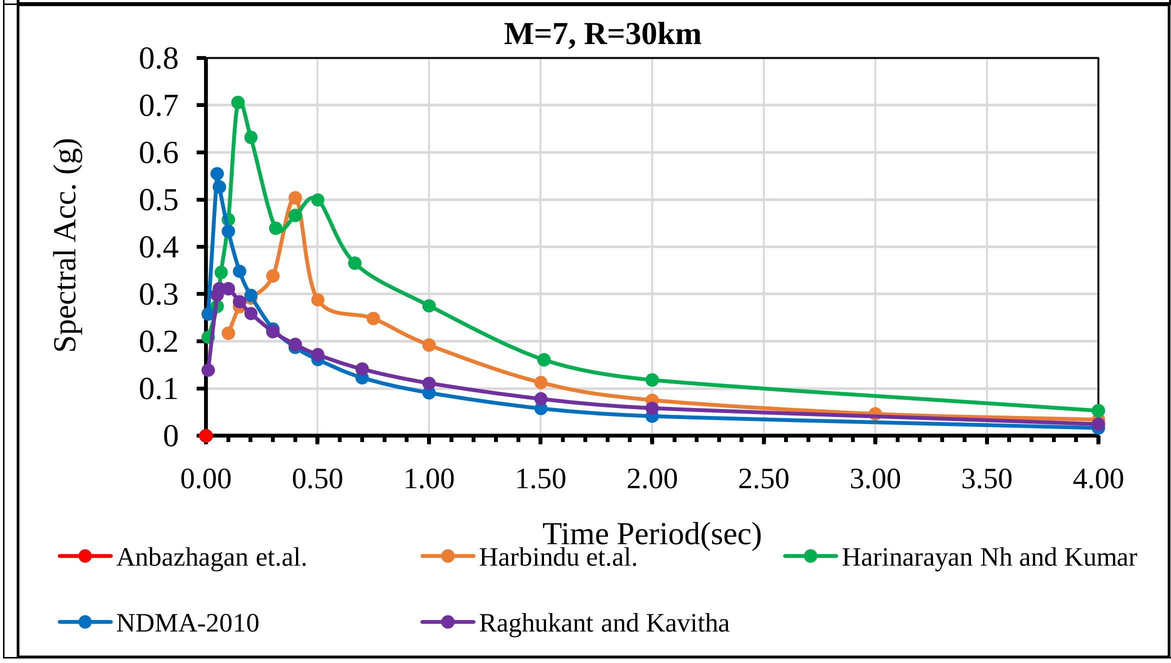
M=8, R=30km
Spectral Acc. (g)
2
1.5
1
0.5
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha


M=4, R=30km
Spectral Acc. (g)
0.03
0.025
0.02
0.015
0.01
0.005
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

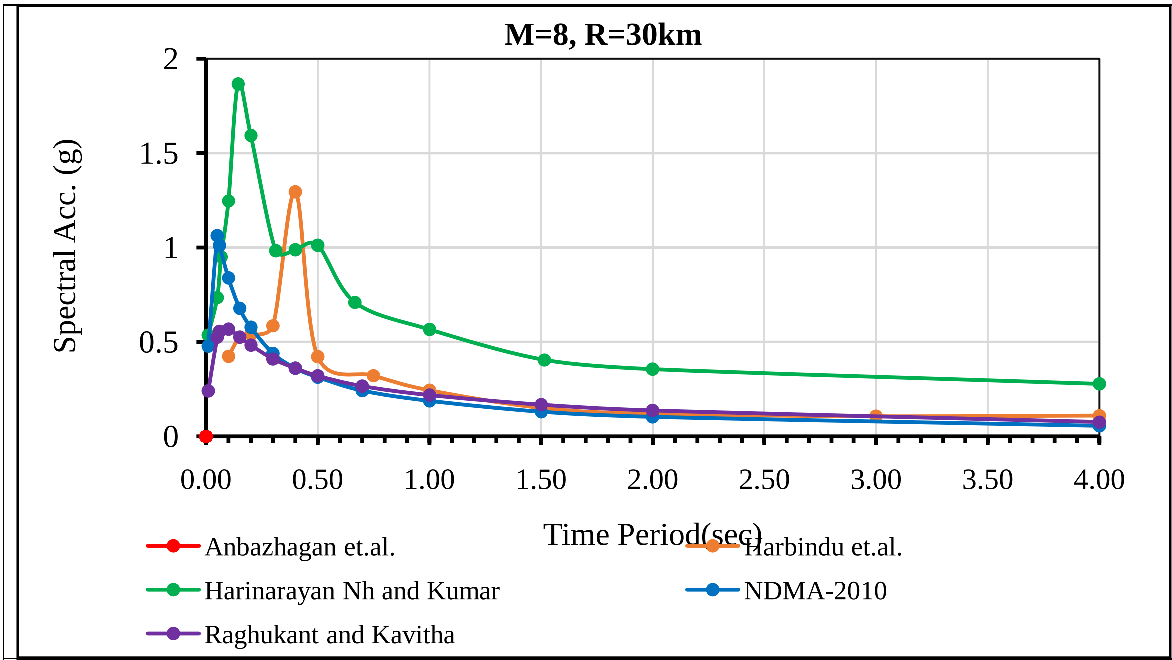

M=5, R=30km
Spectral Acc. (g)
0.1
0.08
0.06
0.04
0.02
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

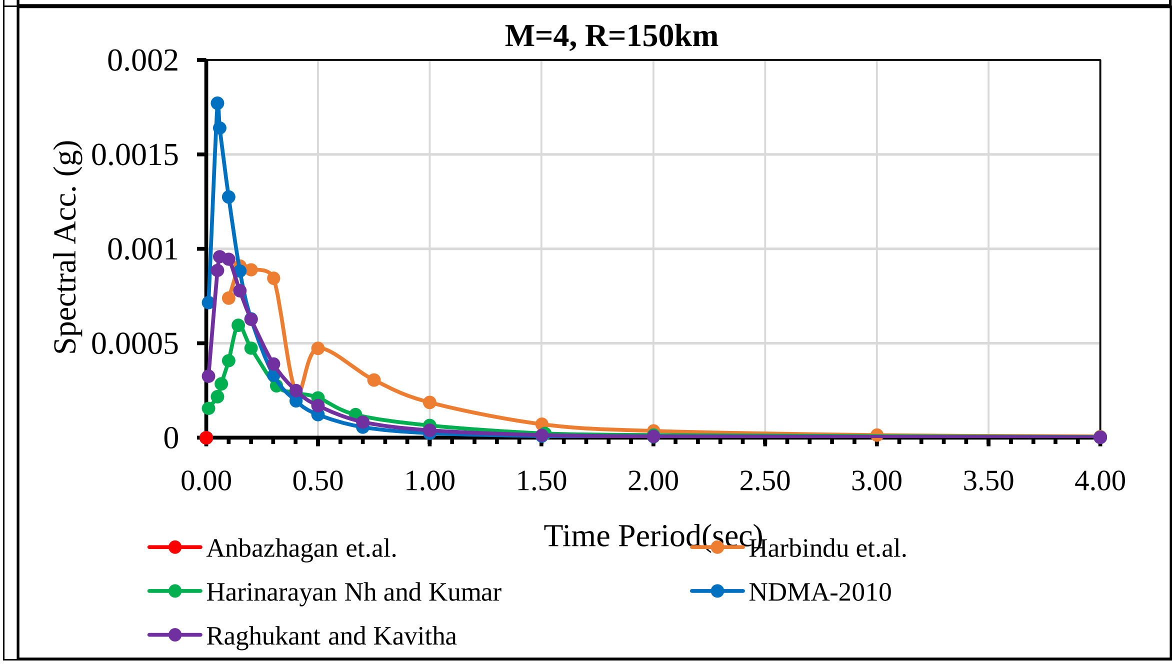


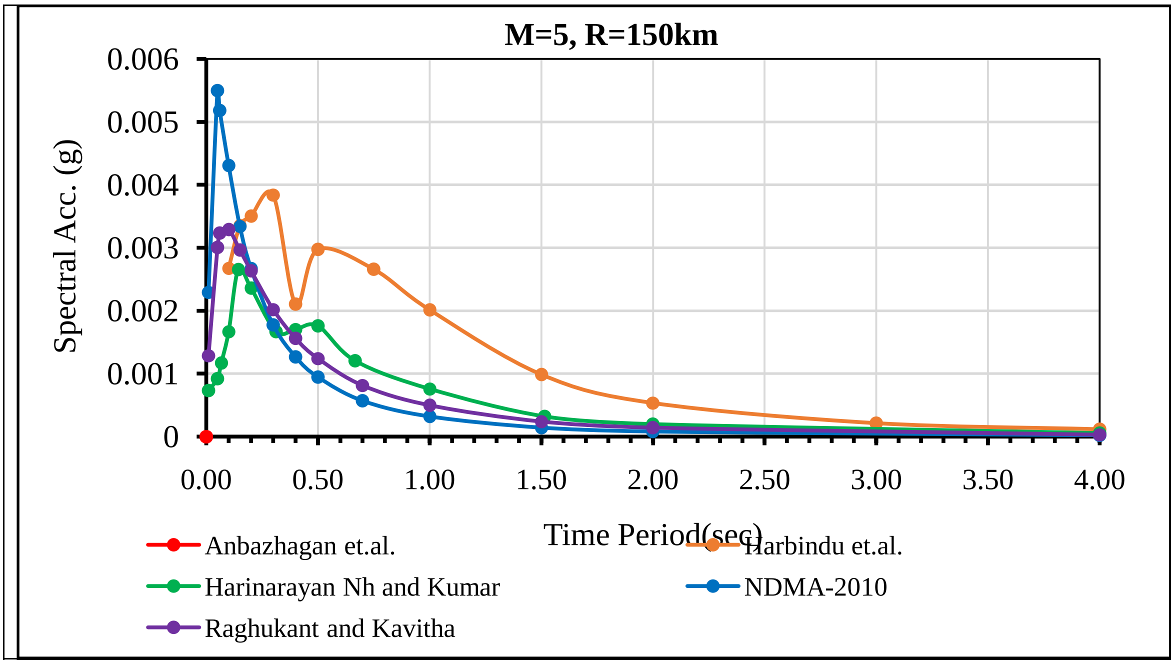
M=6, R=30km
Spectral Acc. (g)
0.25
0.2
0.15
0.1
0.05
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

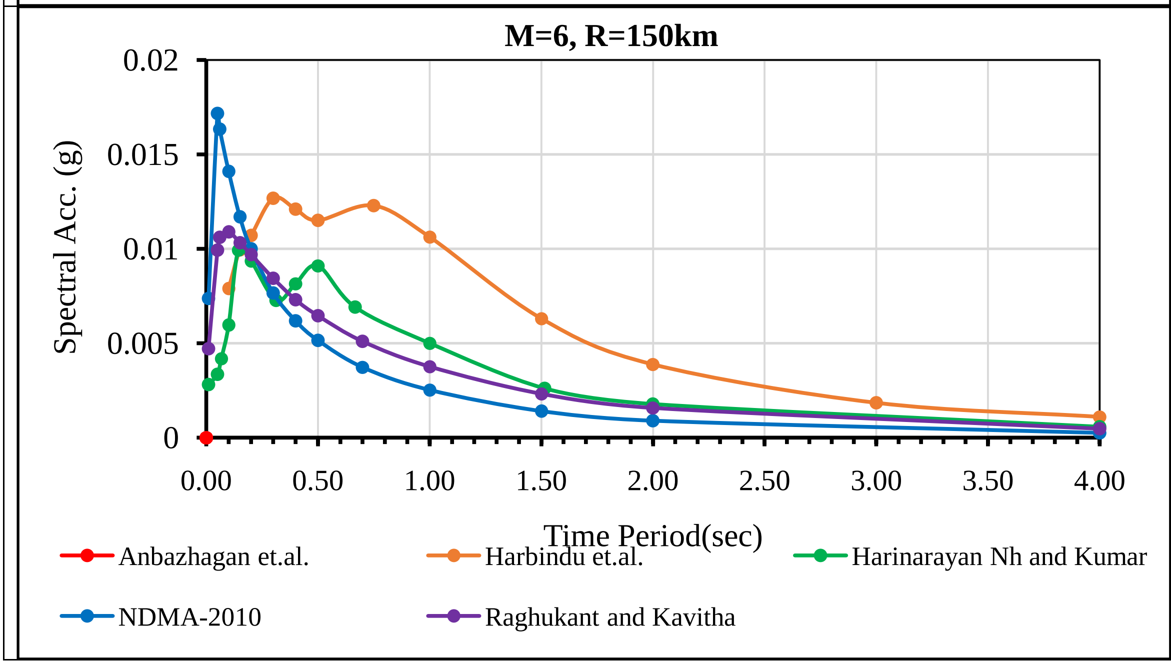


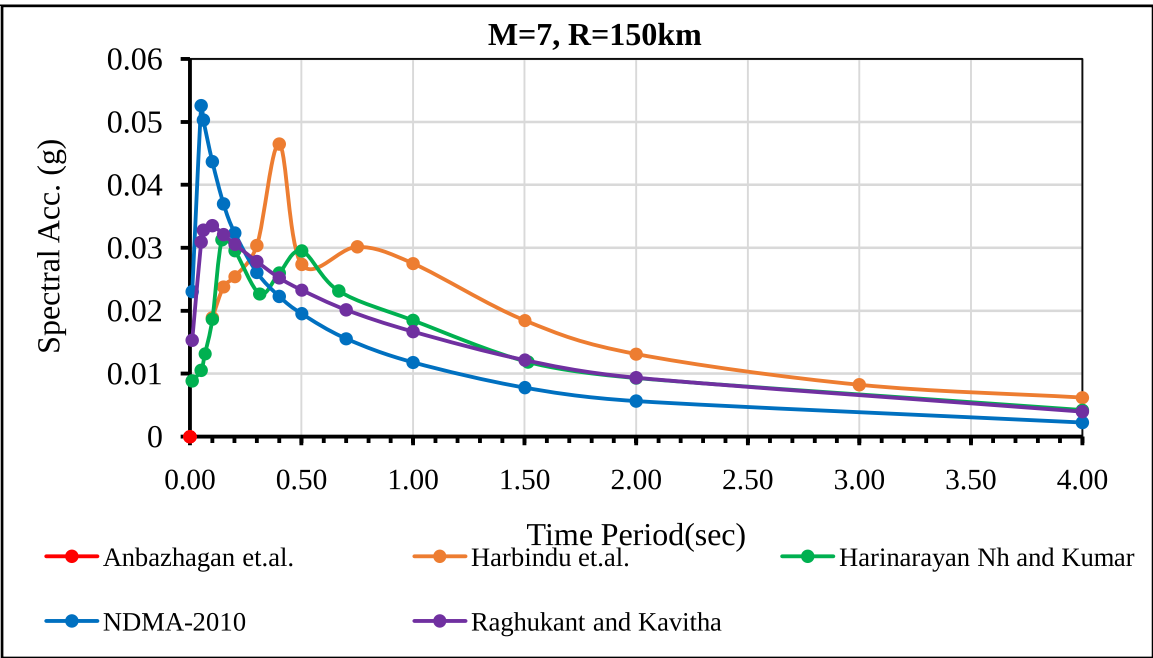
M=7, R=30km
Spectral Acc. (g)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

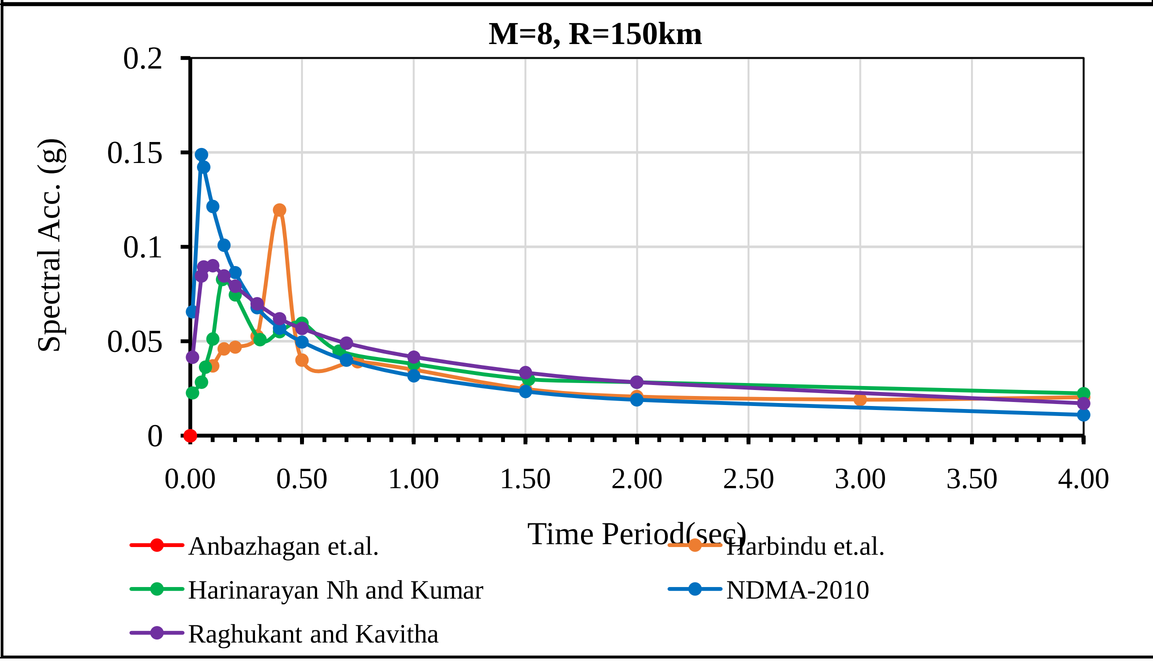

M=8, R=30km
Spectral Acc. (g)
2
1.5
1
0.5
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

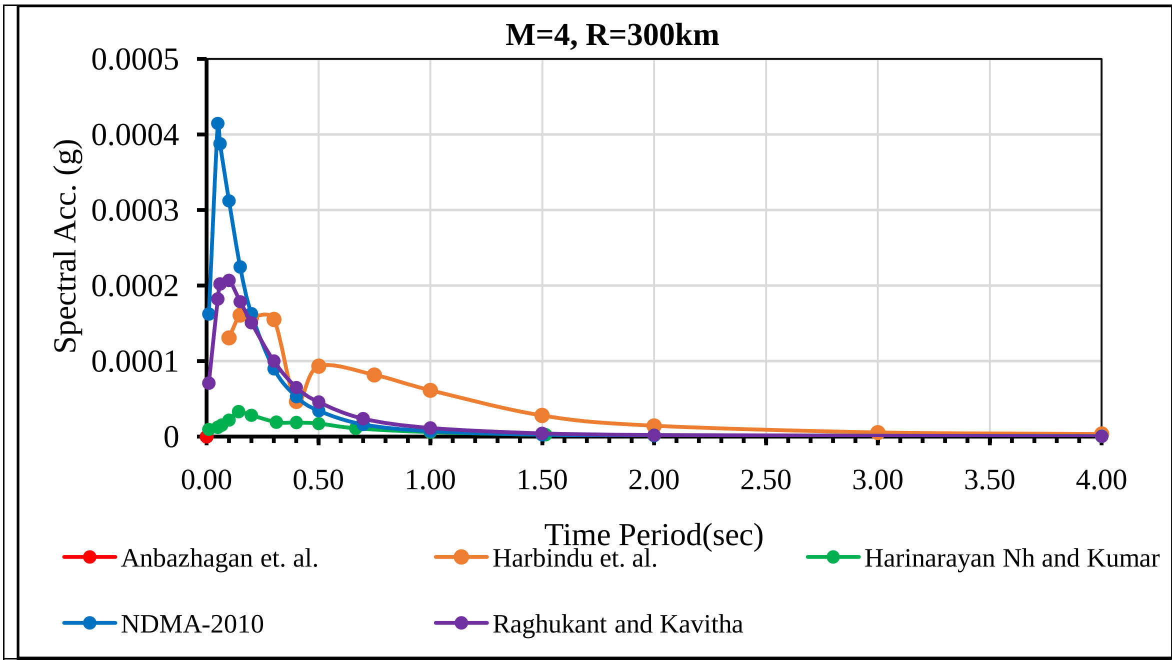

M=4, R=150km
Spectral Acc. (g)
0.002
0.0015
0.001
0.0005
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

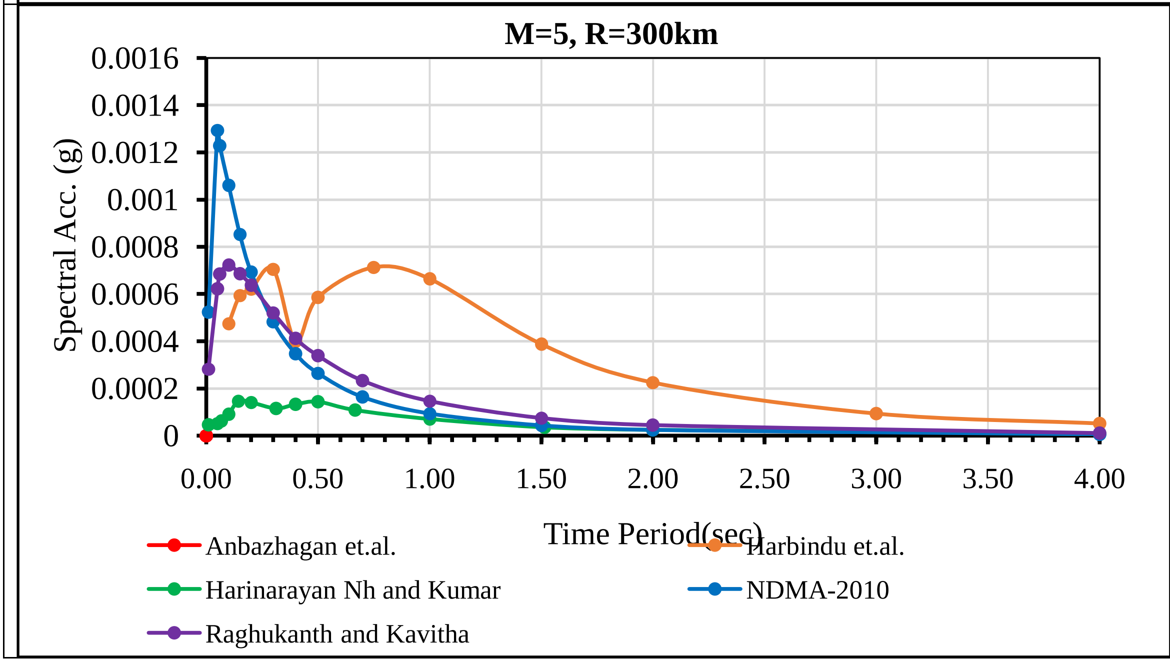

M=5, R=150km
Spectral Acc. (g)
0.006
0.005
0.004
0.003
0.002
0.001
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

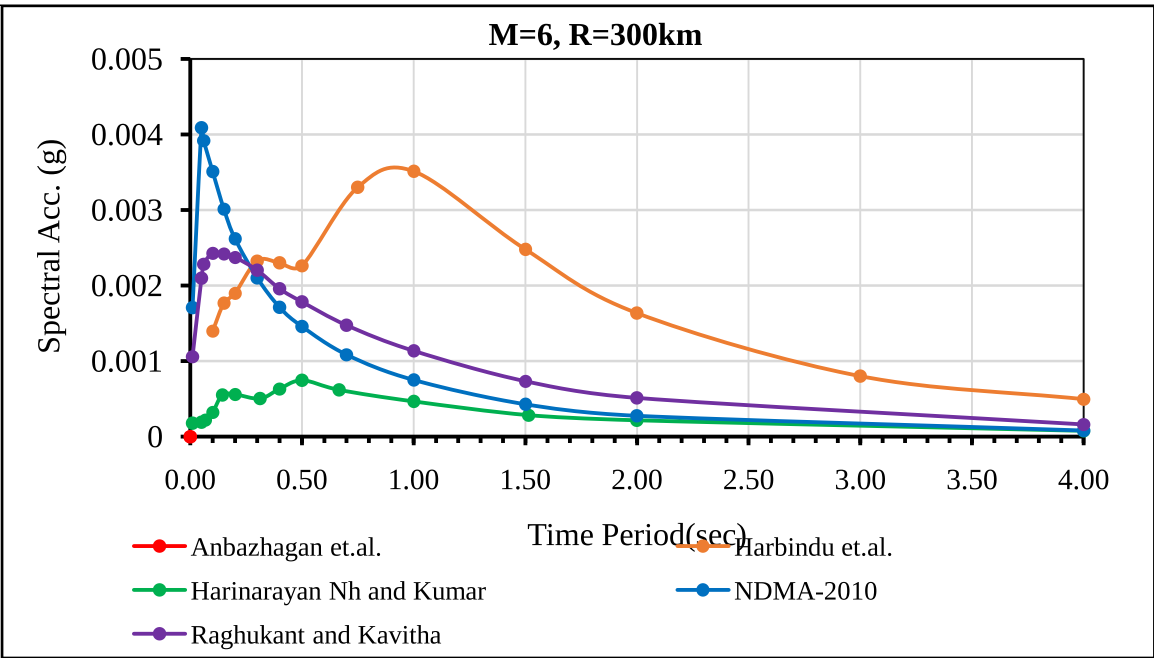

M=6, R=150km
Spectral Acc. (g)
0.02
0.015
0.01
0.005
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

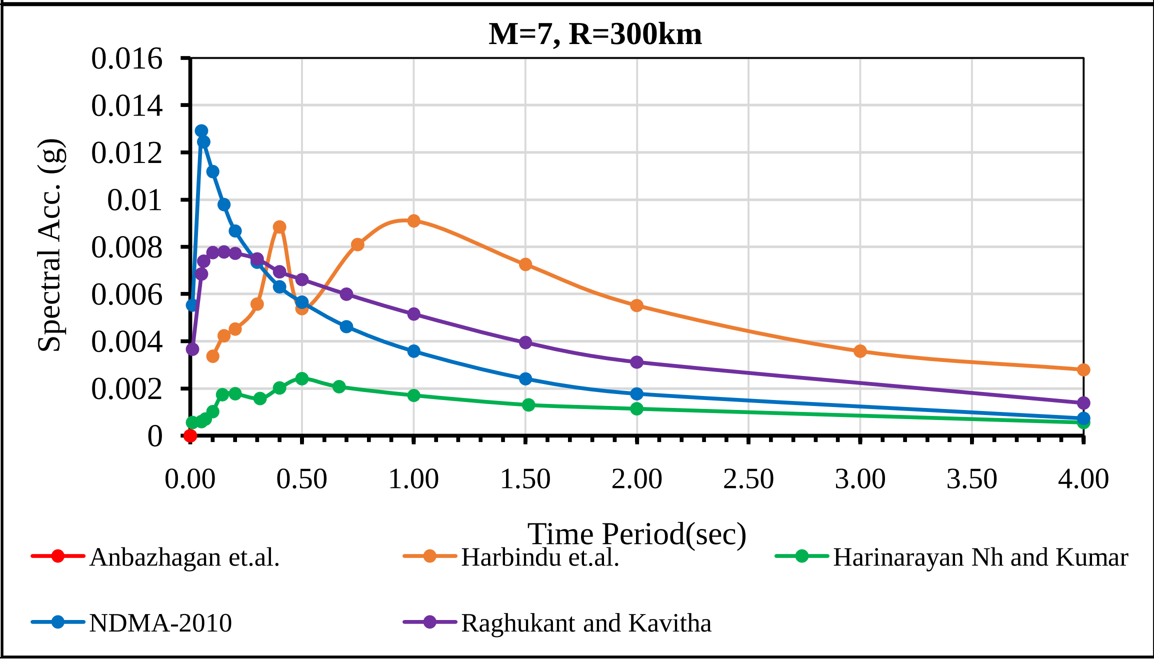

M=7, R=150km
Spectral Acc. (g)
0.06
0.05
0.04
0.03
0.02
0.01
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha


M=8, R=150km
Spectral Acc. (g)
0.2
0.15
0.1
0.05
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha


M=4, R=300km
Spectral Acc. (g)
0.0005
0.0004
0.0003
0.0002
0.0001
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et. al.
Harbindu et. al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha


M=5, R=300km
Spectral Acc. (g)
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukanth and Kavitha


M=6, R=300km
Spectral Acc. (g)
0.005
0.004
0.003
0.002
0.001
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha


M=7, R=300km
Spectral Acc. (g)
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time Period(sec)
Anbazhagan et.al.
Harbindu et.al.
Harinarayan Nh and Kumar
NDMA-2010
Raghukant and Kavitha

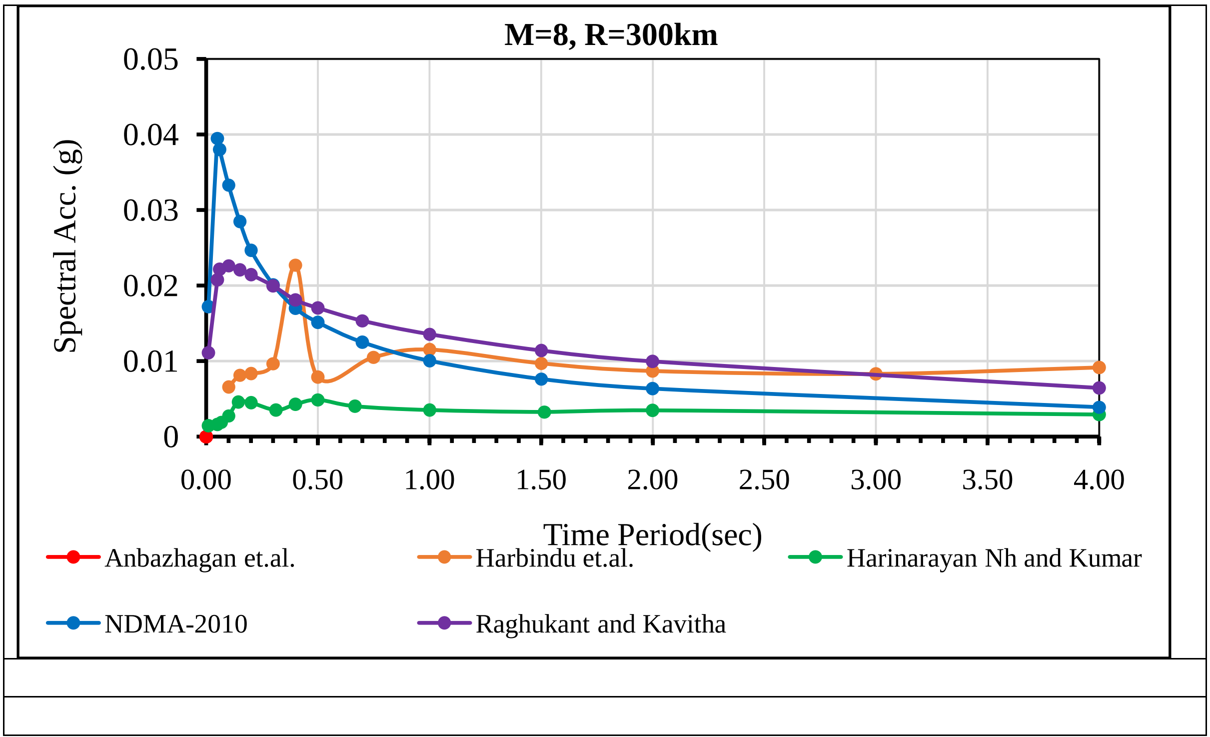


Fig. 3 GMM for spectral acceleration at different time period.

2.6 COMPARATIVE ANALYSIS OF DIFFEREANT GMMS

In past several researchers proposed various GMMs for seismic hazard analysis of Indo Himalayan region. However, it is very confusing to choose accurate GMM. Thus, here an effort has been made to evaluate the accuracy and appropriateness on the basis of past earthquake records. In order to do this, 234 recorded earthquake data were selected (Table 1) and has been predicted using the 13 available GMMs. The residual plots have been presented in Fig. 4.

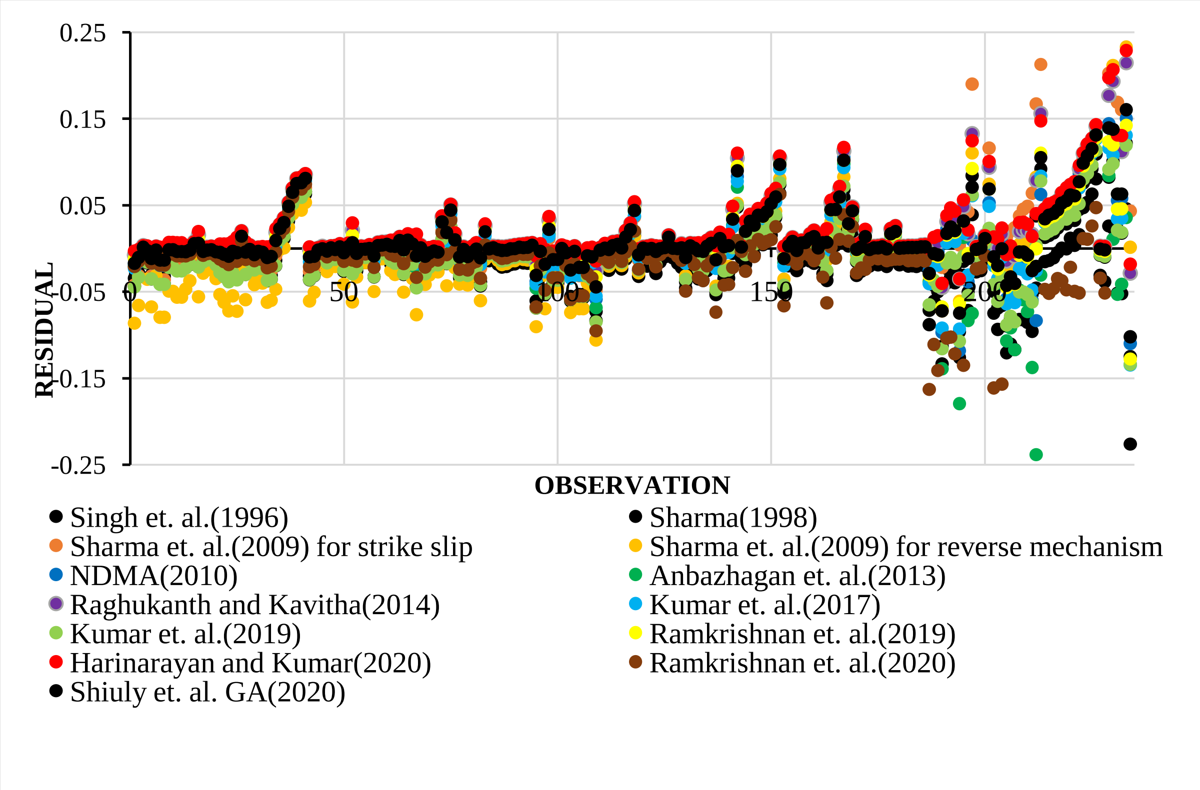


Fig. 4 Residual plot of GMMs developed for India.

This plot will serve to visualize potential biases linked to the GMMs with respect to these variables. Conducting such an analysis will offer valuable insights into the models' performance concerning various explanatory factors, contributing to a more comprehensive understanding of their strengths and limitations. In addition to that, the plot of total standard deviation for each model has been represented in Fig. 5.

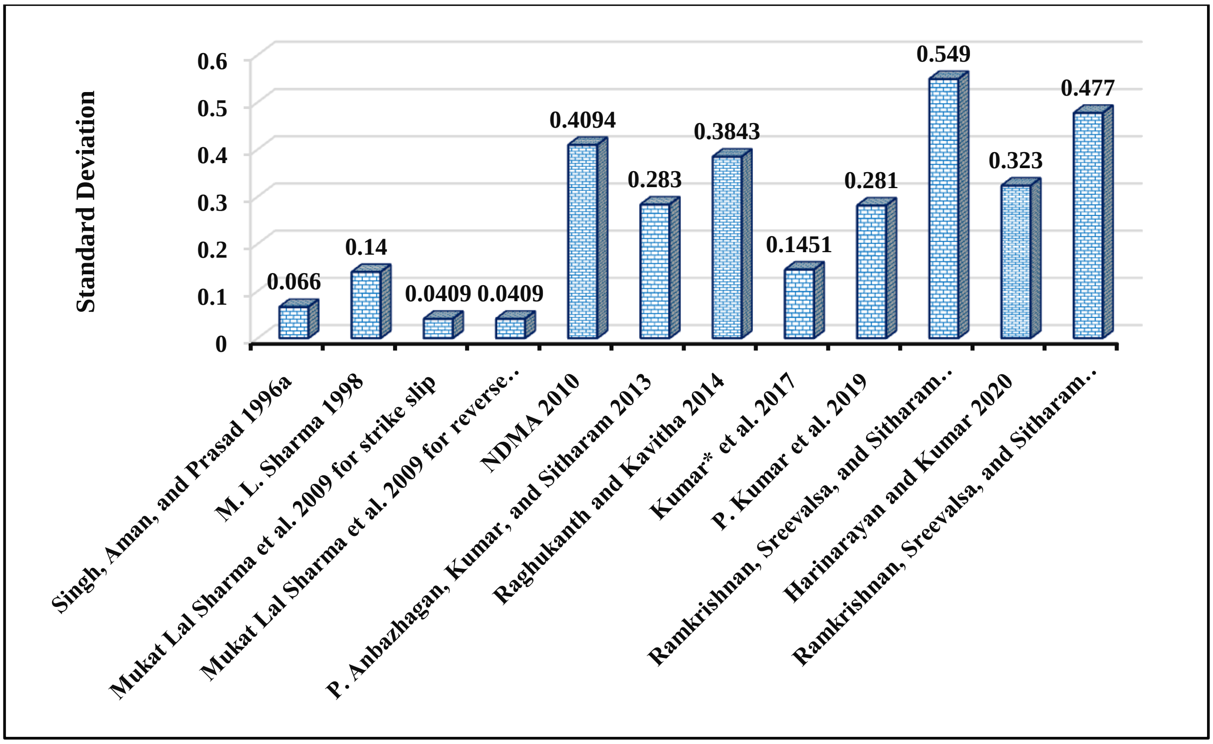


Fig. 5 Standard deviation associated with each model.

The figure bears substantial significance in hazard analysis, as it enhances our comprehension of the model's comprehensive uncertainty and its repercussions on seismic hazard assessments. Further, using the result, RMSE and Chi-square have been computed. It is to be mention that RMSE is a measure of quality of prediction [156]. For any predictive equation it is one of the important tool by which we can know how far values lies as per the equation from the actual values. RSME can be mathematically computed as follows: -

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(A_i - P_i)^2}{n}} \qquad \text{Eq. (1)}$$

Where A_i = actual value of i^{th}term, P_i = corresponding predicted value and n = number of non-missing data points. Further, Chi-square test is statistical test which help us to determine the level of confidence of the proposed equation in our case it is GMMs [157]. This is calculated as follows: -

$$\chi 2 = \sum_{i=1}^{n} \frac{(A_i - P_i)^2}{P_i} \qquad \text{Eq. (2)}$$

Where $\chi 2$ is the Chi-square value. After computing Chi-square value degree of freedom is being evaluated. It shows the number of categories reduced by the number of parameters of the fitted distribution. The $\chi 2$ of specific confidence level is compared with the critical value from $\chi 2$ distribution of specific degree of freedom. Finally, the null hypothesis (H_0), which signifies that there is no difference among expected and the observed value is accepted if $\chi 2$ value does not go beyond the critical value of certain confidence level. However, the null hypothesis has been rejected and alternative hypothesis (H_1), which indicates the difference among observed and expected value is accepted if $\chi 2$ value is bigger than the critical value of certain confidence level.

The RMSE and Chi-square of the different GMMs for predicting PGA are presented in Fig. 6(a) and Fig. 7(a) respectively. In addition to that, Fig. 6(b) and Fig. 7(b) reveals RMSE and Chi-square respectively for predicting PSA. It is to be observed that RMSE values are very less for almost all the GMMs for predicting PGA, except the GMMs proposed by Ramkrishnan et al. 2019 [34]. The increase of the error for predicting the PGA may be due to predefined form of the regression equation. The same results are obtained in case of Chi-square test. It is to be mentioned that, corresponding to 234 number of data the degree of freedom is 233 and related Chi-square value for 99.5% confidence level is 181.153. This depicts that the predicted PGA by all the above mentioned GMMs yield satisfactory result for 99.5% confidence level. On the other hand, for 5 numbers of GMMs, the RMSE values are almost same for PSA. The Chi-square values for the 5 numbers of GMMs indicates that it is within 95% confidence level (1029.62 for 979 degree of freedom).

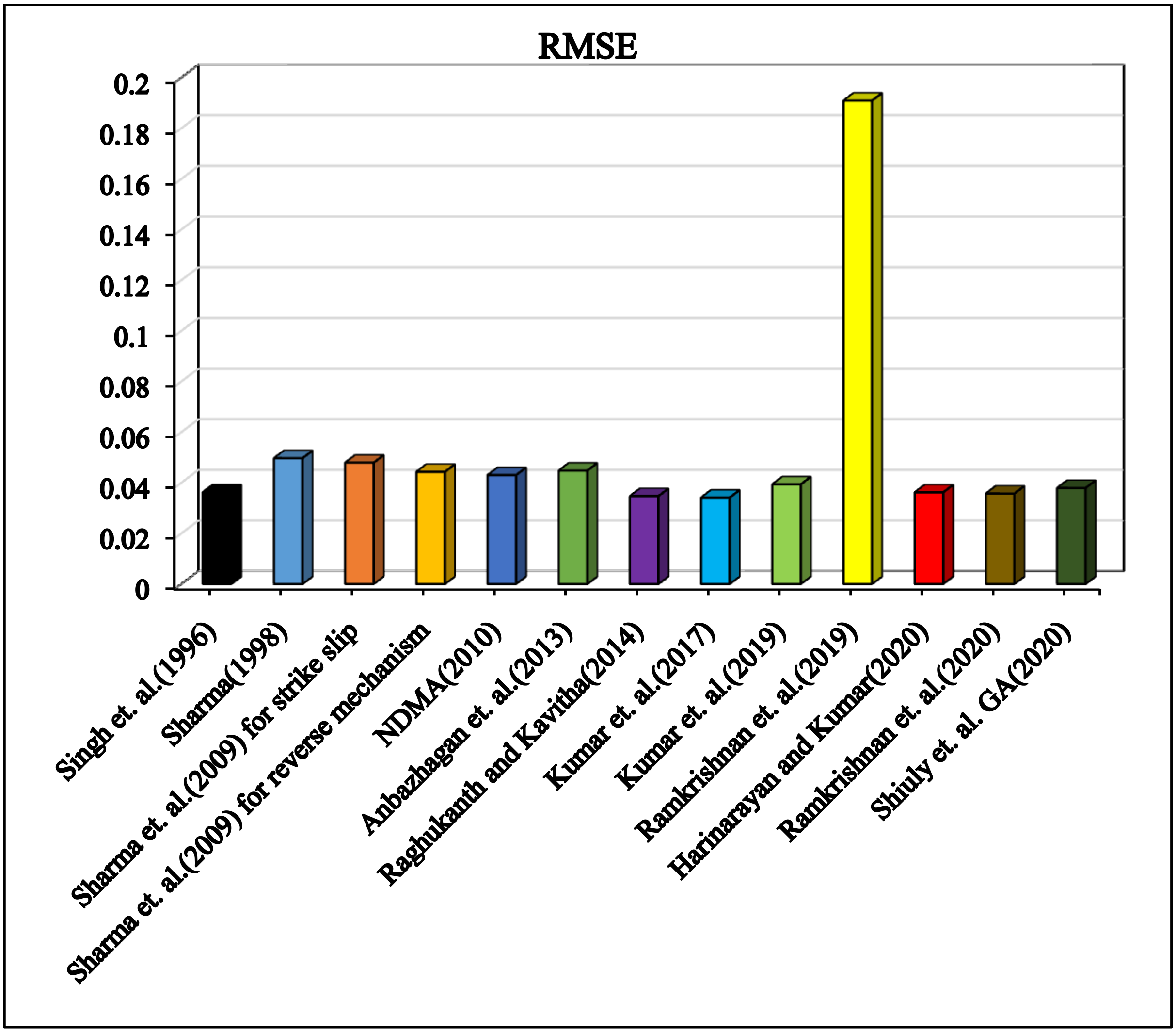


Fig. 6(a) RMSE for different GMM for predicting PGA.

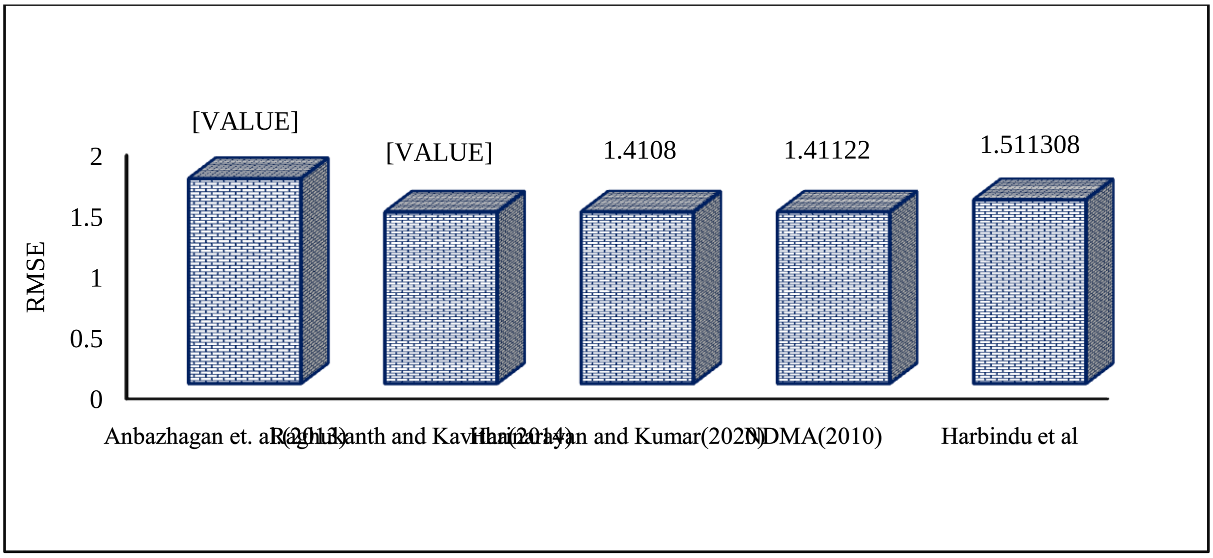


Fig. 6(b) RMSE for different GMM for predicting PSA.

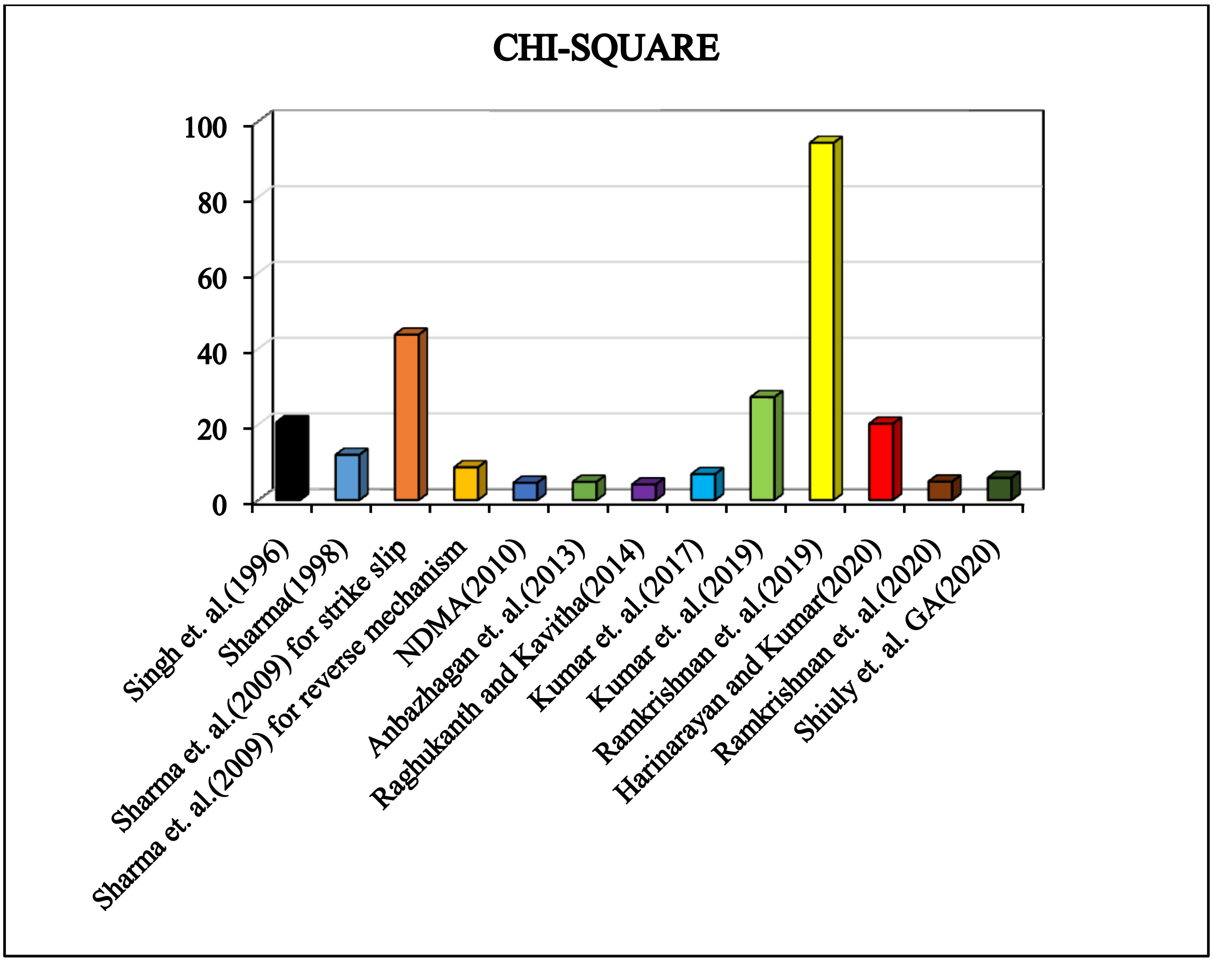


Fig. 7(a) Chi square value for different GMM for predicting PGA.

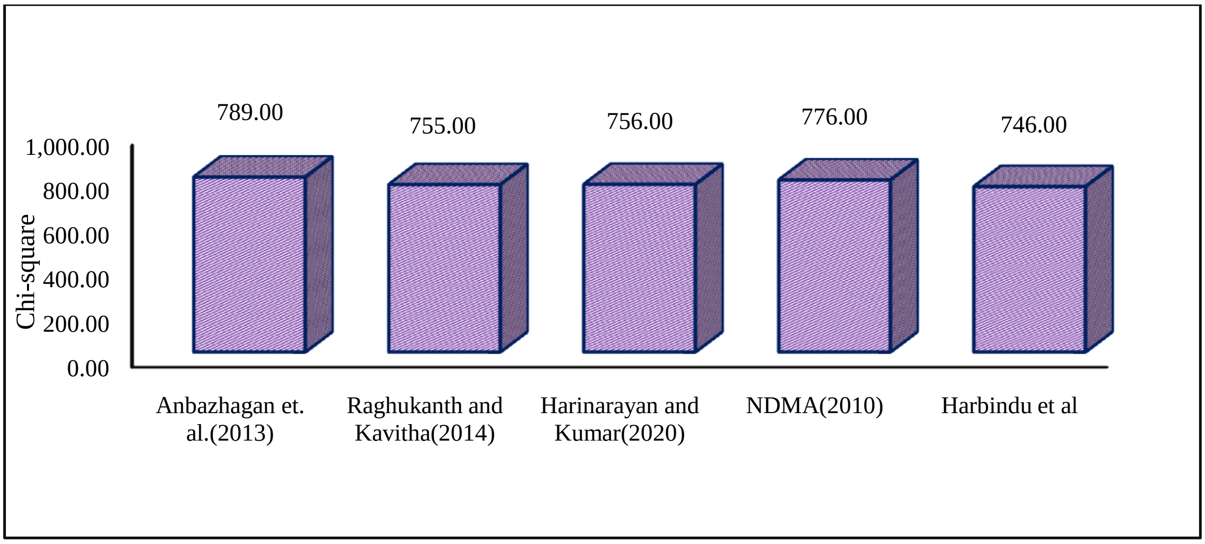


Fig. 7(b) Chi square value for different GMM for predicting PSA.

To comprehensively address the intricacies and uncertainties inherent in seismic hazard assessment, the incorporation of suitable weighting techniques grounded in statistical methodologies is essential. As demonstrated in the work by Lanzano et al. [158], such an approach can yield a more nuanced understanding of model performance and its resilience. Thus, it is to be considered for proposing appropriate weighting strategies for the selected models employing these statistical methodologies. This adjustment will significantly enhance the evaluation process, rendering the models more dependable and valuable for future studies and users seeking precise seismic hazard assessments.

In the realm of decision theory, a scoring rule serves as a means to gauge the precision of probabilistic forecasts [159]. Its utility becomes evident in scenarios where predictions necessitate the assignment of probabilities to a collection of exclusive and non-overlapping potential outcomes. A crucial characteristic of a scoring rule is its propriety, which implies that the forecaster's model attains the highest possible score when assessed against the dataset employed to construct the model. Furthermore, a scoring rule is deemed strictly proper when this peak score is singularly unique.

In order to evaluate the effectiveness of GMMs in assessing performance, the scoring process relies on residuals which are computed as the logarithmic disparities between observed values and predictions, then they are scaled by the overall standard deviations [160][159]. It is presupposed that these data are normally distributed. The scoring methods can be able to determine model performance as they can capture different features, related to the hazard analysis, and help in capturing the epistemic uncertainty related to GMMs.

In order to select and weight the GMMs using scores on the basis of likelihoods, Scherbaum et al. [161]suggested an objective method. This methods [162] have become very widespread and have been amply used for the determination of models in PSHA [163]. In this particular context, the central challenge revolves that on the basis of the concept of likelihood for a set of observations is to decide the distance in the model space between the unknown model, representing the reality, and the candidate model. The likelihood yields under a model the probability of the observed data [164][160][163][162] .

Let it be assumed that the likelihood of a model, characterized by a continuous probability density function f(x), for set of independent observations x ={x_i} with i=1,..,N. The Log-likelihood (LLH) of the model is

$$log_b L(x) = -\frac{1}{N}\sum_{i=1}^{N} log_b\left(g(x_i)\right) \qquad \text{Eq. (3)}$$

In the equation N represents the number of observations and the base b of the logarithm is set to 2 to get the results in bit. This approach calculates the mean log-likelihood value for 'x' within the context of a normal density function, which is defined by its median and corresponding variance. The method is put into practice with the aim of minimizing the LLH value when the model achieves its optimal performance.

The weight of each model can be computed as [73]

$$w_k = \frac{2^{-LLH_k}}{\sum_{k=1}^{5} 2^{-LLH_k}} \qquad \text{Eq. (4)}$$

In the present study, LLH has been computed by above mentioned methodology for 13 GMMs for predicting PGA and 5 GMMs for predicting PSA which is presented in Fig. 8a and Fig. 8 b respectively. Fig. 8 a corroborates that LLH score is high for the GMM proposed by Ramkrishnan et al. [73]. However, Fig. 8 b reveals that LLH score is almost same for all the 5 GMMs. The weight for 13 GMMs for predicting PGA and 5 GMMs for predicting PSA are presented in Fig. 9 a and in Fig. 9 b respectively. It is evident that weight for GMMs proposed by Ramkrishnan et al.[73] are comparatively less. It is to be noted that weights for 5 GMMs are almost equal.

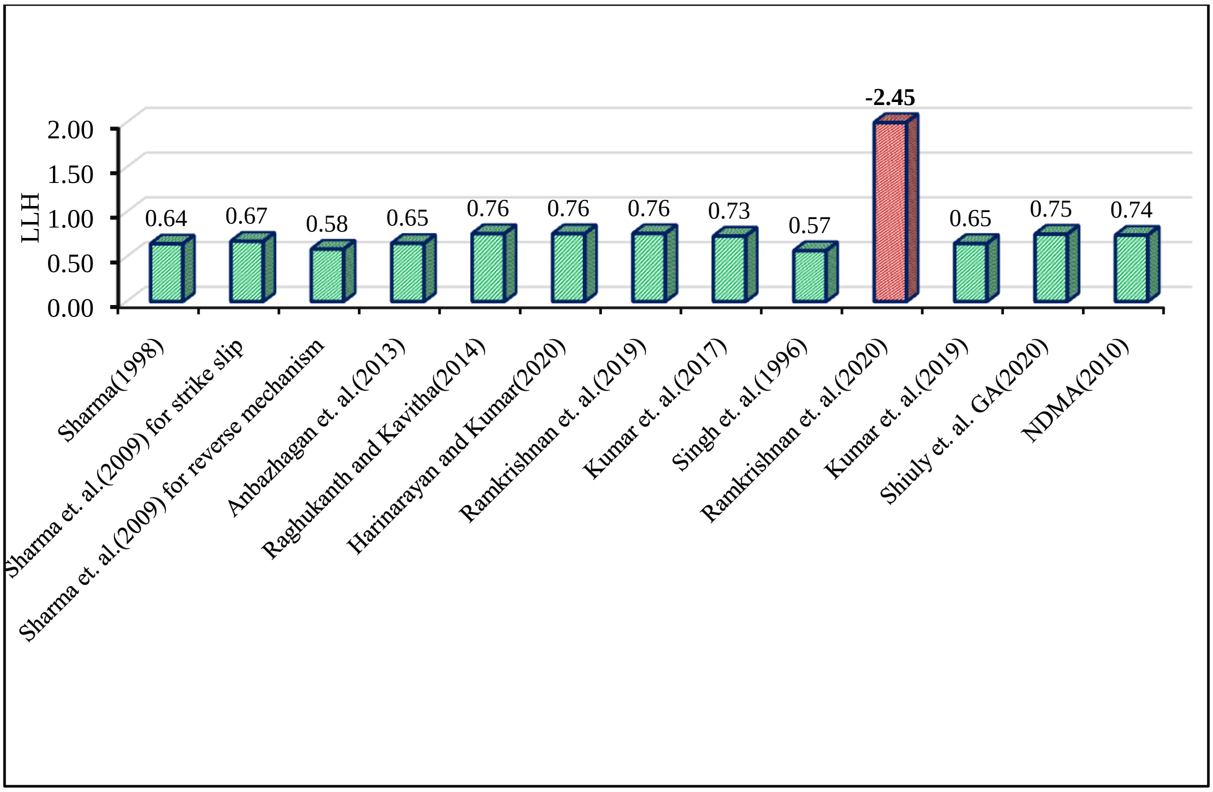


Fig. 8(a) Log-likelyhood (LLH) of different GMM for predicting PGA.

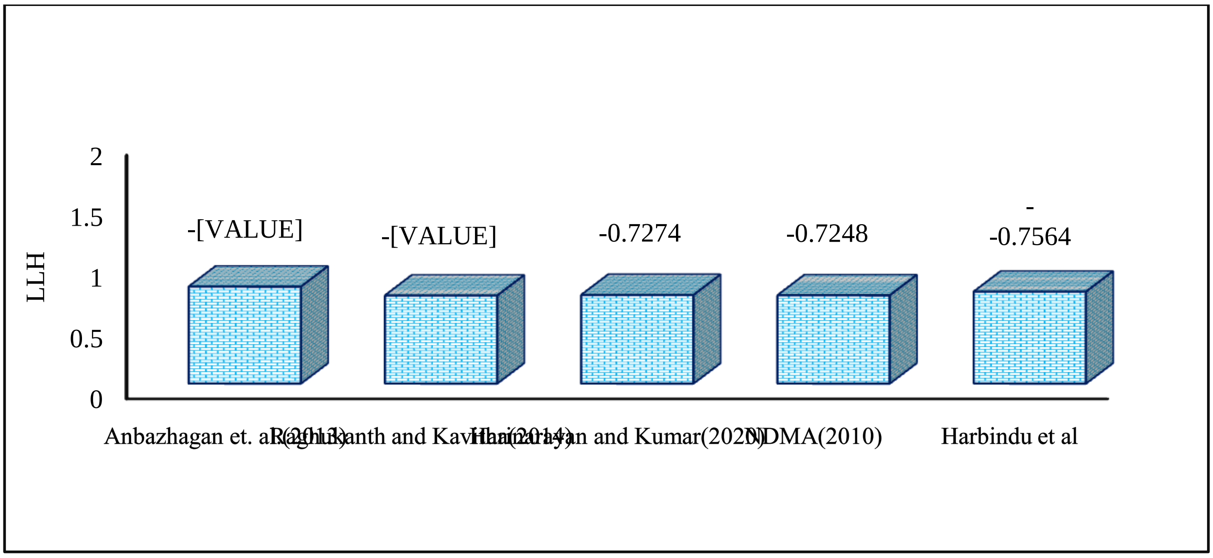


Fig. 8 (b) Log-likelyhood (LLH) of different GMM for predicting PSA.

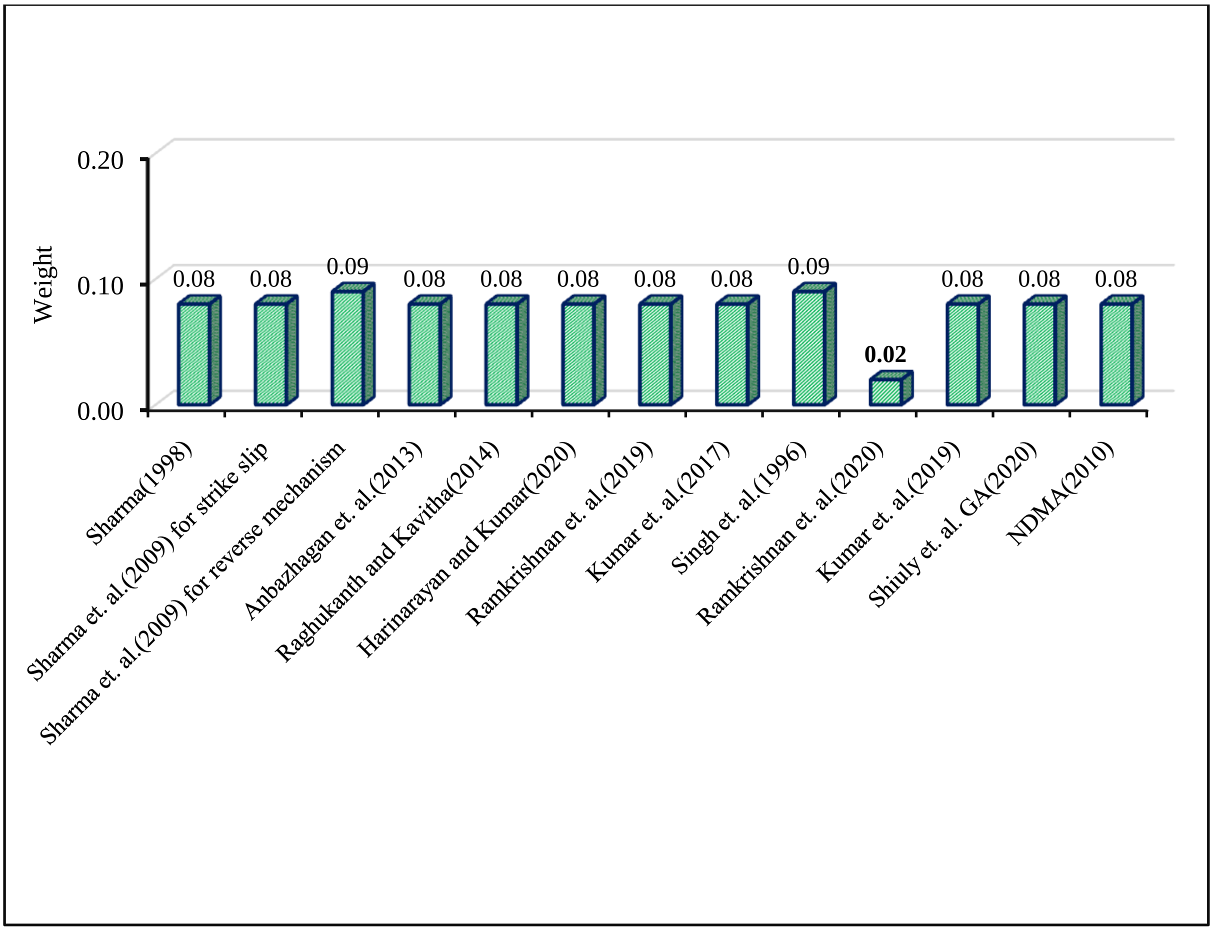


Fig. 9 (a) Weight proposed of different GMM for predicting PGA.

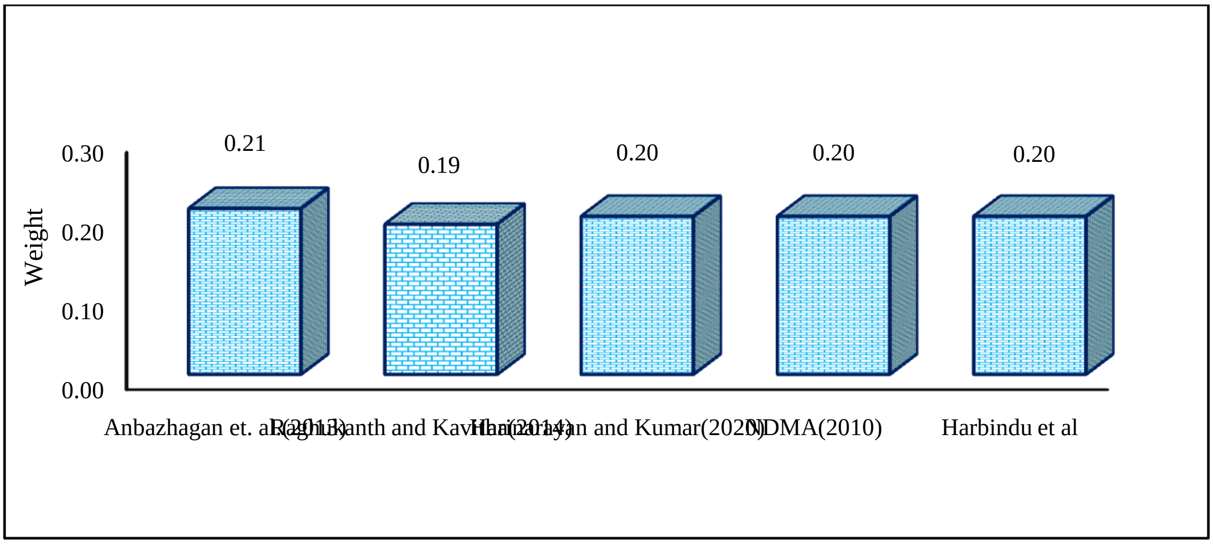


Fig. 9 (b) Weight proposed of different GMM for predicting PSA.

2.7 SUMMARY

Many researchers tried developing GMMsfor predicting PGA value. So for reviewing 13 GMMs were selected from rock site condition. Out of these five also given equation for PSA. A plot for different magnitude for PGA and PSA were also presented in this chapter to get better visualisation. All the model for PGA and PSA studied thoroughly. To compare in better way various method were used like RSME, Chi-square and LLH.

3.GROUND MOTION ATTENUATION RELATION FOR INDIAN REGION

3.1. GENERAL

Seismic force is highly unpredictable. We cannot predict with full guarantee that when, where will the seismic activity occur and what will be its intensity. There are several number of earthquake occur every year but there very few only which cause destruction and is matter of concern for us[1]. From chapter 1 it is evident that GMM using machine learning technique has not been studied much. So in this chapter I have tried to throw some light in this area.

3.2. METHODOLOGY

3.2.1 ARTIFICIAL NEURAL NETWORK(ANN): - ANN is inspired by neural network of our brain. It was developed by McCulloch and his colleagues in 1940[37]. ANN can solve problem in pattern recognition, predictive performance, memory related task, etc. From the given pattern we can train the ANN and it has ability to learn automatically from the given pattern. It is helpful in creating model from complex and non-linear data. ANN consists of one input, one output layer and several hidden layer which depends on us how much layer we want to take. The purpose of input layer is to take data from the surrounding, then it is sent to the hidden layers where data is being processed and after that it is sent to output layers for result generation. Each layer contains one or more neurons (except output layer which consists of only one neuron) which is generally called as nodes which are interconnected among the layers. Each link between neurons is assigned a weights. An example of a typical ANN network is shown in Fig. (...). Here in this paper we have we have tried to develop different model with different number of neurons, layers different transfer function.

3.2.2 FUZZY: - It was first proposed by Zadeh, 1965[165]. It is multi valued logic unlike binary logic. Here we can consider intermediate values like low, very low, high, medium, very high and many more as per our choice and requirement, instead of just high/low, yes/no, etc. The idea was developing more human like computer programming where we can consider intermediary values also. Due to its human like decision making nowadays, fuzzy logic is used in a broad range of applications including complex problem like aerospace engineering, automotive traffic control, business decision-making, industrial processes, artificial intelligence, and machine learning. Which couldn't have been possible or been very difficult to handle with binary logic or precise logic. Because of its imprecise nature there is a chance of inaccurate and wrong result also. So it is important to validate the result before reaching any conclusion based on the model developed by fuzzy logic. Steps involved in this method is[166]: -

(i) Fuzzification: - It is a process of fuzzyfying crisp input value into membership function. Degree of membership function is anything between 0 to 1.

(ii) Execution: - In this process execution of all applicable rules in the rule base to compute the fuzzy output functions is done.

(iii) Defuzzification: - Fuzzy output is defuzzified to get crisp output.

3.2.3 ANFIS: - It stands for Adaptive Network-Based Fuzzy Inference System[167]. It is created by integration of ANN and Fuzzy system. In simple we can say Neural Network + Fuzzy = ANFIS. It was first developed by Jang & Chuen-Tsai Sun, 1995[168]. Weakness of Fuzzy is lack of learning ability. ANFIS is the technique of equipping Fuzzy system with learning ability with the help of neural network. Fuzzy consists of three components: (i) rule-base, which contains a selection of fuzzy rules,

(ii) data-base, which defines the membership functions (MF) (iii) reasoning mechanism, which performs the inference procedure on the rules to get the output. Fuzzy implements non-linear mapping from input space to output space. Several if-then rules in Fuzzy used for getting this mapping. The parameters of the if-thenrules (antecedents or premises in fuzzy modelling) define a fuzzy region of the input space, andthe output parameters (also consequents in fuzzy modelling) specify the corresponding output.Hence, the efficiency of the FIS depends on the estimated parameters. However, the selection ofthe shape of the fuzzy set (described by the antecedents) corresponding to input is not guided by any procedure. With Fuzzy system allows human expertise to decide relevant inputs, MFs (membership function) and corresponding data for parameter estimation. To curb the parameter identification process in Fuzzy system adaptive network has employed which is a generalization of back-propagation neural network. An adaptive network is a multi-layered feed forward structure whose overall behaviour is determined by the value of a collection of modifiable parameters. Configuration of adaptive consist of number of nodes connected through directional links. Each node is a processing unit which performs a static node function on its incoming signal and create a single node output.

3.2.4 <u>GENETIC ALGORITHM: -</u> It is derived from natural biological process of evolution of living beings. It was presented for the first time in Ferreira 2001 [169]. Where he proposed the use of genetic algorithm for the creation of computer programme. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. You can apply the genetic algorithm to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, non-differentiable, stochastic, or highly nonlinear. The genetic algorithm can address problems of mixed integerprogramming, where some components are restricted to be integer-valued. The schematic diagram how the genetic algorithm work is given as: -

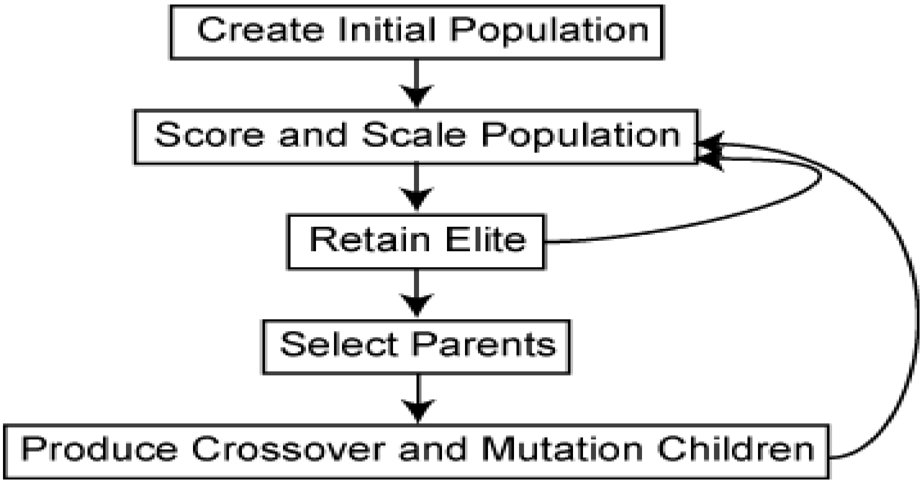


Fig. 10A schematic diagram how does GA work.

Here in this paper to develop Ground Motion Model software GeneXproTools 5.0 were used to develop model based on genetic algorithm.

3.2.5 RANDOM FOREST:- Random forest is a commonly-used machine learning algorithm trademarked by Leo Breiman and Adele Cutler, which combines the output of multiple decision trees to reach a single result. Its ease of use and flexibility have fueled its adoption, as it handles both classification and regression problems.Since the random forest model is made up of multiple decision trees, it would be helpful to start by describing the decision tree algorithm briefly[170]. Decision trees start with a basic question, such as, “Should I surf?” From there, you can ask a series of questions to determine an answer, such as, “Is it a long period swell?” or “Is the wind blowing offshore?”. These questions make up the decision nodes in the tree, acting as a means to split the data. Each question helps an individual to arrive at a final decision, which would be denoted by the leaf node. Observations that fit the criteria will follow the “Yes” branch and those that don’t will follow the alternate path. Decision trees seek to find the best split to subset the data, and they are typically trained through the Classification and Regression Tree (CART) algorithm. Metrics, such as Gini impurity, information gain, or mean square error (MSE), can be used to evaluate the quality of the split. This decision tree is an example of a classification problem, where the class labels are "surf" and "don't surf."While decision trees are common supervised learning algorithms, they can be prone to problems, such as bias and overfitting. However, when multiple decision trees form an ensemble in the random forest algorithm, they predict more accurate results, particularly when the individual trees are uncorrelated with each other. The random forest algorithm is made up of a collection of decision trees, and each tree in the ensemble is comprised of a data sample drawn from a training set with replacement, called the bootstrap sample. Of that training sample, one-third of it is set aside as test data, known as the out-of-bag (oob) sample, which we’ll come back to later. Another instance of randomness is then injected through feature bagging, adding more diversity to the dataset and reducing the correlation among decision trees. Depending on the type of problem, the determination of the prediction will vary. For a regression task, the individual decision trees will be averaged, and for a classification task, a majority vote—i.e. the most frequent categorical variable—will yield the predicted class. Finally, the oob sample is then used for cross-validation, finalizing that prediction.

Here in this paper a total 11 number Forest has been created, of which 60 number of tree has produced best data. And this 60 tree forest were considered for the GMM model.

3.2.6 REGRESSION: - It is statistical method used in various discipline like engineering, finance investment, marketing etc. The term regression was first coined by the Francis Galton in 19th century. Most of previous researcher work on GMM was based on regression analysis. Here we try to obtain closely fit curve as much as possible according to the given data. If error is under the tolerance limit, we can use this data for prediction as well as for prediction. Here I have tried to develop 5 regression ground motion model for prediction of PGA based on two input magnitude and hypo-central distance. 5 regression model taken are as follows: -

i) Log(PGA) = a + b*M + c*Log(D) + d*D

ii) Log(PGA) = a + b*M + c*Log(D)

iii) Log(PGA) = a + b*(M-6) + c*(M-6)^2 + d*Log(D) + e*D

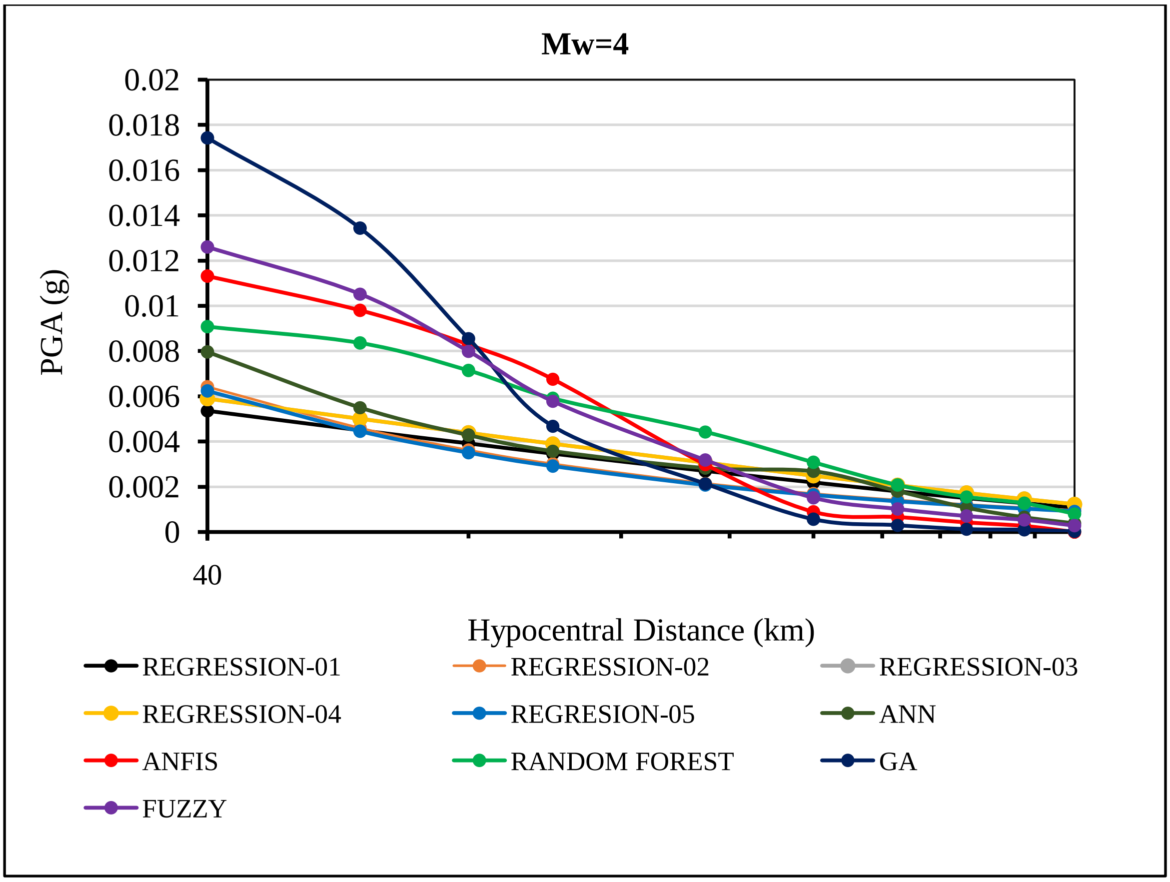
iv) Log(PGA) = a + b*M + c*M^2 + d*Log(D) + e*D

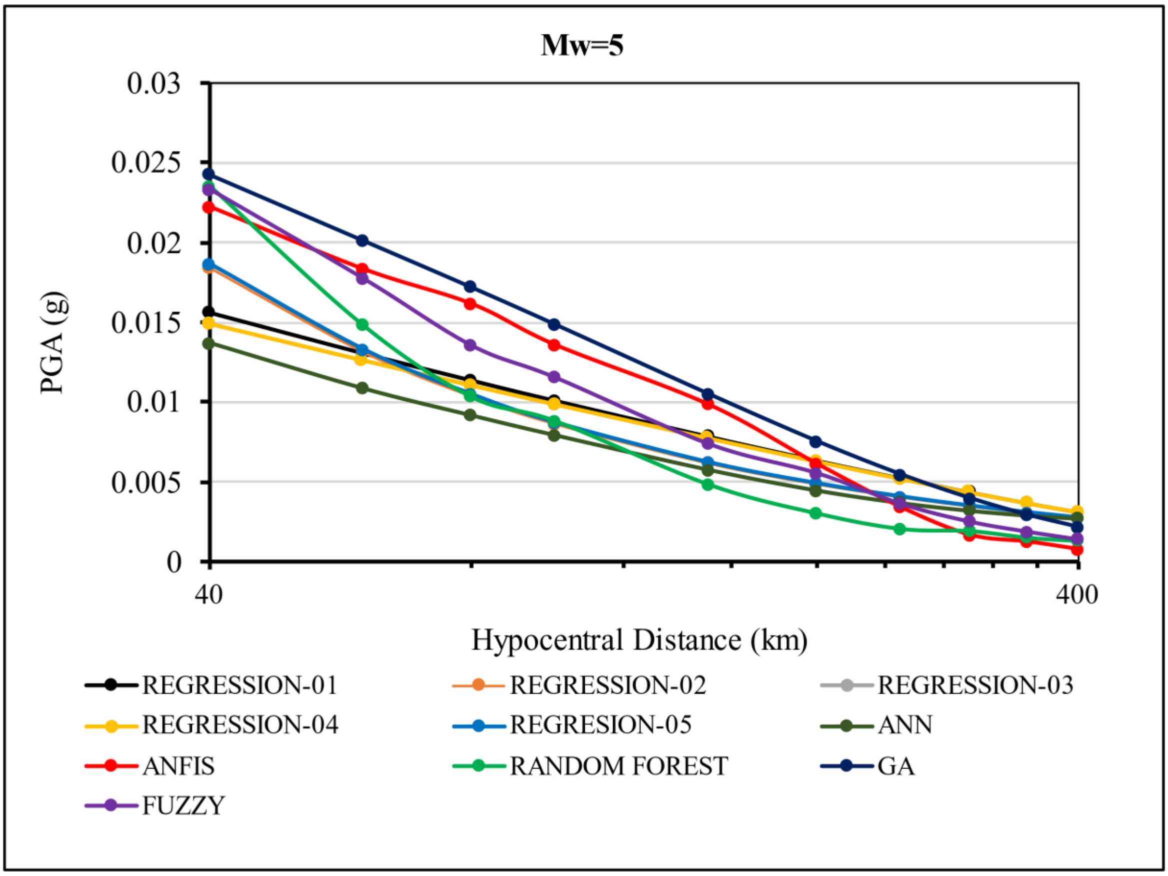
v) Log(PGA) = a + b*Log(M) + c*Log(D)

Where PGA is peak ground acceleration in g, M is moment magnitude, D is hypo-central distance in km.

3.3 RESULT

To develop GMM model 234 (Table no. 1) data from 79 earthquakes has been taken into consideration for training and testing. About 90% of data 211 were taken for training the model and 23 data were kept aside for testing of result obtained from the model. Magnitude moment ranging from 3.9 to 8 and hypo-central distance ranging from 20.6km to 1480.4km. This data was downloaded from the PESMOS website. GMM developed on the basis of above mentioned method. Based on the model developed PGA for different magnitude and hypo-central distance has been plotted in Fig. 11(a).


Mw=4
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
PGA (g)
40
Hypocentral Distance (km)
REGRESSION-01
REGRESSION-02
REGRESSION-03
REGRESSION-04
REGRESION-05
ANN
ANFIS
RANDOM FOREST
GA
FUZZY


Mw=5
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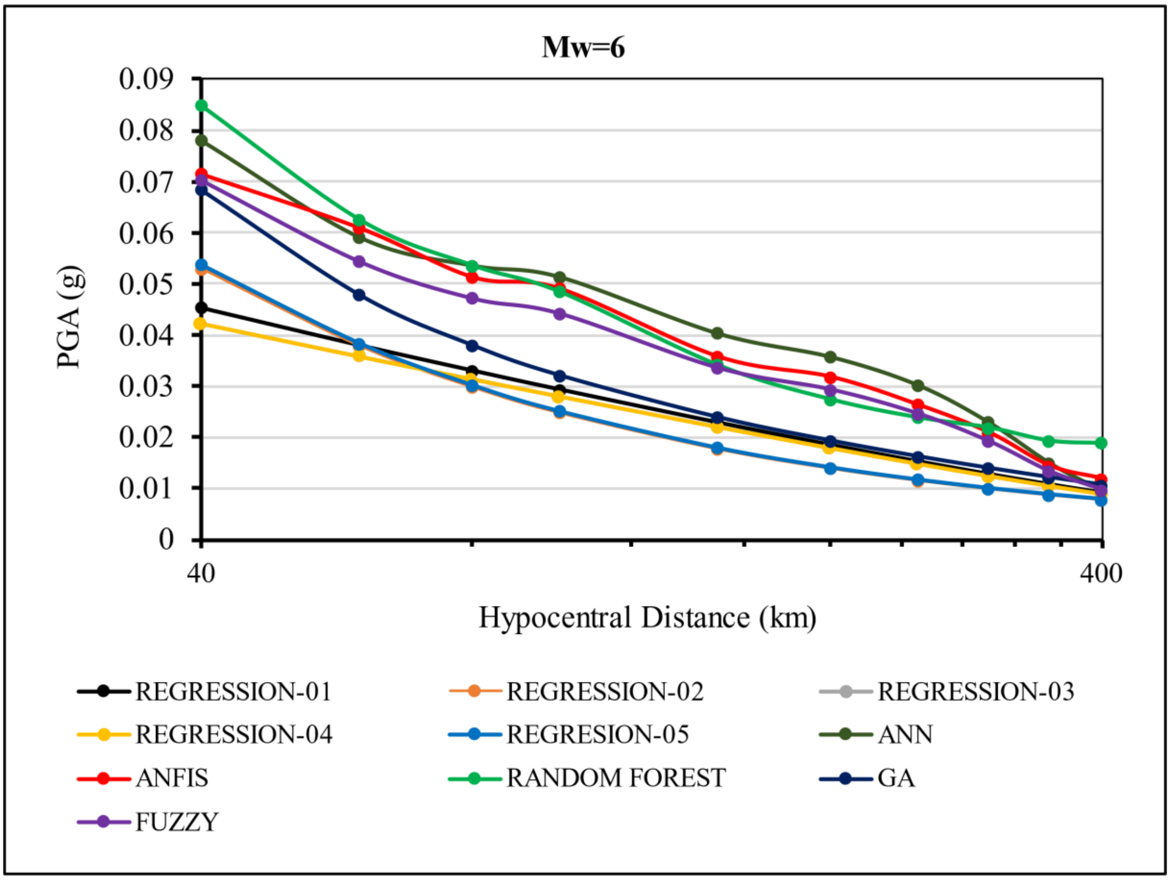
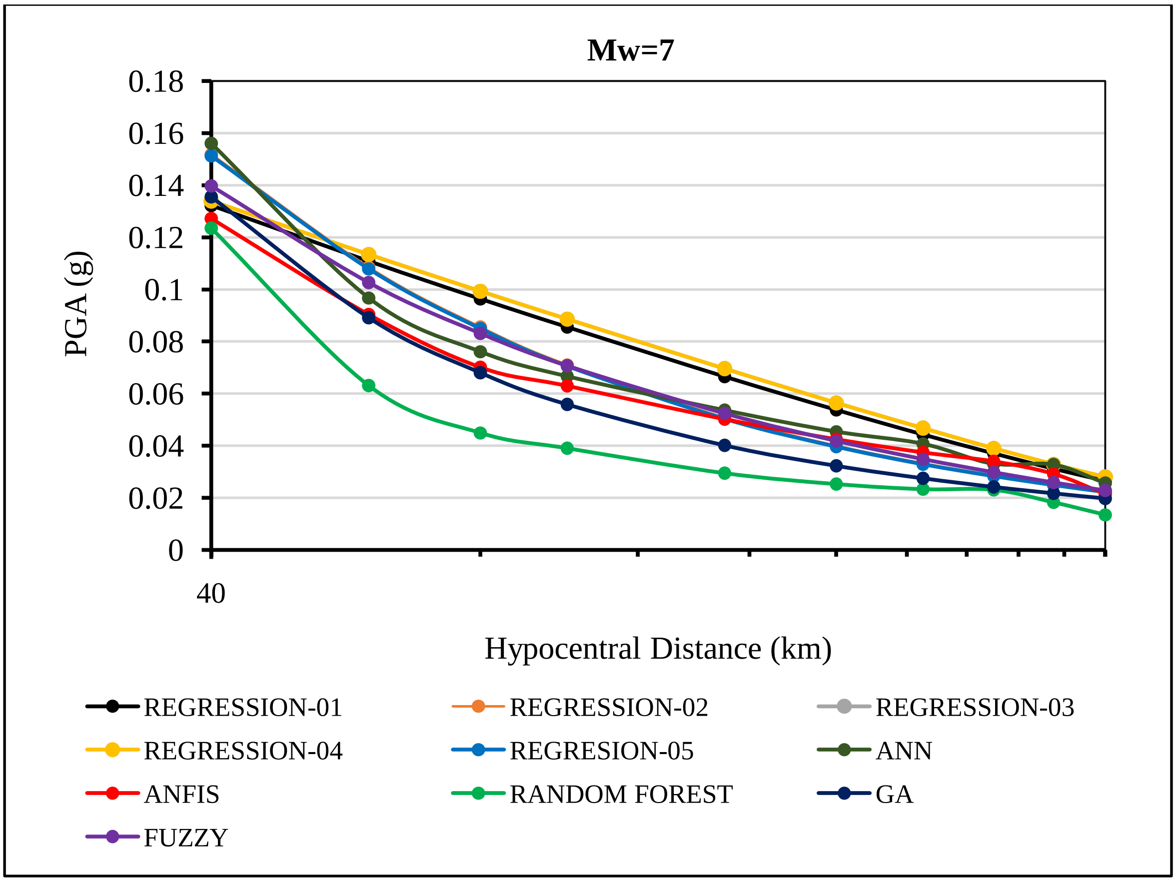
0.025
0.02
0.015
0.01
0.005
0
PGA (g)
40
400
Hypocentral Distance (km)
REGRESSION-01
REGRESSION-02
REGRESSION-03
REGRESSION-04
REGRESION-05
ANN
ANFIS
RANDOM FOREST
GA
FUZZY


Mw=6
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
PGA (g)
40
400
Hypocentral Distance (km)
REGRESSION-01
REGRESSION-02
REGRESSION-03
REGRESSION-04
REGRESION-05
ANN
ANFIS
RANDOM FOREST
GA
FUZZY


Mw=7
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0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
PGA (g)
40
Hypocentral Distance (km)
REGRESSION-01
REGRESSION-02
REGRESSION-03
REGRESSION-04
REGRESION-05
ANN
ANFIS
RANDOM FOREST
GA
FUZZY

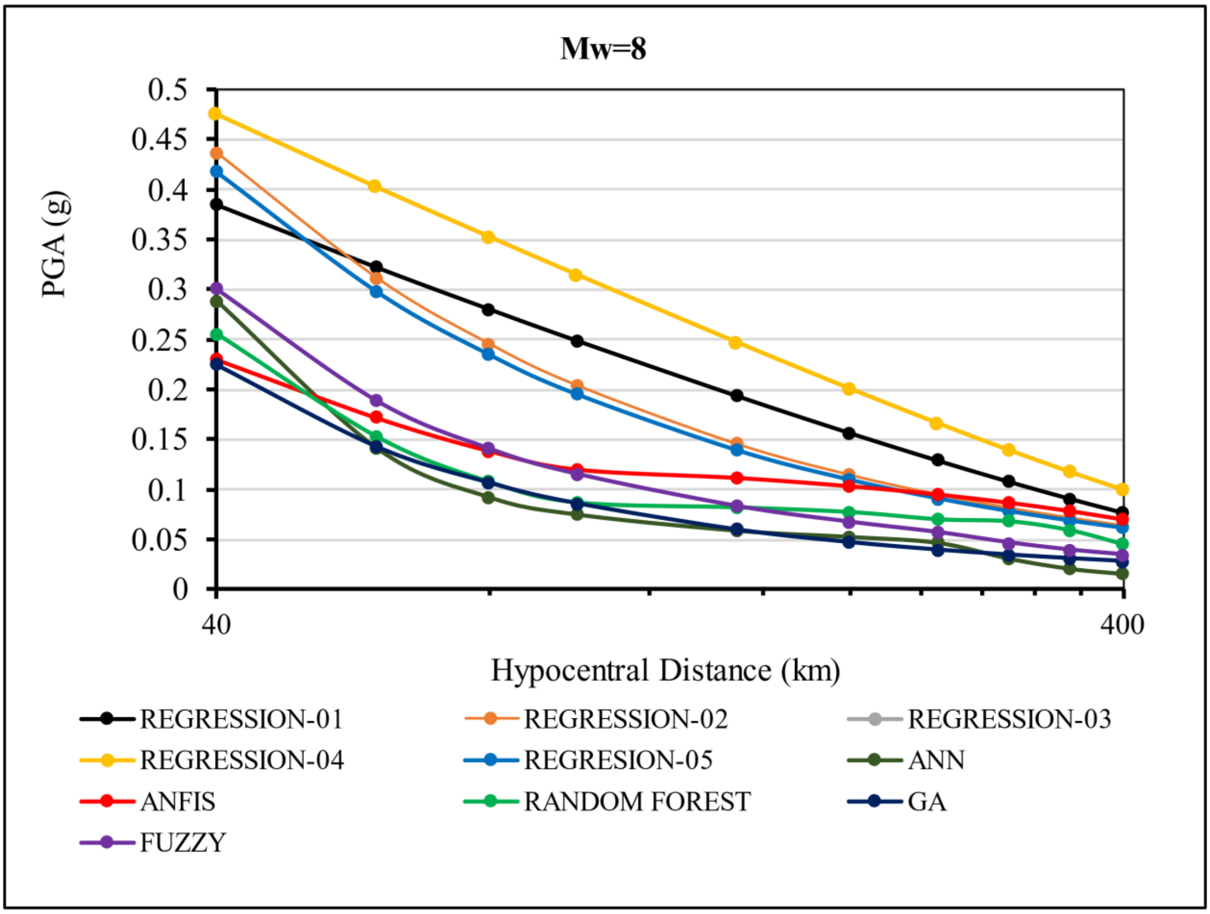
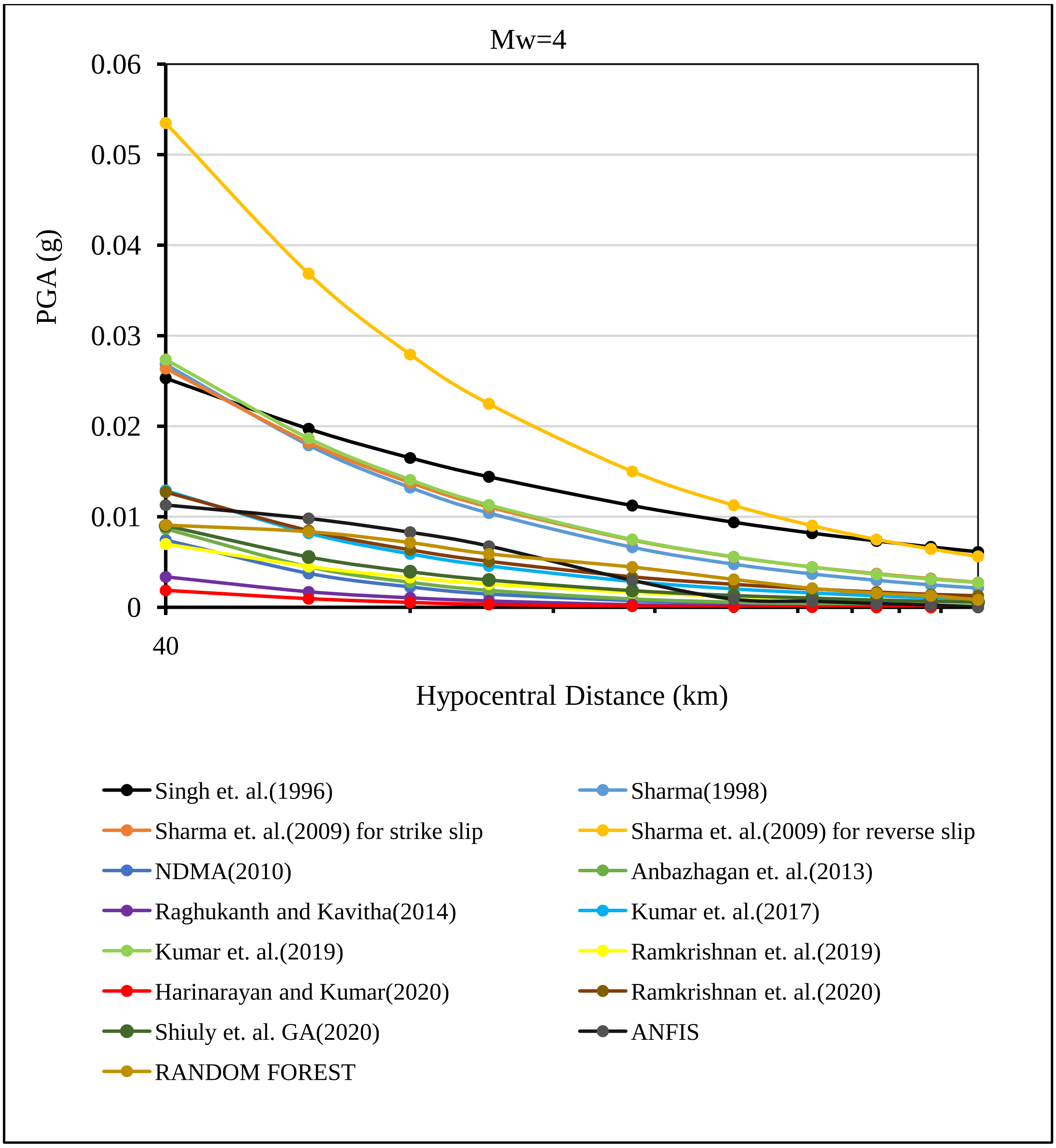
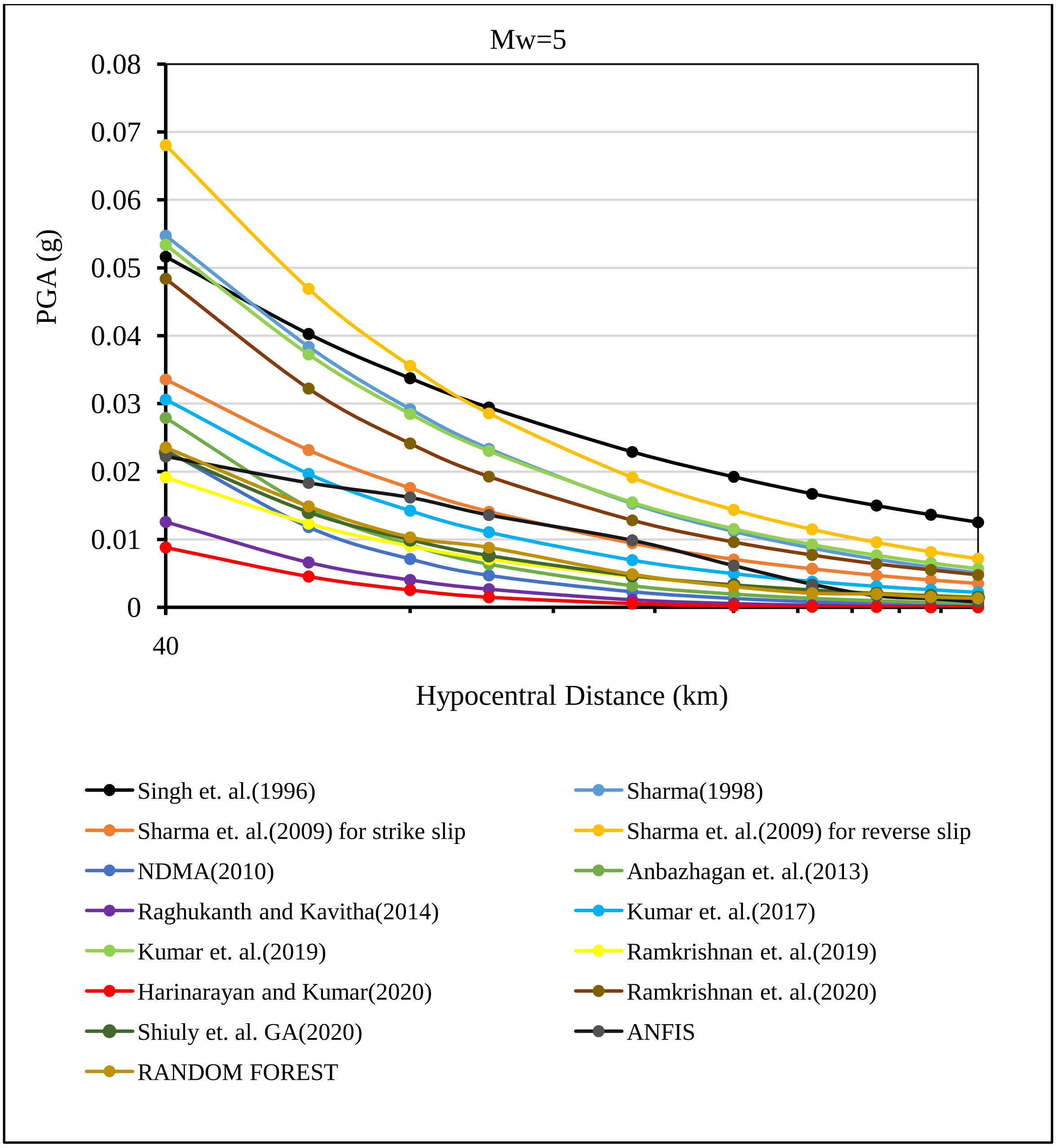


Fig.: - 11(a)PGA for different magnitude and hypo-central distances.

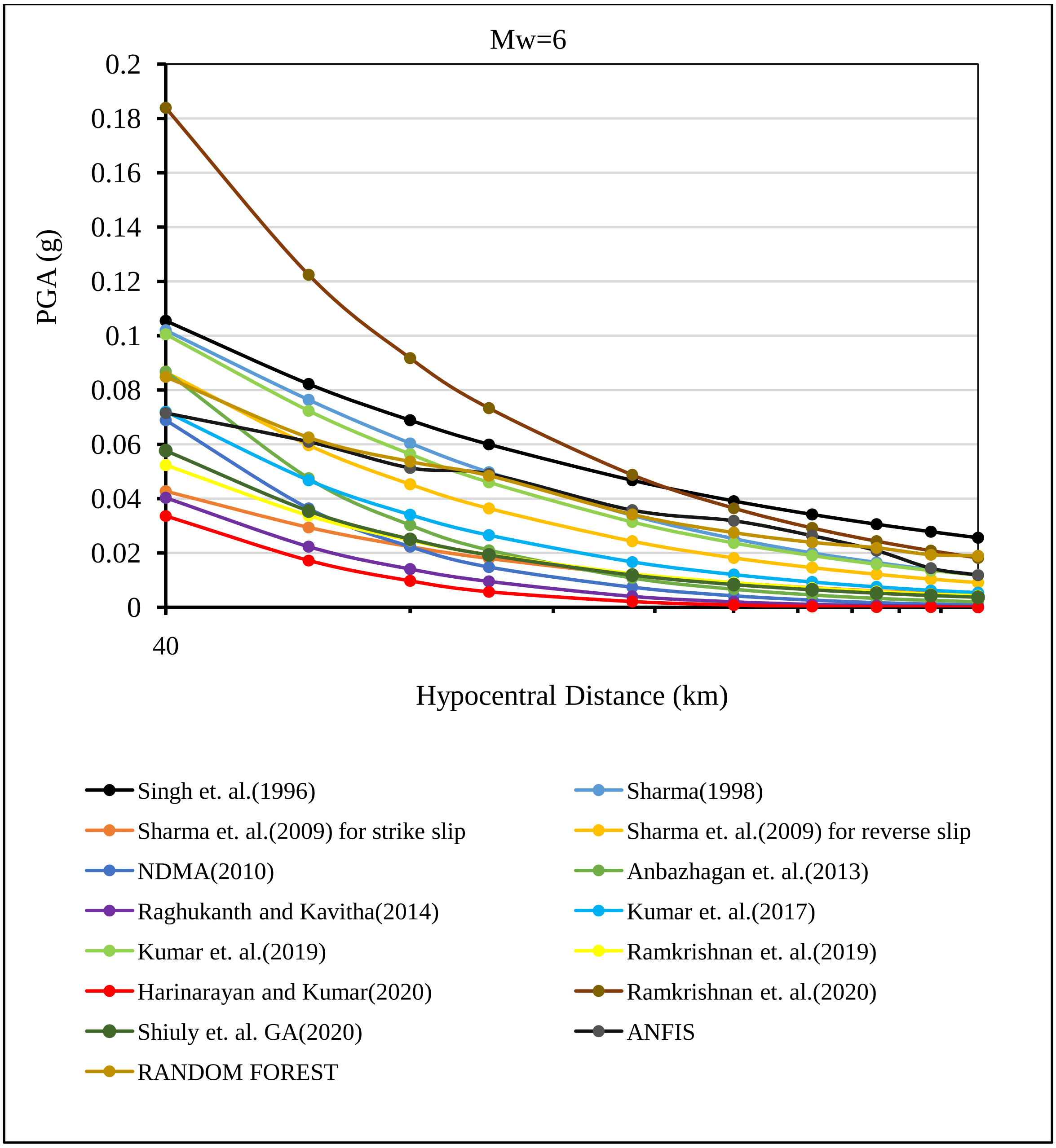
In fig. 11(b) graph of GMM of given by previous researcher and GMM developed by ANFIS and RANDOM FOREST in this chapter has been plotted to visualise the currently developed GMM with respect to the previously developed GMM.

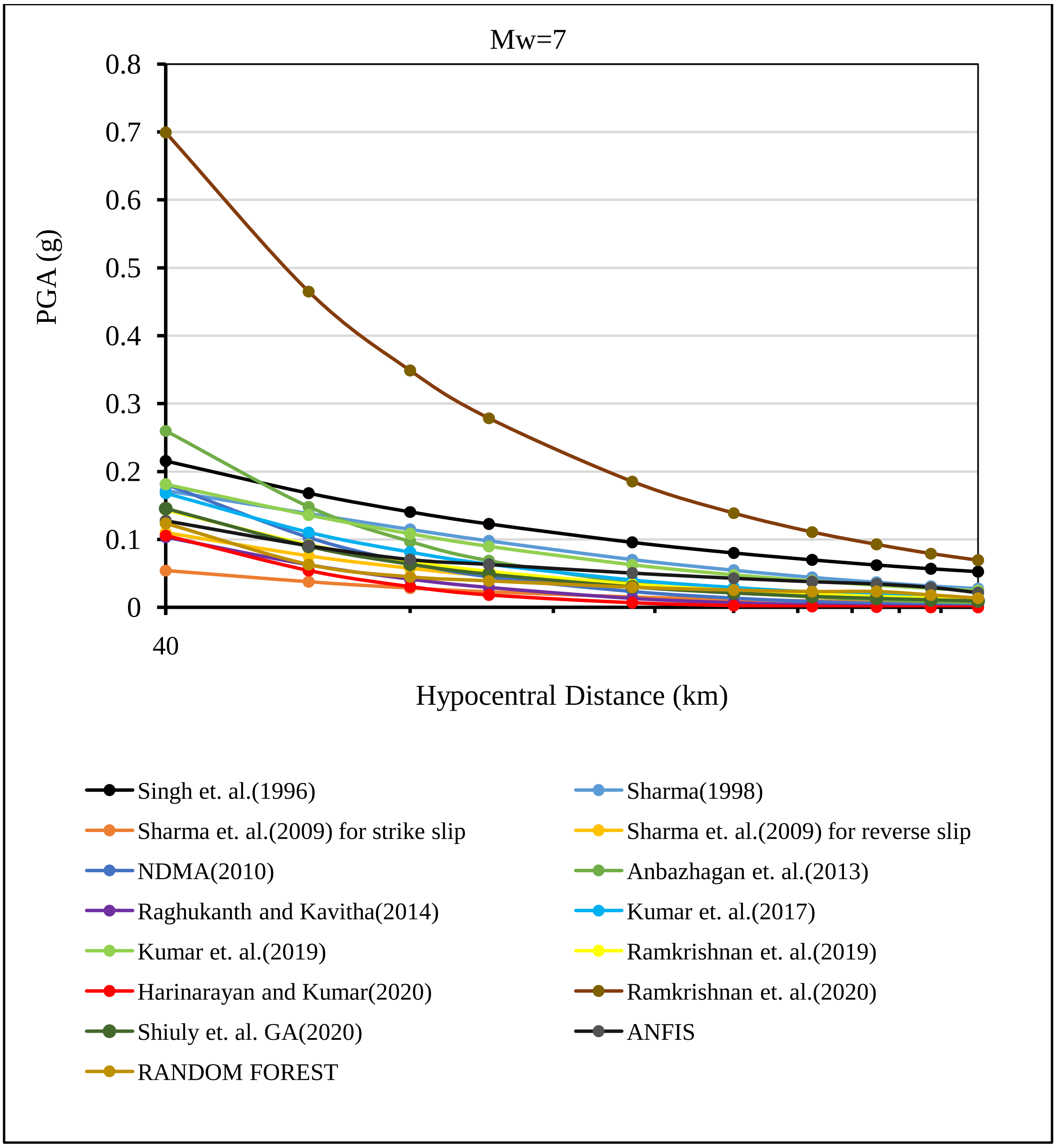


Mw=4
PGA (g)
0.06
0.05
0.04
0.03
0.02
0.01
0
40
Hypocentral Distance (km)
Singh et. al.(1996)
Sharma(1998)
Sharma et. al.(2009) for strike slip
Sharma et. al.(2009) for reverse slip
NDMA(2010)
Anbazhagan et. al.(2013)
Raghukanth and Kavitha(2014)
Kumar et. al.(2017)
Kumar et. al.(2019)
Ramkrishnan et. al.(2019)
Harinarayan and Kumar(2020)
Ramkrishnan et. al.(2020)
Shiuly et. al. GA(2020)
ANFIS
RANDOM FOREST



Mw=5
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
PGA (g)
40
Hypocentral Distance (km)
Singh et. al.(1996)
Sharma(1998)
Sharma et. al.(2009) for strike slip
Sharma et. al.(2009) for reverse slip
NDMA(2010)
Anbazhagan et. al.(2013)
Raghukanth and Kavitha(2014)
Kumar et. al.(2017)
Kumar et. al.(2019)
Ramkrishnan et. al.(2019)
Harinarayan and Kumar(2020)
Ramkrishnan et. al.(2020)
Shiuly et. al. GA(2020)
ANFIS
RANDOM FOREST


Mw=6
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
PGA (g)
40
Hypocentral Distance (km)
Singh et. al.(1996)
Sharma(1998)
Sharma et. al.(2009) for strike slip
Sharma et. al.(2009) for reverse slip
NDMA(2010)
Anbazhagan et. al.(2013)
Raghukanth and Kavitha(2014)
Kumar et. al.(2017)
Kumar et. al.(2019)
Ramkrishnan et. al.(2019)
Harinarayan and Kumar(2020)
Ramkrishnan et. al.(2020)
Shiuly et. al. GA(2020)
ANFIS
RANDOM FOREST


Mw=7
PGA (g)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
40
Hypocentral Distance (km)
Singh et. al.(1996)
Sharma(1998)
Sharma et. al.(2009) for strike slip
Sharma et. al.(2009) for reverse slip
NDMA(2010)
Anbazhagan et. al.(2013)
Raghukanth and Kavitha(2014)
Kumar et. al.(2017)
Kumar et. al.(2019)
Ramkrishnan et. al.(2019)
Harinarayan and Kumar(2020)
Ramkrishnan et. al.(2020)
Shiuly et. al. GA(2020)
ANFIS
RANDOM FOREST

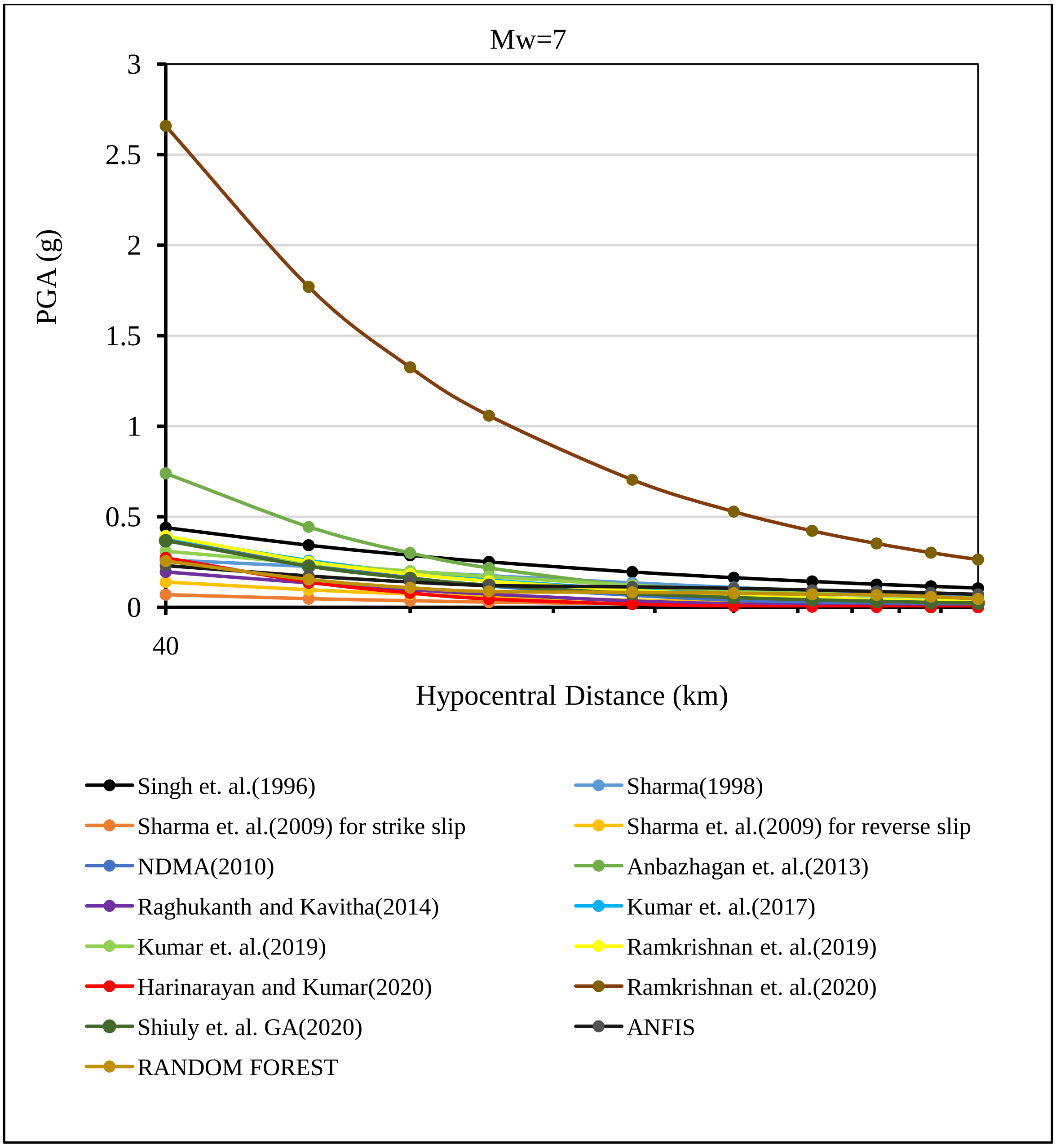


Fig. 11(b) ANFIS and RANDOM FOREST plot with respect to previous GMM.

3.4. COMPARITIVE STUDY OF DIFFERENT GMMs.

There are various methods to develop ground motion attenuation relation. Some them has been demonstrated in this chapter. Still it is impossible claim that this particular method is 100 percent accurate. We can only compare which one is best. So here effort has been made to evaluate the most appropriate and correct method. The residual plot has been presented in Fig. 12. This will give idea of potential biases linked to GMMs. Conducting such an analysis will offer valuable insights into the models' performance concerning various explanatory factors, contributing to a more comprehensive understanding of their strengths and limitations

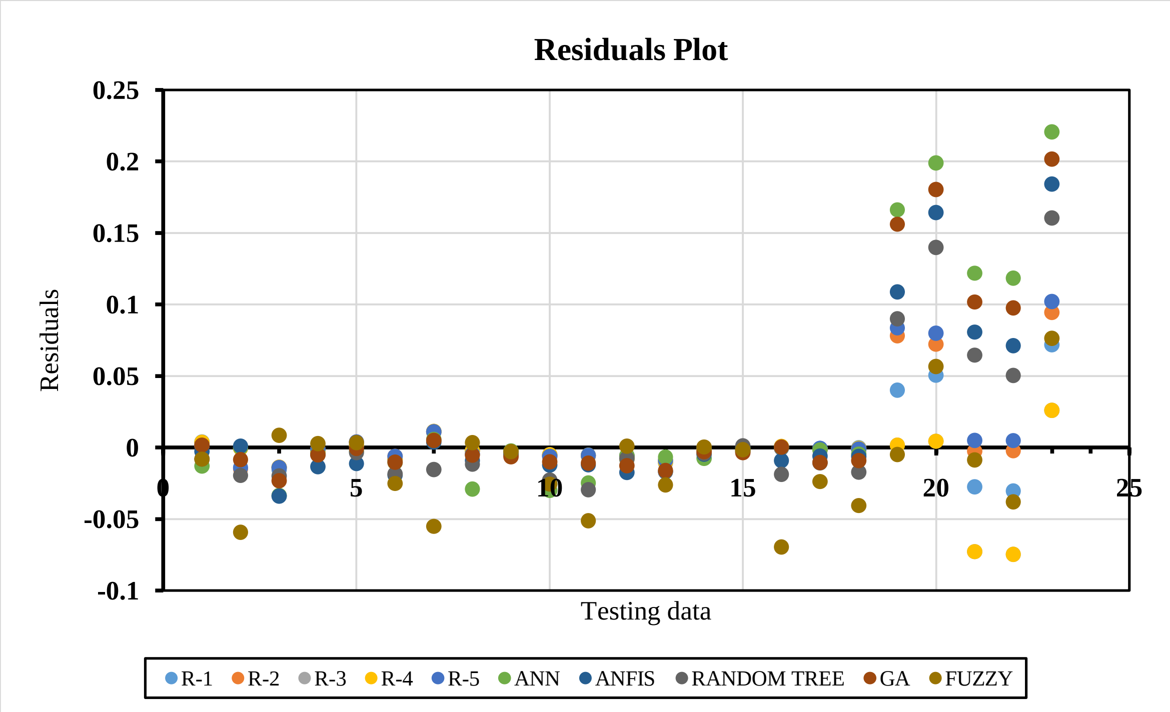


Fig. 12 Residual plot for GMM developed for Indian region.

Further, using the result, RMSE and Chi-square have been computed. It is to be mention that RMSE is a measure of quality of prediction [156]. For any predictive equation it is one of the important tool by which we can know how far values lies as per the equation from the actual values. RSME can be mathematically computed as follows: -

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(A_i - P_i)^2}{n}} \quad \text{Eq. (1)}$$

Where A_i = actual value of i^{th}term, P_i = corresponding predicted value and n = number of non-missing data points. Further, Chi-square test is statistical test which help us to determine the level of confidence of the proposed equation in our case it is GMMs[157]. This is calculated as follows: -

$$\chi 2 = \sum_{i=1}^{n} \frac{(A_i - P_i)^2}{P_i} \quad \text{Eq. (2)}$$

Where $\chi 2$ is the Chi-square value. After computing Chi-square value degree of freedom is being evaluated. It shows the number of categories reduced by the number of parameters of the fitted distribution. The $\chi 2$ of specific confidence level is compared with the critical value from $\chi 2$ distribution of specific degree of freedom. Finally, the null hypothesis(H_0), which signifies that there is no difference among expected and the observed value is accepted if $\chi 2$ value does not go beyond the critical value of certain confidence level. However, the null hypothesis has been rejected and alternative hypothesis (H_1), which indicates the difference among observed and expected value is accepted if $\chi 2$ value is bigger than the critical value of certain confidence level. RSME and the chi-square value for the all the GMM has been plotted in Fig. 13 and Fig 14 respectively.

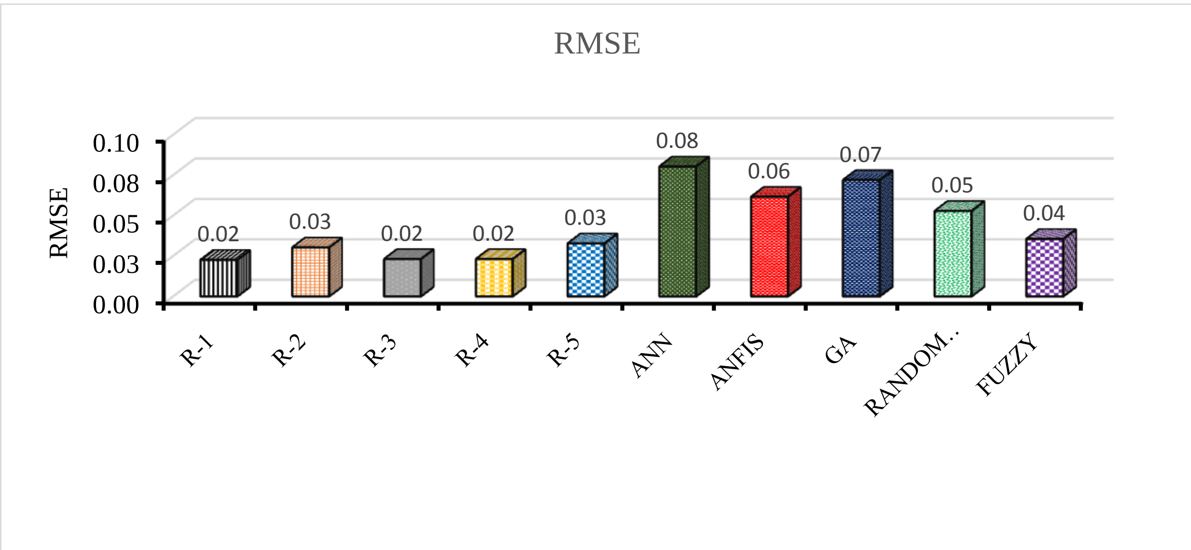


Fig. 13 RSME of different GMMs.

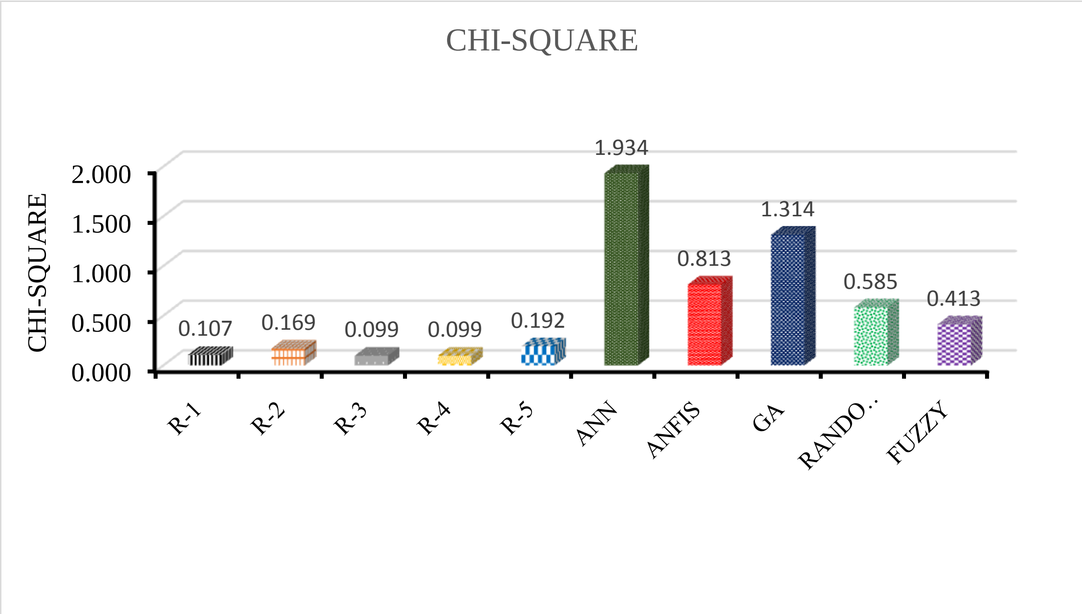


Fig. 14 Chi-Square of different GMMs.

From the above figure we can notice that RSME value is very less for all the GMM. The same results are obtained in case of Chi-square test. It is to be mentioned that, corresponding to 211 number of data the degree of freedom is 210 and related Chi-square value for 99.5% confidence level is 160.969. This depicts that the predicted PGA by all the above mentioned GMMs yield satisfactory result for 99.5% confidence level.

To comprehensively address the intricacies and uncertainties inherent in seismic hazard assessment, the incorporation of suitable weighting techniques grounded in statistical methodologies is essential. As demonstrated in the work by Lanzano et al. [158], such an approach can yield a more nuanced understanding of model performance and its resilience. Thus, it is to be considered for proposing appropriate weighting strategies for the selected models employing these statistical methodologies. This adjustment will significantly enhance the evaluation process, rendering the models more dependable and valuable for future studies and users seeking precise seismic hazard assessments.

In the realm of decision theory, a scoring rule serves as a means to gauge the precision of probabilistic forecasts [159]. Its utility becomes evident in scenarios where predictions necessitate the assignment of probabilities to a collection of exclusive and non-overlapping potential outcomes. A crucial characteristic of a scoring rule is its propriety, which implies that the forecaster's model attains the highest possible score when assessed against the dataset employed to construct the model. Furthermore, a scoring rule is deemed strictly proper when this peak score is singularly unique.

In order to evaluate the effectiveness of GMMs in assessing performance, the scoring process relies on residuals which are computed as the logarithmic disparities between observed values and predictions, then they are scaled by the overall standard deviations [160][159]. It is presupposed that these data are normally distributed. The scoring methods can be able to determine model performance as they can capture different features, related to the hazard analysis, and help in capturing the epistemic uncertainty related to GMMs.

In order to select and weight the GMMs using scores on the basis of likelihoods, Scherbaum et al. [161]suggested an objective method. This methods [162] have become very widespread and have been amply used for the determination of models in PSHA [163]. In this particular context, the central challenge revolves that on the basis of the concept of likelihood for a set of observations is to decide the distance in the model space between the unknown model, representing the reality, and the candidate model. The likelihood yields under a model the probability of the observed data [164][160][163][162] .

Let it be assumed that the likelihood of a model, characterized by a continuous probability density function f(x), for set of independent observations x ={x_i} with i=1,..,N. The Log-likelihood (LLH) of the model is

$$log_b L(x) = -\frac{1}{N}\sum_{i=1}^{N} log_b\big(g(x_i)\big) \quad \text{Eq. (3)}$$

In the equation N represents the number of observations and the base b of the logarithm is set to 2 to get the results in bit. This approach calculates the mean log-likelihood value for 'x' within the context of a normal density function, which is defined by its median and corresponding variance. The method is put into practice with the aim of minimizing the LLH value when the model achieves its optimal performance.

The weight of each model can be computed as [73]

$$w_k = \frac{2^{-LLH_k}}{\sum_{k=1}^{5} 2^{-LLH_k}} \qquad \text{Eq. (4)}$$

In the present study, LLH has been computed by above mentioned methodology for 10 GMMs for predicting PGA which is presented in Fig. 15.

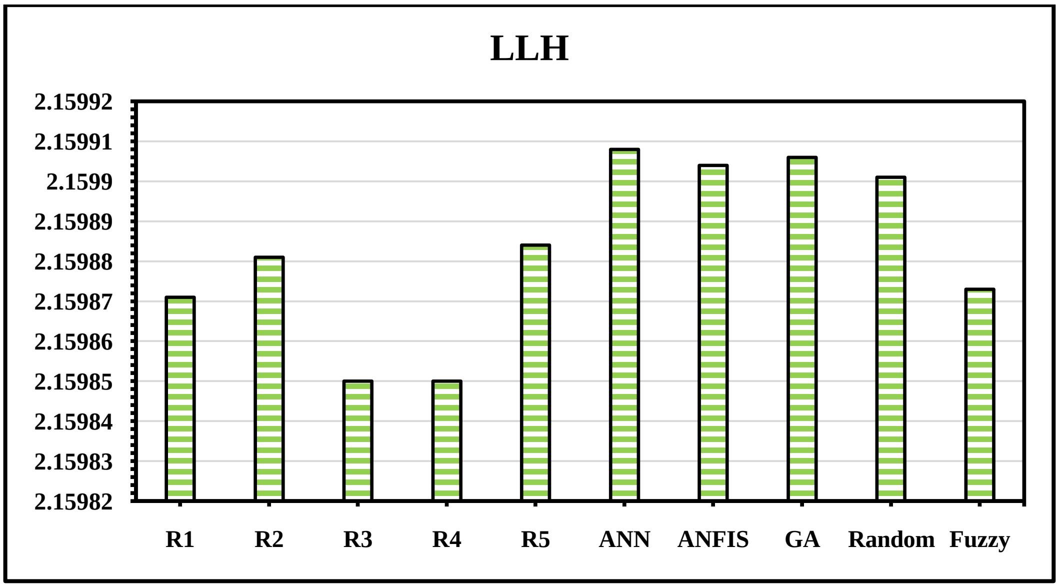


Fig. 15 LLH (log likelihood) of different GMMs.

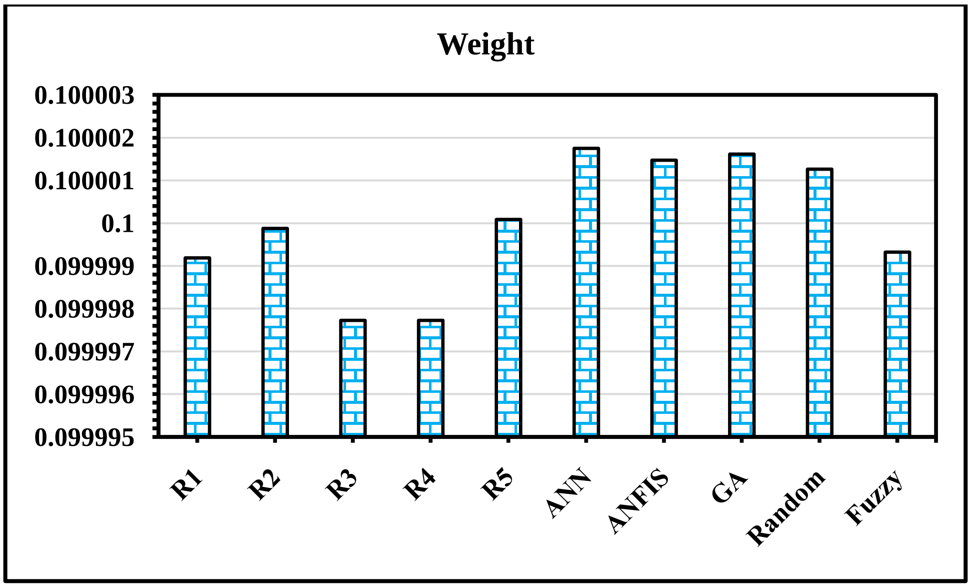


Fig. 16 Weights proposed for different GMMs.

3.5. SUMMARY

GMM developed using several methods. Regression method were done with help of MS-Excel, for GA genexprotools5.0 has been used. Remaining model were developed with the help of MATLAB. To visualise the data, graph has been plotted. Various mathematical method incorporated to evaluate appropriateness of data. RSME, Chi-square value and LLH which gives idea of accuracy of data were used here. A residual plot was also given.

4.CONCLUSION AND FUTURE SCOPE

4.1 SUMMARY

In the present paper comparison of different GMM presented by the previous researcher has been done. As we know proper prediction of earthquake force is very important for designing structure resistant to seismic force. About 13 GMM from various paper for the Himalayan region has been considered. And various values like RSME, Chi-square and Log-likelihood were evaluated to get better idea of accuracy. Most of the previous paper was based on the regression method only. There were very few paper on GMM based on machine learning technique. So here in present paper effort was also to develop GMM oneself with the help of machine learning technique and compare them. Here comparison is also done between the developed GMM in this paper and the previously developed GMM. RSME, Chi-square and log-likelihood value are also evaluated for GMM developed using machine learning method to get the idea of the appropriateness of the method.

4.2 MAJOR FINDINGS

The major conclusion can be drawn from the paper is as follows: -

- Almost all the GMM proposed previously ware based on regression method except the GMMs proposed by Shiuly et al. 2020 [38] where modern ML techniques were used.
- RMSE, Chi-square and LLH scoring results reveals that almost all the GMMs predict accurately the ground motion.
- Proposing appropriate weights based on statistical approaches can provide a more comprehensive understanding of model performance and

robustness, which will be very much useful for future seismic hazard analysis.

- GMM developed by machine learning method gives result almost close to each other except for the GA method for magnitude 4 gives different result as compared other one.
- RSME, Chi-square and LLH value reveals that all the predicted models were accepted for GMM model data prediction. But may vary case to case where more data were required for machine learning data prediction otherwise well-defined for data prediction in regression analysis where less data were introduced.
- All predicted models of LLH with weightage are in acceptable limit(LLH> 0 and ω<1).

4.3 LIMITATION

In the present investigation following limitations are: -

- Almost all the GMM developed previously were silent about the fault mechanism, rupture distance, etc. which is an important factor for the seismic force.
- To get more appropriate idea a huge number of data is required. Especially for bigger magnitude which were very less in number as compared to smaller one.
- Only rock site data and GMM previously developed were incorporated in the study.
- For development of GMM with the help of machine learning technique only two factor were considered magnitude and hypo-central distance to avoid the complexity.

- To get best and more accurate result it is necessary to incorporate several other factor responsible for seismic force.
- Only 5 method of machine learning were used. To get more appropriate several other machine learning methods could have been used.
- There various mathematical tool or checking correctness of result which were not considered.

4.4 RECOMMENDATION FOR FURTHER STUDY

- More number of data should be considered to get the result.
- Several other factor like site condition, fault mechanism, etc. must consider to get accurate data.
- There is various machine learning method like SVM, etc. that also must be used to develop GMM and compare.
- Other method shall also use to check appropriateness of data.

REFERENCES

[1] "https://www.iris.edu/hq/inclass/fact-sheet/how_often_do_earthquakes_occur."

[2] G. R. Toro, N. A. Abrahamson, and J. F. Schneider, "Model of strong ground motions from earthquakes in central and eastern North America: Best estimates and uncertainties," *Seismol. Res. Lett.*, vol. 68, no. 1, pp. 41–57, 1997, doi: 10.1785/gssrl.68.1.41.

[3] D. L. Orphal and J. A. Lahoud, "Prediction of peak ground motion from earthquakes," *Bull. Seismol. Soc. Am.*, vol. 64, no. 5, pp. 1563–1574, Oct. 1974, doi: 10.1785/BSSA0640051563.

[4] M. D. Trifunac and A. G. Brady, "On the correlation of seismic intensity scales with the peaks of recorded strong ground motion," *Bull. Seismol. Soc. Am.*, vol. 65, no. 1, pp. 139–162, Feb. 1975, doi: 10.1785/BSSA0650010139.

[5] J. G. Anderson, "On the attenuation of Modified Mercalli Intensity with distance in the United States," *Bull. Seismol. Soc. Am.*, vol. 68, no. 4, pp. 1147–1179, Aug. 1978, doi: 10.1785/BSSA0680041147.

[6] A. Lahiri, P. R. Jena, R. K. Rao, and T. K. Sen, "Economic Consequences of Gujarat Earthquake," *Econ. Polit. Wkly.*, vol. XXXVI, no. 16, pp. 1319–1332, 2001, [Online]. Available: http://www.epw.in/special-articles/economic-consequences-gujarat-earthquake.html

[7] J. P. Rafferty, "Nepal earthquake of 2015," *Encyclopedia Britannica*. [Online]. Available: https://www.britannica.com/topic/Nepal-earthquake-of-2015

[8] F. Cotton, M. Campillo, A. Deschamps, and B. K. Rastogi, "Rupture history and seismotectonics of the 1991 Uttarkashi, Himalaya earthquake," *Tectonophysics*, vol. 258, no. 1–4, pp. 35–51, Jun. 1996, doi: 10.1016/0040-1951(95)00154-9.

[9] S. T. G. Raghukanth and S. Nadh Somala, "Modeling of Strong-Motion Data in Northeastern India: Q, Stress Drop, and Site Amplification," *Bull. Seismol. Soc. Am.*, vol. 99, no. 2A, pp. 705–725, Apr. 2009, doi: 10.1785/0120080025.

[10] A. Kumar*, H. Mittal, R. Kumar, and R. S. Ahluwalia, "Empirical Attenuation relationship for Peak Ground Horizontal Acceleration for North-East Himalaya," *VIETNAM J. EARTH Sci.*, vol. 39, no. 1, Feb. 2017, doi: 10.15625/0866-7187/39/1/9183.

[11] National Disaster Management Authority, "Earthquake Disaster Risk Index Report," 2019.

[12] S. Kramer, *Geotechnical Earthquake Engineering*. 1996.

[13] S. Kolathayar, "Recent seismicity in Delhi and population exposure to seismic hazard," *Nat. Hazards*, vol. 109, no. 3, pp. 2621–2648, Dec. 2021, doi: 10.1007/s11069-021-04936-x.

[14] R. N. Iyengar and S. Ghosh, "Microzonation of earthquake hazard in Greater Delhi area," *Curr. Sci.*, vol. 87, no. 9, pp. 1193–1202, 2004.

[15] M. L. Sharma, H. R. Wason, and R. Dimri, "Seismic Zonation of the Delhi Region for Bedrock Ground Motion," *Pure Appl. Geophys.*, vol. 160, no. 12, pp. 2381–2398, Dec. 2003, doi: 10.1007/s00024-003-2400-6.

[16] S. Divakar, E. L. Prakash, and S. Kolathayar, "Land Use Exposure to Deterministic Seismic Hazard in Delhi National Capital Territory," in *Geotechnical Earthquake Engineering and Soil Dynamics V*, Jun. 2018, pp. 135–145. doi: 10.1061/9780784481462.013.

[17] A. Shiuly and J. P. Narayan, "Deterministic seismic microzonation of Kolkata city," *Nat. Hazards*, vol. 60, no. 2, pp. 223–240, Jan. 2012, doi: 10.1007/s11069-011-0004-5.

[18] S. K. Nath, M. D. Adhikari, N. Devaraj, and S. K. Maiti, "Seismic vulnerability and

risk assessment of Kolkata City, India," *Nat. Hazards Earth Syst. Sci.*, vol. 15, no. 6, pp. 1103–1121, Jun. 2015, doi: 10.5194/nhess-15-1103-2015.
[19] W. K. Mohanty and M. Y. Walling, "Seismic hazard in mega city Kolkata, India," *Nat. Hazards*, vol. 47, no. 1, pp. 39–54, Oct. 2008, doi: 10.1007/s11069-007-9195-1.
[20] A. Shiuly, R. B. Sahu, and S. Mandal, "Seismic microzonation of Kolkata," *Geomech. Eng.*, vol. 9, no. 2, pp. 125–144, Aug. 2015, doi: 10.12989/gae.2015.9.2.125.
[21] P. Anbazhagan, K. Bajaj, and S. Patel, "Seismic hazard maps and spectrum for Patna considering region-specific seismotectonic parameters," *Nat. Hazards*, vol. 78, no. 2, pp. 1163–1195, Sep. 2015, doi: 10.1007/s11069-015-1764-0.
[22] P. Anbazhagan, K. Bajaj, K. Matharu, S. S. R. Moustafa, and N. S. N. Al-Arifi, "Probabilistic seismic hazard analysis using the logic tree approach – Patna district (India)," *Nat. Hazards Earth Syst. Sci.*, vol. 19, no. 10, pp. 2097–2115, Oct. 2019, doi: 10.5194/nhess-19-2097-2019.
[23] M. L. Sharma and C. Lindholm, "Earthquake Hazard Assessment for Dehradun, Uttarakhand, India, Including a Characteristic Earthquake Recurrence Model for the Himalaya Frontal Fault (HFF)," *Pure Appl. Geophys.*, vol. 169, no. 9, pp. 1601–1617, Sep. 2012, doi: 10.1007/s00024-011-0427-7.
[24] O. Baro, A. Kumar, and A. Ismail-Zadeh, "Seismic hazard assessment of the Shillong Plateau using a probabilistic approach," *Geomatics, Nat. Hazards Risk*, vol. 11, no. 1, pp. 2210–2238, Jan. 2020, doi: 10.1080/19475705.2020.1833989.
[25] R. Das, M. L. Sharma, and H. R. Wason, "Probabilistic Seismic Hazard Assessment for Northeast India Region," *Pure Appl. Geophys.*, vol. 173, no. 8, pp. 2653–2670, Aug. 2016, doi: 10.1007/s00024-016-1333-9.
[26] S. K. Nath, K. K. S. Thingbaijam, and A. Raj, "Earthquake hazard in Northeast India — A seismic microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city," *J. Earth Syst. Sci.*, vol. 117, no. S2, pp. 809–831, Nov. 2008, doi: 10.1007/s12040-008-0070-6.
[27] R. P. Singh, A. Aman, and Y. J. J. Prasad, "Attenuation relations for strong seismic ground motion in the Himalayan region," *Pure Appl. Geophys. PAGEOPH*, vol. 147, no. 1, pp. 161–180, Jun. 1996, doi: 10.1007/BF00876442.
[28] M. L. Sharma, "Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India," *Bull. Seismol. Soc. Am.*, vol. 88, no. 4, pp. 1063–1069, Aug. 1998, doi: 10.1785/BSSA0880041063.
[29] M. L. Sharma, J. Douglas, H. Bungum, and J. Kotadia, "Ground-Motion Prediction Equations Based on Data from the Himalayan and Zagros Regions," *J. Earthq. Eng.*, vol. 13, no. 8, pp. 1191–1210, Oct. 2009, doi: 10.1080/13632460902859151.
[30] NDMA, "Development of probabilistic seismic hazard map of India, Technical report by National Disaster Management Authority, Govt. of India.," 2010.
[31] P. Anbazhagan, A. Kumar, and T. G. Sitharam, "Ground motion prediction equation considering combined dataset of recorded and simulated ground motions," *Soil Dyn. Earthq. Eng.*, vol. 53, pp. 92–108, Oct. 2013, doi: 10.1016/j.soildyn.2013.06.003.
[32] S. T. G. Raghukanth and B. Kavitha, "Ground Motion Relations for Active Regions in India," *Pure Appl. Geophys.*, vol. 171, no. 9, pp. 2241–2275, Sep. 2014, doi: 10.1007/s00024-014-0807-x.
[33] P. Kumar, B. P. Chamoli, A. Kumar, and A. Gairola, "Attenuation Relationship for Peak Horizontal Acceleration of Strong Ground Motion of Uttarakhand Region of Central Himalayas," *J. Earthq. Eng.*, vol. 25, no. 12, pp. 2537–2554, Oct. 2019, doi: 10.1080/13632469.2019.1634161.
[34] R. Ramkrishnan, K. Sreevalsa, and T. G. Sitharam, "Development of New Ground Motion Prediction Equation for the North and Central Himalayas Using Recorded

Strong Motion Data," *J. Earthq. Eng.*, vol. 25, no. 10, pp. 1903–1926, Aug. 2019, doi: 10.1080/13632469.2019.1605318.
[35] R. Ramkrishnan, K. Sreevalsa, and T. G. Sitharam, "Strong Motion Data Based Regional Ground Motion Prediction Equations for North East India Based on Non-Linear Regression Models," *J. Earthq. Eng.*, vol. 26, no. 6, pp. 2927–2947, Apr. 2020, doi: 10.1080/13632469.2020.1778586.
[36] H. Nh and A. Kumar, "Ground motion prediction equation for north India, applicable for different site classes," *Soil Dyn. Earthq. Eng.*, vol. 139, p. 106425, Dec. 2020, doi: 10.1016/j.soildyn.2020.106425.
[37] H. Huang, R. Ramkrishnan, S. Kolathayar, A. Garg, and J. S. Yadav, "Development of Region-Specific New Generation Attenuation Relations for North India Using Artificial Neural Networks," 2021, pp. 85–101. doi: 10.1007/978-981-33-4324-5_6.
[38] A. Shiuly, N. Roy, and R. B. Sahu, "Prediction of peak ground acceleration for Himalayan region using artificial neural network and genetic algorithm," *Arab. J. Geosci.*, vol. 13, no. 5, p. 215, Mar. 2020, doi: 10.1007/s12517-020-5211-5.
[39] A. Mohammadi, S. Karimzadeh, S. A. Banimahd, V. Ozsarac, and P. B. Lourenço, "The potential of region-specific machine-learning-based ground motion models: Application to Turkey," *Soil Dyn. Earthq. Eng.*, vol. 172, p. 108008, Sep. 2023, doi: 10.1016/j.soildyn.2023.108008.
[40] F. Khosravikia and P. Clayton, "Machine learning in ground motion prediction," *Comput. Geosci.*, vol. 148, p. 104700, Mar. 2021, doi: 10.1016/j.cageo.2021.104700.
[41] J. Dhanya and S. T. G. Raghukanth, "Ground Motion Prediction Model Using Artificial Neural Network," *Pure Appl. Geophys.*, vol. 175, no. 3, pp. 1035–1064, Mar. 2018, doi: 10.1007/s00024-017-1751-3.
[42] A. Harbindu, S. Gupta, and M. L. Sharma, "Earthquake ground motion predictive equations for Garhwal Himalaya, India," *Soil Dyn. Earthq. Eng.*, vol. 66, pp. 135–148, Nov. 2014, doi: 10.1016/j.soildyn.2014.06.018.
[43] K. N. Khattri, A. M. Rogers, D. M. Perkins, and S. T. Algermissen, "A seismic hazard map of India and adjacent areas," *Tectonophysics*, vol. 108, no. 1–2, pp. 93–134, Sep. 1984, doi: 10.1016/0040-1951(84)90156-2.
[44] K. K. Sharma, "Geologic and t e c t o n i c e v o l u t i o n of t h e H i m a l a y a before and after the India-Asia collision," no. 4, pp. 265–282, 1998.
[45] GSI, "Seismotectonic Atlas of India and Its Environs," *Geol. Surv. India*, vol. 10289, no. September, 2008.
[46] M. Verma and B. K. Bansal, "Active fault research in India: achievements and future perspective," *Geomatics, Nat. Hazards Risk*, vol. 7, no. 1, pp. 65–84, 2016, doi: 10.1080/19475705.2013.868371.
[47] P. Sengupta, S. K. Nath, K. K. S. Thingbaijam, and S. Mistri, "Fractal analysis of major faults in India on a regional scale," *J. Geol. Soc. India*, vol. 78, no. 3, pp. 226–232, 2011, doi: 10.1007/s12594-011-0086-4.
[48] R. D. Oldham, *Report of the great earthquake of 12th June, 1897*. Office of the Geological survey, 1899.
[49] T. Nakata, "Geomorphic history and crustal movements of the foothills of the Himalayas," *Sci. Reports Tohoku Univ. 7th Ser.*, vol. 22, pp. 39–177, 1972.
[50] J. N. Malik and T. Nakata, "Active faults and related Late Quaternary deformation along the northwestern Himalayan Frontal Zone, India," *Ann. Geophys.*, 2003.
[51] J. N. Malik, T. Nakata, G. Philip, N. Suresh, and N. S. Virdi, "Active fault and paleoseismic investigation: evidence of a historic earthquake along Chandigarh Fault in the Frontal Himalayan zone, NW India," *Himal. Geol.*, vol. 29, no. 2, pp. 109–117, 2008.

[52] J. N. Malik *et al.*, “Active fault, fault growth and segment linkage along the Janauri anticline (frontal foreland fold), NW Himalaya, India,” *Tectonophysics*, vol. 483, no. 3–4, pp. 327–343, 2010.
[53] N. N. Ambraseys and D. Jackson, “A note on early earthquakes in northern India and southern Tibet, Bangalore, INDE,” *Curr. Sci. Assoc.*, 2003.
[54] G. Kothyari, P. Pant, M. Joshi, K. Luirei, and J. Malik, “Active Faulting and Deformation of Quaternary Landform Sub-Himalaya, India,” *GEOCHR*, vol. 37, no. 1, pp. 63–71, Jan. 2010, doi: 10.2478/v10003-010-0015-3.
[55] D. R. Nandy, *Geodynamics of Northeastern India and the adjoining region*. Scientific Book Centre, 2017.
[56] D. V. Reddy *et al.*, “The great 1950 Assam Earthquake revisited: Field evidences of liquefaction and search for paleoseismic events,” *Tectonophysics*, vol. 474, no. 3–4, pp. 463–472, Sep. 2009, doi: 10.1016/j.tecto.2009.04.024.
[57] D. Guha, S. Bardhan, S. R. Basir, A. K. De, and A. Sarkar, “Imprints of Himalayan thrust tectonics on the Quaternary piedmont sediments of the Neora–Jaldhaka Valley, Darjeeling–Sikkim Sub-Himalayas, India,” *J. Asian Earth Sci.*, vol. 30, no. 3–4, pp. 464–473, May 2007, doi: 10.1016/j.jseaes.2006.11.010.
[58] R. K. M. Devi, S. S. Bhakuni, and P. K. Bora, “Tectonic implication of drainage set-up in the Sub-Himalaya: A case study of Papumpare district, Arunachal Himalaya, India,” *Geomorphology*, vol. 127, no. 1–2, pp. 14–31, Apr. 2011, doi: 10.1016/j.geomorph.2010.11.010.
[59] R. D. Oldham, *The Cutch (Kachh) earthquake of 16th June, 1819: with a revision of the great earthquake of 12th June, 1897*, vol. 46. Government of India, Central Publication Branch, 1926.
[60] H. K. Gupta, B. K. Rastogi, I. Mohan, C. V. R. K. Rao, S. V. S. Sarma, and R. U. M. Rao, “An investigation into the Latur earthquake of September 29, 1993 in southern India,” *Tectonophysics*, vol. 287, no. 1–4, pp. 299–318, Mar. 1998, doi: 10.1016/S0040-1951(98)80075-9.
[61] P. Pande, N. V Venkatraman, S. K. Gupta, and B. Venkatraman, “Terrain changes and associated features consequent to Killari earthquake of 30 th Sept., 1993,” *Geol. Surv. India Spec. Publ*, no. 27, pp. 215–220, 1994.
[62] J. B. Pande P, Sharda YP, Ghevaria ZG, Joshi KC, “Coseismic structural ground deformation, in Kachchh (Bhuj) Earthquake, 26 January 2001,” *Geol. Surv. India Spec. Publ.*, pp. 163–171, 2003.
[63] H. Kaneda *et al.*, “Surface rupture of the 2005 Kashmir, Pakistan, earthquake and its active tectonic implications,” *Bull. Seismol. Soc. Am.*, vol. 98, no. 2, pp. 521–557, 2008.
[64] S. Jade, “Estimates of plate velocity and crustal deformation in the Indian subcontinent using GPS geodesy,” *Curr. Sci.*, pp. 1443–1448, 2004.
[65] V. K. Gahalaut, B. Nagarajan, J. K. Catherine, and S. Kumar, “Constraints on 2004 Sumatra–Andaman earthquake rupture from GPS measurements in Andaman–Nicobar Islands,” *Earth Planet. Sci. Lett.*, vol. 242, no. 3–4, pp. 365–374, 2006.
[66] P. Banerjee, F. Pollitz, B. Nagarajan, and R. Bürgmann, “Coseismic slip distributions of the 26 December 2004 Sumatra–Andaman and 28 March 2005 Nias earthquakes from GPS static offsets,” *Bull. Seismol. Soc. Am.*, vol. 97, no. 1A, pp. S86–S102, 2007.
[67] S. Jade, M. S. M. Vijayan, S. S. Gupta, P. D. Kumar, V. K. Gaur, and S. Arumugam, “Effect of the M 9.3 Sumatra–Andaman islands earthquake of 26 December 2004 at several permanent and campaign GPS stations in the Indian continent,” *Int. J. Remote Sens.*, vol. 28, no. 13–14, pp. 3045–3054, 2007.
[68] R. Bendick, R. Bilham, M. A. Khan, and S. F. Khan, “Slip on an active wedge thrust

from geodetic observations of the 8 October 2005 Kashmir earthquake," *Geology*, vol. 35, no. 3, pp. 267–270, 2007, doi: 10.1130/G23158A.1.

[69] I. A. Parvez, A. K. Sutar, M. Mridula, S. K. Mishra, and S. S. Rai, "Coda Q Estimates in the Andaman Islands Using Local Earthquakes," *Pure Appl. Geophys.*, vol. 165, no. 9–10, pp. 1861–1878, Oct. 2008, doi: 10.1007/s00024-008-0399-4.

[70] R. P. Singh, A. Aman, and Y. J. J. Prasad, "Attenuation relations for strong seismic ground motion in the Himalayan region," *Pure Appl. Geophys. PAGEOPH*, vol. 147, no. 1, pp. 161–180, Jun. 1996, doi: 10.1007/BF00876442.

[71] A. R. Chandrasekaran and J. D. Das, "ISET annual lecture, 1988: Strong motion arrays in India and characteristics of recent recorded events.," *Bull. Indian Soc. Earthq. Technol.*, vol. 27, no. 1, pp. 1–66, 1990.

[72] H. Mittal, A. Kumar, and R. Ramhmachhuani, "Indian National Strong Motion Instrumentation Network and Site Characterization of Its Stations," *Int. J. Geosci.*, vol. 03, no. 06, pp. 1151–1167, 2012, doi: 10.4236/ijg.2012.326117.

[73] R. Ramkrishnan, K. Sreevalsa, and T. G. Sitharam, "Strong Motion Data Based Regional Ground Motion Prediction Equations for North East India Based on Non-Linear Regression Models," *J. Earthq. Eng.*, vol. 26, no. 6, pp. 2927–2947, Apr. 2022, doi: 10.1080/13632469.2020.1778586.

[74] R. Das *et al.*, "Earthquake Magnitude Conversion Problem," *Bull. Seismol. Soc. Am.*, vol. 108, no. 4, pp. 1995–2007, Apr. 2018, doi: 10.1785/0120170157.

[75] "https://www.strongmotioncenter.org/vdc/scripts/default.plx."

[76] I. R. Department of Earthquake Engineering, "https://pesmos.org/."

[77] N. Puri and A. Jain, "Possible seismic hazards in Chandigarh city of North-western India due to its proximity to Himalayan frontal thrust," *J. Indian Geophys. Union*, vol. 22, no. 5, pp. 485–506, 2018.

[78] IS-1893-Part-1-(2016), "Criteria for Earthquake resistant design of structures, Part 1:General Provisions and buildings," *Bur. Indian Stand. New Delhi*, vol. 1893, no. December, pp. 1–44, 2016.

[79] A. Shiuly and N. Roy, "A generalized VS–N correlation using various regression analysis and genetic algorithm," *Acta Geod. Geophys.*, vol. 53, no. 3, pp. 479–502, Sep. 2018, doi: 10.1007/s40328-018-0220-5.

[80] A. Shiuly, "Performance of Buildings Using Site Specific Ground Motion of Kolkata, India," *Int. J. Geotech. Earthq. Eng.*, vol. 10, no. 1, pp. 17–29, Jan. 2019, doi: 10.4018/IJGEE.2019010102.

[81] A. Shiuly, R. B. Sahu, and S. Mandal, "Effect of Soil on Ground Motion Amplification of Kolkata City," *Int. J. Geotech. Earthq. Eng.*, vol. 5, no. 1, pp. 1–20, Jan. 2014, doi: 10.4018/ijgee.2014010101.

[82] R. N. Iyengar and S. Ghosh, "SEISMIC HAZARD MAPPING OF DELHI CITY," Nov. 2004.

[83] N. Puri and A. Jain, "Microzonation of Seismic Hazard for the State of Haryana, India," *J. Geol. Soc. India*, vol. 94, no. 3, pp. 297–308, Sep. 2019, doi: 10.1007/s12594-019-1310-x.

[84] A. Ansari, F. Zahoor, K. S. Rao, and A. Jain, "Seismic hazard assessment studies based on deterministic and probabilistic approaches for the Jammu region, NW Himalayas," *Arab. J. Geosci.*, vol. 15, no. 11, 2022, doi: 10.1007/s12517-022-10330-z.

[85] A. Ansari, F. Zahoor, K. S. Rao, and A. K. Jain, "Deterministic Approach for Seismic Hazard Assessment of Jammu Region, Jammu and Kashmir," in *Geo-Congress 2022*, Mar. 2022, pp. 590–598. doi: 10.1061/9780784484043.057.

[86] F. Zahoor, A. Ansari, K. S. Rao, and N. Satyam, "Seismic Hazard Assessment of Kashmir Region Using Logic Tree Approach: Focus on Sensitivity of PSHA Results

Towards Declustering Procedures and GMPEs," *Pure Appl. Geophys.*, vol. 180, no. 3, pp. 789–827, Mar. 2023, doi: 10.1007/s00024-023-03239-5.
[87] R. Chandra *et al.*, "Seismic hazard and probability assessment of Kashmir valley, northwest Himalaya, India," *Nat. Hazards*, vol. 93, no. 3, pp. 1451–1477, Sep. 2018, doi: 10.1007/s11069-018-3362-4.
[88] S. F. H. Shah, C. Ningsheng, A. H. Khaliq, M. Alam, H. Ahmad, and M. Rahman, "Probabilistic Seismic Hazard Analysis of Hazara Kashmir Syntaxes and its Surrounding," *J. Geol. Soc. India*, vol. 98, no. 9, pp. 1308–1319, Sep. 2022, doi: 10.1007/s12594-022-2167-y.
[89] H. Sana, "A probabilistic approach to the seismic hazard in Kashmir basin, NW Himalaya," *Geosci. Lett.*, vol. 6, no. 1, p. 5, Dec. 2019, doi: 10.1186/s40562-019-0136-0.
[90] A. Shiuly, V. Kumar, and J. P. Narayan, "Computation of ground motion amplification in Kolkata megacity (India) using finite-difference method for seismic microzonation," *Acta Geophys.*, vol. 62, no. 3, pp. 425–450, Jun. 2014, doi: 10.2478/s11600-013-0169-2.
[91] A. Shiuly, R. B. Sahu, S. Mandal, and N. Roy, "Local Site Effect Due to Past Earthquakes in Kolkata," *J. Geol. Soc. India*, vol. 91, no. 4, pp. 400–410, Apr. 2018, doi: 10.1007/s12594-018-0872-3.
[92] N. Shaligram Patil, J. Das, A. Kumar, M. Mohan Rout, and R. Das, "Probabilistic seismic hazard assessment of Himachal Pradesh and adjoining regions," *J. Earth Syst. Sci.*, vol. 123, no. 1, pp. 49–62, 2014, doi: 10.1007/s12040-013-0378-8.
[93] P. Muthuganeisan and S. T. G. Raghukanth, "Site-specific Probabilistic Seismic Hazard Map of Himachal Pradesh, India. Part II. Hazard Estimation," *Acta Geophys.*, vol. 64, no. 4, pp. 853–884, Aug. 2016, doi: 10.1515/acgeo-2016-0011.
[94] S. Rao, T. Thaker, A. Aggarwal, T. Bhandari, and S. Kabra, "Deterministic Seismic Hazard Analysis of Ahmedabad Region, Gujarat," *Int. J. Earth Sci. Eng.*, vol. 05, pp. 206–213, Apr. 2012.
[95] M. D. Petersen, B. K. Rastogi, E. S. Schweig, S. C. Harmsen, and J. S. Gomberg, "Sensitivity analysis of seismic hazard for the northwestern portion of the state of Gujarat, India," *Tectonophysics*, vol. 390, no. 1–4, pp. 105–115, Oct. 2004, doi: 10.1016/j.tecto.2003.06.004.
[96] P. Choudhury, S. Chopra, and M. R. Kumar, "A review of seismic hazard assessment of Gujarat: A highly active intra-plate region," *Earth-Science Rev.*, vol. 187, pp. 205–218, Dec. 2018, doi: 10.1016/j.earscirev.2018.09.014.
[97] A. Kumar, P. Anbazhagan, and T. G. Sitharam, "Seismic hazard analysis of Lucknow considering local and active seismic gaps," *Nat. Hazards*, vol. 69, no. 1, pp. 327–350, Oct. 2013, doi: 10.1007/s11069-013-0712-0.
[98] Anbazhagan P, K. Bajaj, N. Dutta, S. S. R Moustafa, and N. S. N Al-Arifi, "Region-specific deterministic and probabilistic seismic hazard analysis of Kanpur city," *J. Earth Syst. Sci.*, vol. 126, no. 1, p. 12, Feb. 2017, doi: 10.1007/s12040-016-0779-6.
[99] A. Paul, P. Chakrabortty, A. Burman, and S. Kumar, "Probabilistic Seismic Hazard Analysis of Sitamarhi near Bihar-Nepal Region." Research Square, 2021. doi: 10.21203/rs.3.rs-475275/v1.
[100] S. Sinha and S. Selvan, "An Improved Probabilistic Seismic Hazard Assessment of Tripura, India," *Pure Appl. Geophys.*, vol. 179, no. 12, pp. 4371–4393, Dec. 2022, doi: 10.1007/s00024-022-03176-9.
[101] K. Pallav, S. T. G. Raghukanth, and K. D. Singh, "Probabilistic seismic hazard estimation of Manipur, India," *J. Geophys. Eng.*, vol. 9, no. 5, pp. 516–533, Oct. 2012, doi: 10.1088/1742-2132/9/5/516.

[102] M. Rahman, S. Siddiqua, and A. S. M. Kamal, *Probabilistic seismic hazard analysis for Dhaka city, Bangladesh*. 2017.
[103] N. Borah and A. Kumar, "Probabilistic seismic hazard analysis of the North-East India towards identification of contributing seismic sources," *Geomatics, Nat. Hazards Risk*, vol. 14, no. 1, pp. 1–38, Dec. 2023, doi: 10.1080/19475705.2022.2160662.
[104] S. Kumar *et al.*, "Probabilistic Seismic Hazard Analysis (PSHA) to estimate the input ground motions for Co-seismic landslide hazard assessment: A case study on Himalayan highways, Sikkim India," *Phys. Chem. Earth, Parts A/B/C*, vol. 127, p. 103157, Oct. 2022, doi: 10.1016/j.pce.2022.103157.
[105] R. Yadav and D. Kumar, "Evaluating the seismic hazard to Sikkim region of Himalaya using simulated accelerograms," *J. Earth Syst. Sci.*, vol. 131, no. 2, p. 84, Jun. 2022, doi: 10.1007/s12040-022-01833-0.
[106] G. N. S. N. Rao and D. N. Satyam, "Deterministic and Probabilistic Seismic Hazard Analysis of Tindharia, Darjeeling Sikkim Himalaya, India," *J. Geol. Soc. India*, vol. 98, no. 9, pp. 1295–1300, Sep. 2022, doi: 10.1007/s12594-022-2165-0.
[107] S. Akkar and J. J. Bommer, "Empirical Equations for the Prediction of PGA, PGV, and Spectral Accelerations in Europe, the Mediterranean Region, and the Middle East," *Seismol. Res. Lett.*, vol. 81, no. 2, pp. 195–206, Mar. 2010, doi: 10.1785/gssrl.81.2.195.
[108] N. A. Abrahamson and W. J. Silva, "Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes," *Seismol. Res. Lett.*, vol. 68, no. 1, pp. 94–127, Jan. 1997, doi: 10.1785/gssrl.68.1.94.
[109] D. M. Boore and G. M. Atkinson, "Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s," *Earthq. Spectra*, vol. 24, no. 1, pp. 99–138, Feb. 2008, doi: 10.1193/1.2830434.
[110] G. R. Toro, N. A. Abrahamson, and J. F. Schneider, "Model of Strong Ground Motions from Earthquakes in Central and Eastern North America: Best Estimates and Uncertainties," *Seismol. Res. Lett.*, vol. 68, no. 1, pp. 41–57, Jan. 1997, doi: 10.1785/gssrl.68.1.41.
[111] R. R. Youngs, S.-J. Chiou, W. J. Silva, and J. R. Humphrey, "Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes," *Seismol. Res. Lett.*, vol. 68, no. 1, pp. 58–73, Jan. 1997, doi: 10.1785/gssrl.68.1.58.
[112] J. J. Abrahamson, Norman A. and Litehiser, "Attenuation of Vertical Peak Accelerations," *Bull. Seismol. Soc. Am.*, vol. 79, pp. 549–580, 1989.
[113] T. Kanno, "A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data," *Bull. Seismol. Soc. Am.*, vol. 96, no. 3, pp. 879–897, Jun. 2006, doi: 10.1785/0120050138.
[114] H. Ghasemi, M. Zare, Y. Fukushima, and K. Koketsu, "An empirical spectral ground-motion model for Iran," *J. Seismol.*, vol. 13, no. 4, pp. 499–515, Oct. 2009, doi: 10.1007/s10950-008-9143-x.
[115] R. Ramkrishnan, S. Kolathayar, and T. G. Sitharam, "Seismic Hazard Assessment and Land Use Analysis of Mangalore City, Karnataka, India," *J. Earthq. Eng.*, vol. 25, no. 12, pp. 2349–2370, Oct. 2021, doi: 10.1080/13632469.2019.1608333.
[116] G. M. Atkinson and D. M. Boore, "Earthquake Ground-Motion Prediction Equations for Eastern North America," *Bull. Seismol. Soc. Am. G. M., Boore, D. M. (2006). Earthq. Ground-Motion Predict. Equations East. North Am. Bull. Seismol. Soc. Am. 96(6), 2181–2205. https//doi.org/10.1785/01*, vol. 96, no. 6, pp. 2181–2205, Dec. 2006, doi: 10.1785/0120050245.
[117] S. K. Nath, M. Das Adhikari, S. K. Maiti, and C. Ghatak, "Earthquake hazard potential

of Indo-Gangetic Foredeep: its seismotectonism, hazard, and damage modeling for the cities of Patna, Lucknow, and Varanasi," *J. Seismol.*, vol. 23, no. 4, pp. 725–769, Jul. 2019, doi: 10.1007/s10950-019-09832-3.
[118] Kenneth W. Campbell and Yousef Bozorgnia, "Updated near-source ground motion (attenuation) relations forthe horizontal and vertical components of peak ground acceleration and acceleration responsespectra," *Bull. Seismol. Soc. Am.*, vol. 93, pp. 314–331, 2003.
[119] NDMA, "Development of probabilistic seismic hazard map of India. Technical Report of the Working Committee of Experts (WCE) National Disaster Management Authority (NDMA), Govt of India," 2011.
[120] I. M. Idriss, "An NGA-West2 Empirical Model for Estimating the Horizontal Spectral Values Generated by Shallow Crustal Earthquakes," *Earthq. Spectra*, vol. 30, no. 3, pp. 1155–1177, Aug. 2014, doi: 10.1193/070613EQS195M.
[121] K. S. Rao and G. W. Rathod, "Seismic Microzonation of Indian Megacities: A Case Study of NCR Delhi," *Indian Geotech. J.*, vol. 44, no. 2, pp. 132–148, Jun. 2014, doi: 10.1007/s40098-013-0084-0.
[122] I. M. Idriss, "An NGA Empirical Model for Estimating the Horizontal Spectral Values Generated by Shallow Crustal Earthquakes," *Earthq. Spectra*, vol. 24, no. 1, pp. 217–242, Feb. 2008, doi: 10.1193/1.2924362.
[123] K. Kanai, "On the spectrum of strong earthquake motions," *東京大學地震研究所彙報= Bull. Earthq. Res. Institute, Univ. Tokyo*, vol. 40, no. 1, pp. 71–90, 1962.
[124] S. Akkar and J. J. Bommer, "Prediction of elastic displacement response spectra in Europe and the Middle East," *Earthq. Eng. Struct. Dyn.*, vol. 36, no. 10, pp. 1275–1301, Aug. 2007, doi: 10.1002/eqe.679.
[125] K. W. Campbell and Y. Bozorgnia, "NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s," *Earthq. Spectra*, vol. 24, no. 1, pp. 139–171, Feb. 2008, doi: 10.1193/1.2857546.
[126] N. N. Ambraseys, J. Douglas, S. K. Sarma, and P. M. Smit, "Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Horizontal Peak Ground Acceleration and Spectral Acceleration," *Bull. Earthq. Eng.*, vol. 3, no. 1, pp. 1–53, Jan. 2005, doi: 10.1007/s10518-005-0183-0.
[127] K. Sadigh, C.-Y. Chang, J. A. Egan, F. Makdisi, and R. R. Youngs, "Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data," *Seismol. Res. Lett.*, vol. 68, no. 1, pp. 180–189, Jan. 1997, doi: 10.1785/gssrl.68.1.180.
[128] D. Motazedian, "Stochastic Finite-Fault Modeling Based on a Dynamic Corner Frequency," *Bull. Seismol. Soc. Am.*, vol. 95, no. 3, pp. 995–1010, Jun. 2005, doi: 10.1785/0120030207.
[129] S. T. G. RaghuKanth, "Engineering models for earthquake sources," Indian Institute of Science, Bangalore, India, 2005.
[130] J. J. Abrahamson, Norman A. and Litehiser, "Attenuation of vertical peak acceleration," *Bull. Seismol. Soc. Am.*, vol. 79, Jun. 1989.
[131] P. Muthuganeisan and S. T. G. Raghukanth, "Site-specific Probabilistic Seismic Hazard Map of Himachal Pradesh, India. Part I. Site-specific Ground Motion Relations," *Acta Geophys.*, vol. 64, no. 2, pp. 336–361, Apr. 2016, doi: 10.1515/acgeo-2016-0010.
[132] R. N. Iyengar and S. T. G. R. Kanth, "Attenuation of Strong Ground Motion in

Peninsular India," *Seismol. Res. Lett.*, vol. 75, no. 4, pp. 530–540, Jul. 2004, doi: 10.1785/gssrl.75.4.530.

[133] P. Mandal, N. Kumar, C. Satyamurthy, and I. P. Raju, "Ground-motion Attenuation Relation from Strong-motion Records of the 2001 Mw 7.7 Bhuj Earthquake Sequence (2001–2006), Gujarat, India," *Pure Appl. Geophys.*, vol. 166, no. 3, pp. 451–469, Mar. 2009, doi: 10.1007/s00024-009-0444-y.

[134] S. K. Nath, M. Vyas, I. Pal, and P. Sengupta, "A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry," *J. Geophys. Res. Solid Earth*, vol. 110, no. B1, 2005.

[135] S. Das, I. D. Gupta, and V. K. Gupta, "A Probabilistic Seismic Hazard Analysis of Northeast India," *Earthq. Spectra*, vol. 22, no. 1, pp. 1–27, Feb. 2006, doi: 10.1193/1.2163914.

[136] S. Baruah, S. Baruah, N. K. Gogoi, O. Erteleva, F. Aptikaev, and J. R. Kayal, "Ground motion parameters of Shillong plateau: One of the most seismically active zones of northeastern India," *Earthq. Sci.*, vol. 22, no. 3, pp. 283–291, 2009, doi: 10.1007/s11589-009-0285-2.

[137] I. D. Gupta, "Response spectral attenuation relations for in-slab earthquakes in Indo-Burmese subduction zone," *Soil Dyn. Earthq. Eng.*, vol. 30, no. 5, pp. 368–377, May 2010, doi: 10.1016/j.soildyn.2009.12.009.

[138] P. Anbazhagan, C. V. Smitha, A. Kumar, and D. Chandran, "Estimation of design basis earthquake using region-specific Mmax, for the NPP site at Kalpakkam, Tamil Nadu, India," *Nucl. Eng. Des.*, vol. 259, pp. 41–64, Jun. 2013, doi: 10.1016/j.nucengdes.2013.02.047.

[139] K. W. Campbell, "Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra," *Seismol. Res. Lett.*, vol. 68, no. 1, pp. 154–179, Jan. 1997, doi: 10.1785/gssrl.68.1.154.

[140] P. Spudich, W. B. Joyner, A. G. Lindh, D. M. Boore, B. M. Margaris, and J. B. Fletcher, "SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes," *Bull. Seismol. Soc. Am.*, vol. 89, no. 5, pp. 1156–1170, Oct. 1999, doi: 10.1785/BSSA0890051156.

[141] G. M. Atkinson, "Empirical Ground-Motion Relations for Subduction-Zone Earthquakes and Their Application to Cascadia and Other Regions," *Bull. Seismol. Soc. Am.*, vol. 93, no. 4, pp. 1703–1729, Aug. 2003, doi: 10.1785/0120020156.

[142] S. K. Nath, A. Raj, K. K. S. Thingbaijam, and A. Kumar, "Ground Motion Synthesis and Seismic Scenario in Guwahati City--A Stochastic Approach," *Seismol. Res. Lett.*, vol. 80, no. 2, pp. 233–242, Mar. 2009, doi: 10.1785/gssrl.80.2.233.

[143] J. X. Zhao, "Attenuation Relations of Strong Ground Motion in Japan Using Site Classification Based on Predominant Period," *Bull. Seismol. Soc. Am.*, vol. 96, no. 3, pp. 898–913, Jun. 2006, doi: 10.1785/0120050122.

[144] N. A. Abrahamson, "Abrahamson & Silva NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters," *PEER Rep. Draft v2, Pacific Earthq. Eng. Res. Center, Berkeley, CA*, p. 380, 2007.

[145] S. Jain, R. A D, J. Arlekar, and P. Basu, *EMPIRICAL ATTENUATION RELATIONSHIPS FOR THE HIMALAYAN EARTHQUAKES BASED ON INDIAN STRONG MOTION DATA*. 2000.

[146] D. M. Boore, J. P. Stewart, E. Seyhan, and G. M. Atkinson, "NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes,"

Earthq. Spectra, vol. 30, no. 3, pp. 1057–1085, Aug. 2014, doi: 10.1193/070113EQS184M.

[147] K. Bajaj and P. Anbazhagan, "Regional stochastic GMPE with available recorded data for active region – Application to the Himalayan region," *Soil Dyn. Earthq. Eng.*, vol. 126, p. 105825, Nov. 2019, doi: 10.1016/j.soildyn.2019.105825.

[148] N. Abrahamson and W. Silva, "Summary of the Abrahamson & Silva NGA Ground-Motion Relations," *Earthq. Spectra*, vol. 24, no. 1, pp. 67–97, Feb. 2008, doi: 10.1193/1.2924360.

[149] B.-J. Chiou and R. R. Youngs, "An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra," *Earthq. Spectra*, vol. 24, no. 1, pp. 173–215, Feb. 2008, doi: 10.1193/1.2894832.

[150] N. A. Abrahamson, W. J. Silva, and R. Kamai, "Summary of the ASK14 Ground Motion Relation for Active Crustal Regions," *Earthq. Spectra*, vol. 30, no. 3, pp. 1025–1055, Aug. 2014, doi: 10.1193/070913EQS198M.

[151] J. P. Stewart, D. M. Boore, E. Seyhan, and G. M. Atkinson, "NGA-West2 Equations for Predicting Vertical-Component PGA, PGV, and 5%-Damped PSA from Shallow Crustal Earthquakes," *Earthq. Spectra*, vol. 32, no. 2, pp. 1005–1031, May 2016, doi: 10.1193/072114eqs116m.

[152] K. W. Campbell and Y. Bozorgnia, "NGA-West2 Ground Motion Model for the Average Horizontal Components of PGA, PGV, and 5% Damped Linear Acceleration Response Spectra," *Earthq. Spectra*, vol. 30, no. 3, pp. 1087–1115, Aug. 2014, doi: 10.1193/062913EQS175M.

[153] B. S.-J. Chiou and R. R. Youngs, "Update of the Chiou and Youngs NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra," *Earthq. Spectra*, vol. 30, no. 3, pp. 1117–1153, Aug. 2014, doi: 10.1193/072813EQS219M.

[154] G. M. Atkinson and D. M. Boore, "Earthquake Ground-Motion Prediction Equations for Eastern North America," *Bull. Seismol. Soc. Am.*, vol. 96, no. 6, pp. 2181–2205, Dec. 2006, doi: 10.1785/0120050245.

[155] J. X. Zhao, "An Empirical Site-Classification Method for Strong-Motion Stations in Japan Using H/V Response Spectral Ratio," *Bull. Seismol. Soc. Am.*, vol. 96, no. 3, pp. 914–925, Jun. 2006, doi: 10.1785/0120050124.

[156] D. S. K. Karunasingha, "Root mean square error or mean absolute error? Use their ratio as well," *Inf. Sci. (Ny).*, vol. 585, pp. 609–629, Mar. 2022, doi: 10.1016/j.ins.2021.11.036.

[157] N. Das, *Statistical Methods*. Tata McGraw-Hill Publishing Company Ltd., New Delhi, 2008.

[158] G. Lanzano *et al.*, "Ground motion models for the new seismic hazard model of Italy (MPS19): selection for active shallow crustal regions and subduction zones," *Bull. Earthq. Eng.*, vol. 18, no. 8, pp. 3487–3516, Jun. 2020, doi: 10.1007/s10518-020-00850-y.

[159] P. Roselli, W. Marzocchi, and L. Faenza, "Toward a New Probabilistic Framework to Score and Merge Ground- Motion Prediction Equations: The Case of the Italian Region," *Bull. Seismol. Soc. Am.*, vol. 106, no. 2, pp. 720–733, Apr. 2016, doi: 10.1785/0120150057.

[160] D. Arroyo, M. Ordaz, and R. Rueda, "On the Selection of Ground-Motion Prediction Equations for Probabilistic Seismic-Hazard Analysis," *Bull. Seismol. Soc. Am.*, vol. 104, no. 4, pp. 1860–1875, Aug. 2014, doi: 10.1785/0120130264.

[161] F. Scherbaum, "On the Use of Response Spectral-Reference Data for the Selection and Ranking of Ground-Motion Models for Seismic-Hazard Analysis in Regions of

Moderate Seismicity: The Case of Rock Motion," *Bull. Seismol. Soc. Am.*, vol. 94, no. 6, pp. 2164–2185, Dec. 2004, doi: 10.1785/0120030147.

[162] F. Scherbaum, E. Delavaud, and C. Riggelsen, "Model Selection in Seismic Hazard Analysis: An Information-Theoretic Perspective," *Bull. Seismol. Soc. Am.*, vol. 99, no. 6, pp. 3234–3247, Dec. 2009, doi: 10.1785/0120080347.

[163] E. Delavaud *et al.*, "Toward a ground-motion logic tree for probabilistic seismic hazard assessment in Europe," *J. Seismol.*, vol. 16, no. 3, pp. 451–473, Jul. 2012, doi: 10.1007/s10950-012-9281-z.

[164] O. Kale and S. Akkar, "A New Procedure for Selecting and Ranking Ground-Motion Prediction Equations (GMPEs): The Euclidean Distance-Based Ranking (EDR) Method," *Bull. Seismol. Soc. Am.*, vol. 103, no. 2A, pp. 1069–1084, Apr. 2013, doi: 10.1785/0120120134.

[165] L. A. Zadeh, "Fuzzy sets," *Inf. Control*, vol. 8, no. 3, pp. 338–353, Jun. 1965, doi: 10.1016/S0019-9958(65)90241-X.

[166] E. H. Mamdani, "Application of fuzzy algorithms for control of simple dynamic plant," *Proc. Inst. Electr. Eng.*, vol. 121, no. 12, p. 1585, 1974, doi: 10.1049/piee.1974.0328.

[167] Y. Kurtgoz and E. Deniz, "Comparison of ANN, Regression Analysis, and ANFIS Models in Estimation of Global Solar Radiation for Different Climatological Locations," in *Exergetic, Energetic and Environmental Dimensions*, Elsevier, 2018, pp. 133–148. doi: 10.1016/B978-0-12-813734-5.00008-1.

[168] J.-S. R. Jang and Chuen-Tsai Sun, "Neuro-fuzzy modeling and control," *Proc. IEEE*, vol. 83, no. 3, pp. 378–406, Mar. 1995, doi: 10.1109/5.364486.

[169] C. Ferreira, "Gene Expression Programming: A New Adaptive Algorithm for Solving Problems," *Complex Syst*, vol. 13, Mar. 2001.

[170] J. Ali, R. Khan, N. Ahmad, and I. Maqsood, "Random Forests and Decision Trees," *Int. J. Comput. Sci. Issues(IJCSI)*, vol. 9, Sep. 2012.