Estimation of Peak Ground Acceleration (PGA) and Spectral Acceleration (Sa) Vertical Component for Interface Subduction Zone Earthquakes of North-east India (NEI) and Adjacent Regions

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Estimation of Peak Ground Acceleration (PGA) and Spectral Acceleration (S_a) Vertical Component for Interface Subduction Zone Earthquakes of North-east India (NEI) and Adjacent Regions

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Summary

This article presented ground motion model (GMM) for vertical peak ground acceleration (PGA) and pseudo spectral acceleration (S_a) at 5 % damping for North-east India (NEI) and adjacent regions at a time period of 0.01 to 5 s, and hypocentral distance 40 to 300 km. We used combined point source ($4.5 \leq M_w \leq 6.5$) and finite fault model ($6.5 < M_w \leq 9.5$) (refer as combined model) to develop GMM for vertical component of ground motion (VCGM) for the region. The vertical GMM obtained is validated with the available recorded events in NEI and adjacent regions for the interface subduction zone earthquakes. It is observed that peak ground accelerations and spectral accelerations are 55 to 65% lesser than the horizontal components of ground motions. VCGM parameters obtained in this study play an important role in designing low rise buildings and linear superstructures such as bridges, silos and chimneys.

Introduction

This article is a companion article published by Rahman and Chhangte (2021). Rahman and Chhangte (2021) developed ground motion model (GMM) for the horizontal component of peak ground acceleration (PGA) and 5% damping spectral acceleration (S_a) for the interface subduction earthquakes of NEI and adjacent regions (hereon refer as NEI). Seismo-tectonic characteristics of the interface subduction zone earthquakes of NEI was presented in details in the companion article (Rahman and Chhangte, 2021).

Beside the horizontal component of ground motions, vertical component of ground motions (VCGM) parameter also induced damage in the buildings, bridges and other engineering structures for the high magnitude earthquakes. Based on the past seismicity, many researchers have predicted that NEI may face high magnitude ($M_w > 8.0$) interface zone earthquakes in future (Rahman and Chhangte, 2021; Singh et al., 2016; Steckler et al., 2016; Rahman, 2012; Goswami and Sharma, 1982). The vertical ground motions obtained from this high magnitude

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earthquakes ($M_w > 8.0$) cannot be ignored in designing the engineering structures. The vertical ground motion obtained from the subduction earthquakes ($M_w 8.5$) which occurred in 1897 in NEI was estimated to be 1.1 g (Oldham, 1899). Rahman (2008) had simulated VCGM for earthquake $M_w 8.0$ using Empirical Green Function (EMF) approach based on earthquake of $M_w 5.9$ occurred in 18th May 1987 at the recording station namely Bamungaon, Berlongfar and Laisong. He observed that simulated VCGM at these 3 recording stations for earthquake of $M_w 8.0$ were 0.82 g, 0.65 g and 0.81 g respectively. This type of vertical component induced due to high magnitude interface earthquakes is disastrous for man-made structures. This higher value of vertical strong motions may uplift or throw low-rise building, bridges and other engineering structures. The strong ground motion parameter due to vertical component may also overturn a high rise building during liquefaction. An interface subduction earthquake of $M_w 8.7$ occurred on 1950 in the region which has uplifted several bridges. This earthquake had also uplifted and buckled the railway line track laid from Guwahati city to Dibrugarh town for several 100 km. This earthquake had also diverted the line of course of the river Brahmaputra from the original mainstream. The vertical ground motions for this earthquake were estimated as 1.2 g (Raghukanth, 2008; Rahman, 2008; Tiwari, 2002).

Based on this study, it is observe that vertical component of earthquakes also contribute to the destructive effect on structures as well. In the past, VCGM were totally ignored while designing ordinary structures as it was commonly believed that vertical ground accelerations are significantly lower than corresponding horizontal ground accelerations (Cagnan et al. 2017).

In this article, we have simulated 50,000 vertical component of PGA and S_a for $4.5 \leq M_w \leq 6.5$ using Boore's (1983; 2003) point source seismological model. We have also simulated 50000 vertical component of ground motion for $6.5 < M_w \leq 9.5$ using finite fault model. We used combined point source and finite fault model as point source have some limitation in ground motion simulation for high magnitude earthquake (Rahman and Chhange, 2021).

We used the same data and resources, path duration, geometrical spreading factor, stress drops for the interface subduction earthquakes presented in our companion article (Rahman and Chhange, 2021).

We have estimated quality factor (Q) for VCGM which are further used in ground motion simulations for vertical component using the combined point source and finite fault model (called combined model). The 12 NEI seismic events considered in this article for the analysis of vertical component of ground motions for Boore (1983; 2003) point source and FINSIM finite fault model is presented in Table 1. The seismo-tectonic map and the earthquakes considered in this article are shown in Figure 1.

Estimation of Quality Factor (Q_V) for VCGM

We used the same mathematical technique of Rahman and Chhange (2021) to estimate the quality factor (Q_V) for the vertical component of 12 number of strong motion records for the interface subduction earthquakes (Table 2).

$\log_{10}A + (1/5)\log_{10}R$ versus R is plotted in Figures 2 (a) to (f) for VCGM of $Q_V(f)$ at the frequency of 0.2 Hz for 10th September 1986, 18th May 1987, 6th February 1988, 8th May 1997, 9th December 2004 and 3rd January 2017 earthquakes respectively.

The dependence of $Q_V(f)$ on f is given in Figures 3 (a) to (f) for VCGM of 10th September 1986, 18th May 1987, 6th February 1988, 8th May 1997, 9th December 2004 and 3rd January 2017 earthquakes respectively.

In this article, $Q_V(f)$ value for the 12 strong motion events for the VCGM of NEI interface earthquakes are presented in Table 2. The average of the vertical component of Q for all 12 interface earthquakes for NEI is calculated as

$$Q_{VT}(f) = 106.84f^{0.95} \quad (1)$$

with the standard deviation (σ_I) values as (13.7 (Q_0), 0.038 (η)).

The boot-strap method is applied similar to our companion paper Rahman and Chhange (2021). The operation is repeated 150 times and 150 sets of parameters are generated from which we can draw distributions that represents the observed variability of the Q_V shown in Figures 4 (a) and (b). The anelastic model parameters obtained for $Q_V(f)$ using bootstrap technique are $\log_{10}(Q_0)$ as 2.34 ± 0.16 , $\gamma = 1.02 \pm 0.007$ and $\eta = 0.91 - 0.99$ presented in Table 3.

Simulation of Ground Motions

The ranges of seismic input parameters used for VCGM simulations of NEI interface earthquakes are presented in Table 3. Ground motions are simulated similar to Rahman and Chhangte (2021). Smaller range of M_w (4.5 to 6.5) and hypocentral distance (30 to 300 km) corresponding to V_{S30} as 2800 m/s are simulated using point source model. There are 500 scenario pairs of magnitude and distance bins from which 50,000 ground motions are simulated for smaller magnitude to develop the GMM for NEI interface earthquakes vertical component of ground motion. For each scenario, 100 sets of ground motions are simulated which presented in Table 4.

Region specific seismic input parameters for NEI used in the program SMSIM for point source model and FINSIM for finite fault model are presented in Table 5. For NEI finite fault modelling for vertical components of ground motions, we used Strasser et al. (2010) equation to estimate the size of subfault valid for interface subduction earthquakes;

$$M_w = a_1 + b_1 \times \log_{10}(L) \quad (2)$$

$$M_w = a_2 + b_2 \times \log_{10}(W) \quad (3)$$

$$M_w = a_3 + b_3 \times \log_{10}(A) \quad (4)$$

where L , W and A are the length, width and area of the fault. The constants a_1 to a_3 and b_1 to b_3 are regression coefficients in Equations (2) to (4) which were calculated by Strasser et al. (2010) for NEI interface earthquakes which are presented in Table 6.

GMM for VCGM for Interface Subduction Zone at Hard Rock Level

The following functional GMM form used by Abrahamson et al. (2016) for global interface subduction earthquakes is used in this study. The same mathematical form is also used in Rahman and Chhangte (2021). The functional GMM form is as follow:

$$\ln(S_a) = \theta_1 + \theta_4 \Delta C_1 + (\theta_2 + \theta_3(M_w - 7.8)) \ln(R + C_2 \exp(\theta_7(M_w - 6))) + \theta_6 R + f_{mag}(M_w) + \theta_{10} + f_{site}(PGA_{1000}, V_{S30}) \quad (5)$$

where

$\theta_1 - \theta_{10}$ = regression coefficients

For NEI, $F_{FABA} = 0$ considering NEI being an unknown site.

$$f_{mag}(M_w) = \begin{cases} \frac{\theta_4(M_w - (C_1 + \Delta C_1)) + \theta_9(10 - M_w)^2}{\theta_5(M_w - (C_1 + \Delta C_1)) + \theta_9(10 - M_w)^2} & \text{for } M_w \leq C_1 + \Delta C_1 \\ \theta_5(M_w - (C_1 + \Delta C_1)) + \theta_9(10 - M_w)^2 & \text{for } M_w > C_1 + \Delta C_1 \end{cases} \quad (6)$$

where $C_1 = 7.8$. The values of ΔC_1 is period-dependent variations based on the size of the NEI interface earthquake.

$$f_{site}(PGA_{1000}, V_{S30}) = \begin{cases} \theta_8 \ln\left(\frac{V_s}{V_{lin}}\right) - b \ln(PGA_{1000} + c) + b \ln(PGA_{1000} + c \left(\frac{V_s}{V_{lin}}\right)^n) & \text{(for } V_{S30} < V_{lin}) \\ \theta_8 \ln\left(\frac{V_s}{V_{lin}}\right) + b n \ln\left(\frac{V_s}{V_{lin}}\right) & \text{(for } V_{S30} \geq V_{lin}) \end{cases} \quad (7)$$

Here, $V_{S30} = 2800$ m/s

The regression coefficients in Equation (5) are presented in Tables 7 and 8.

The regression coefficients θ_1 to θ_{11} are calculated using a Joyner and Boore (1981) two-stage regression method (Joyner and Boore, 1981) to check and minimize the errors in calculation of regression coefficients. Sensivity analysis is also carried out to check the errors for the various seismic input parameters used in this study.

Site coefficient (F_s) for all sites class can be expressed using Iyenger and Raghukanth (2004) and Singh et al. (2016). The site coefficients equation is as follows;

$$\ln(F_s) = a_1 Y_{br} + a_2 + \ln(\sigma_s) \quad (8)$$

where Y_{br} is the hard rock acceleration and σ_s are the standard deviations which were assigned for NEI for Site Classes A to D (Singh et al., 2016).

Sensitivity Analysis

The sensitivity analysis performed in this study for different parameters is similar to the procedure adopted by Rahman and Chhangte (2021). The sensitivity analysis results obtained from our model are presented in Table 9.

It is observed that the spread of standard deviations for VCGM input parameters vary from 0.042 to 0.416 (Table 9). The standard deviations input parameters namely focal depth, cut-off frequency, stress drop, radiation pattern, anelastic attenuation, geometric attenuation and time

duration are negligible (Table 9). The small distribution of standard deviation give the impression that the developed GMM for VCGM is not biased with respect to the region-specific input parameters.

Comparison with Other GMM

GMM for VCGM interface subduction zone earthquakes for NEI is not yet develop. We have validated our present GMM for VCGM with the available recorded events on Site Class C and also compared with Rahman and Chhange (2021) GMM for horizontal component of ground motions for NEI interface subduction zone earthquakes. We have also compared our present GMM for VCGM with the Abrahamson et al. (2016) global interface earthquakes.

In this study, we developed GMM for VCGM on hard rock level corresponding to $V_{S30} = 2,800$ m/s which is scaled to Site Class C ($V_{S30} \approx 400$ to 500 m/s) using site coefficients calculated by Singh et al. (2016). We also checked our model with Abrahamson et al. (2016) GMM which is a function of V_{S30} . During comparison with Abrahamson et al. (2016) model, we have considered average $V_{S30} \approx 560$ m/s for Site Class C. We have also checked our GMM for VCGM with Rahman and Chhange (2021) at Site Class C of the horizontal component of ground motions.

We have checked our GMM for VCGM of the NEI interface earthquakes with the strong motion records for M_w 5.3 on 10 September 1986, M_w 5.9 on 18 May 1987, M_w 5.8 on 6 February 1988, M_w 6.0 on 8 May 1997, M_w 5.4 on 9 December 2004, and M_w 5.7 on 3 January 2017 in Figures 5 (a) to (f) respectively. It is seen from Figures 5 (a) to (f) that our GMM for VCGM is not biased with respect to both magnitude and hypocentral distance. We have estimated the residuals, mean residuals $\pm$ standard deviation for Peak Ground Acceleration (PGA) with respect to magnitude which is presented in Figure 6. From Figure 6, it is seen that residuals for PGA are not bias for all range of magnitude. We have also estimated the residuals for VCGM of PGA and Spectral Acceleration (S_a) at 2.0 s with respect to hypocentral distance for the available strong motion records of NEI interface subduction zone earthquakes which are shown in Figures 7 (a) and (b) respectively. It is seen from Figures 6 and 7 (a) to (b) that residuals of PGA and S_a with respect to magnitude and hypocentral distance are not bias.

We have compared our GMM for VCGM of the interface earthquakes with the GMM of Rahman and Chhange (2021) and Abrahamson et al. (2016) for PGA with respect to hypocentral distance for magnitude M_w 6.5, 7.5, 8.5, and 9.5 which are shown in Figures 8 (a) to (d). We have also

168 compared for S_a at 0.25 s for M_w 6.5, 7.5, 8.5, and 9.5 with respect to hypocentral distance which
169 are shown in Figures 9 (a) to (d). It is seen from Figures 8 and 9 that our GMM for VCGM give
170 lesser values than Rahman and Chhangte (2021) and Abrahamson et al. (2016).

171 We also compared our GMM for S_a at different time periods with the GMM of Rahman and
172 Chhangte (2021) and Abrahamson et al. (2016) for M_w 6.5, 7.5, 8.5, and 9.5 at hypocentral
173 distance 50, 100, 150 and 200 km which are shown in Figures 10 (a) to (d) respectively. It is
174 observed that our GMM gives lower values than our GMM give lesser values than Rahman and
175 Chhangte (2021) and Abrahamson et al. (2016).

176 It is observed from Figures 8 to 10 that our GMM based on combined models give less PGA and
177 S_a values as compared to Rahman and Chhangte (2021) and Abrahamson et al. (2016) GMM.
178 Our GMM for VCGM give lower values because Rahman and Chhangte (2021) and
179 Abrahamson et al. (2016) calculated GMM for horizontal component of ground motions. It is
180 also observed that these differences may also arises due to different value of V_{S30} .

181 **Conclusions**

182 In this study, we developed a new GMM for VCGM of interface subduction zone earthquakes
183 for NEI based on Boore's point source and FINSIM finite fault model (combined model). Our
184 GMM is based on simulated 50,000 vertical component of ground motions (VCGM) database for
185 magnitude M_w 5.0 to 9.5 and hypocentral distances 30 to 300 km. These VCGM samples are
186 theoretically simulated using the region-specific seismic input parameters related to VCGM in
187 NEI interface earthquakes.

188 Our present GMM for VCGM is well fitted and un-bias with respect to both magnitude and
189 hypocentral distance. This model will give suitable VCGM parameters for NEI interface
190 subduction earthquakes which will be further useful in estimating the seismic hazard for the
191 region.

192 **Data Availability**

193 Earthquake database used in this study are obtained from Rahman and Chhangte (2021),
194 Geological Survey of India, International Seismological Centre and National Earthquake
195 Information Centre catalog. The ground motions database from seismic research centre used in
196 this study can be accessed using unique identifier system.

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235 **Table 1.** Events and Finite Fault Modelling Parameters for VCGM of NEI interface earthquakes

Date (yy/mm/dd)	Magnitude (M _w)	Strike (Degree)	Dip (Degree)	Fault Size (km X km)	Subfault Size (km)	Radiation Strength Factor
2018/01/07	5.6	210	27	3.9 X 3.9	0.8	1.1
2017/01/03	5.7	147	17	4.5 X 4.5	0.9	1.3
2014/11/20	5.6	156	14	3.9 X 3.9	0.8	1.2
2013/03/02	5.2	329	23	2.2 X 2.2	0.4	0.9
2009/09/21	6.3	27	19	10.9 X 10.9	2.2	1.6
2007/11/11	5.5	251	22	3.4 X 3.9	0.7	1.2
2004/12/09	5.4	243	32	2.9 X 2.9	0.6	1.1
2003/07/26	5.7	2	16	4.5 X 4.5	0.9	1.1
1997/05/08	6.0	78	33	7.0 X 7.0	1.4	1.3
1988/02/06	5.8	239	29	5.2 X 5.2	1.0	1.2
1987/05/18	5.9	67	34	6.1 X 6.1	1.2	1.4
1986/09/10	5.3	156	31	2.5 X 2.5	0.5	0.9

236
 237 **Table 2.** Calculated VCGM quality factor (Q_V) values for NEI interface earthquakes

Date (yy-mm-dd)	Magnitude (M _w)	Vertical Q (Q_V), (σ_I)
1986-09-10	5.3	$101.26f^{0.92}$, (12.7, 0.042)
1987-05-18	5.9	$114.96f^{0.96}$, (15.2, 0.023)
1988-02-06	5.8	$108.57f^{0.98}$, (14.6, 0.032)
1997-05-08	6.0	$111.29f^{0.94}$, (13.6, 0.029)
2003-07-26	5.7	$104.33f^{0.95}$, (15.3, 0.058)
2004-12-09	5.4	$105.91f^{0.93}$, (13.4, 0.022)
2007-11-11	5.5	$102.87f^{0.97}$, (12.9, 0.025)
2009-09-21	6.3	$121.38f^{0.99}$, (13.8, 0.04)
2013-03-02	5.2	$115.56f^{0.93}$, (14.2, 0.03)
2014-11-20	5.6	$90.78f^{0.94}$, (16.4, 0.05)
2017-01-03	5.7	$89.27f^{0.95}$, (15.8, 0.045)
2018-01-07	5.6	$100.16f^{0.96}$, (12.4, 0.05)

238
 239 **Table 3.** Ranges for VCGM of GMM input parameters

Parameters	Distribution	Ranges
Cut off frequency	Uniform	20-50 Hz
Radiation coefficient	Uniform	0.48-0.64
Focal depth	Uniform	10-50 km
Stress parameter	Uniform	110-280 bars
Attenuation model	Uniform	$\log_{10}(Q_0)=2.34 \pm 0.16$ $\gamma = 1.02 \pm 0.007$ $\eta = 0.91 - 0.99$
Time duration model	Uniform	R(16.5/60), if R < 60 km 16.5 + 0.05(R - 60), if R ≥ 60 km

Kappa	-	0.006 s
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Table 4. Magnitude and ranges of hypocentral distance for VCGM of NEI interface earthquakes

Moment Magnitude, M_w	Hypocentral Distance, R (km)	No. of distance samples	No. of samples
4.5	30-300	100	10000
5.0	30-300	100	10000
5.5	30-300	100	10000
6.0	30-300	100	10000
6.5	30-300	100	10000
Total no. of samples			50,000

Table 5. Generic modelling parameters for VCGM of NEI interface earthquakes

Parameters	Parameter Value
Quality factor	$106.84f^{0.95}$
Geometric Spreading	$G = 1/R$ for $R < 100$ km
	$G = 1/(10\sqrt{R})$ for $R > 100$ km
Path Duration Model	TP = $R \times (16.5/60)$ [R < 60 km] TP = $16.5 + 0.05 \times (R - 60)$ [R $\geq$ 60 km]
Crustal Amplification	Singh et al. (2016)
Kappa	0.006 s
Stress Parameters	180 bars
Window Functioning	Saragoni-Hart (Beresnev and Atkinson, 1999)
Crustal Shear Wave Velocity	3.6 km/s (Singh et al. (2016)
Rupture Velocity	0.8 X Shear wave velocity (Beresnev and Atkinson, 1999)
Crustal Density	2.8 gm/cc (Singh et al., 2016)
Fault-Slip Distribution	Uniform
Stochastic Trial	3 (Beresnev and Atkinson, 1999)

Table 6. Regression relations between rupture dimensions and moment magnitude, the multiple determination coefficient (R^2) and total numbers of regression points (N) for interface subduction earthquakes (Strasser et al., 2010), where S.E is the standard deviation of coefficient under consideration

Sl No.	a	S.E (a)	b	S.E (b)	σ	R^2	N
1	4.868	0.141	1.392	0.277	0.277	0.814	95
2	4.410	0.277	1.805	0.392	0.392	0.634	85
3	4.441	0.179	0.846	0.286	0.286	0.805	85

Table7. Variable regression coefficients for VCGM

n	0.6596
c	1.6132
θ_3	0.063
θ_4	0.645
θ_5	0.33
θ_7	0.218
C_2	8.72

Table 8. Variable regression coefficients for (S_a/g) at 5% damping for VCGM

Period	V_{lin}	b	θ_1	θ_2	θ_6	θ_8	θ_9	θ_{10}
0.000	625	-0.789	2.120	-0.846	-0.0089	0.650	-0.0081	0.528
0.020	654	-0.895	2.121	-0.908	-0.0089	0.580	-0.0083	0.668
0.050	761	-1.080	2.215	-0.636	-0.0090	0.769	-0.0086	0.732
0.075	784	-1.284	2.316	-0.465	-0.0092	0.882	-0.0084	0.845
0.100	746	-1.455	2.432	-0.274	-0.0093	0.962	-0.0091	0.871
0.150	634	-1.567	2.541	-0.955	-0.0094	1.121	-0.0096	0.837
0.200	541	-1.657	2.643	-0.136	-0.0096	1.241	-0.0104	0.811
0.250	473	-1.749	2.725	-0.905	-0.0097	1.281	-0.0101	0.761
0.300	429	-1.756	2.659	-0.473	-0.0096	1.417	-0.0113	0.690
0.400	368	-1.710	2.543	-0.712	-0.0095	1.463	-0.0119	0.527
0.500	334	-1.625	2.349	-0.552	-0.0094	1.448	-0.0141	0.435
0.600	315	-1.597	2.127	-0.654	-0.0094	1.369	-0.0156	0.382
0.750	304	-1.302	2.093	-0.028	-0.0093	1.215	-0.0184	0.313
1.000	301	-0.682	1.967	-0.841	-0.0091	0.896	-0.0223	0.215
1.500	297	-0.199	1.896	-0.654	-0.0090	0.249	-0.0372	0.202
2.000	294	-0.104	1.734	-0.165	-0.0088	0.244	-0.0439	0.196
2.500	289	-0.060	1.602	-0.561	-0.0088	-0.435	-0.0481	0.194
3.000	289	-0.013	1.496	-0.223	-0.0087	-0.406	-0.0563	0.193
4.000	287	0.000	1.352	-0.615	0.0085	-0.378	-0.0591	0.192
5.000	286	0.000	1.157	-0.021	0.0083	0.362	-0.0597	0.189

Table 9. Estimated standard deviation of GMM for VCGM parameters in sensitivity analysis

Serial no.	Model uncertainty parameters	Standard deviation (ln)
1	Focal depth	± 0.083
2	Cut-off frequency	± 0.072
3	Stress drop	± 0.096
4	Radiation pattern	± 0.042
5	Anelastic attenuation	± 0.136
6	Geometric attenuation	± 0.124
7	Time duration	± 0.086
8	κ (kappa)	± 0.363
9	Site coefficient	± 0.416
10	Total uncertainties	± 0.587

Figure 1. Seismotectonic map of NEI. Coordinates of earthquake epicentres considered in this article are shown in the figure.

Figure 2. Variation of $\log_{10}A + Y/Y_1$ versus R (km) for VCGM at 0.2 Hz for (a) 10 September 1986, (b) 18 May 1987, (c) 6 February 1988, (d) 8 May 1997, (e) 9 December 2004 and (f) 3 January 2017. $Y = \log_{10}R$ ($R < 100$ km) and $Y_1 = 5\log_{10}R$ ($R > 100$ km).

Figure 3. Weighted average of the $\log_{10}Q$ versus $\log_{10}f$ for VCGM of (a) 10 September 1986, (b) 18 May 1987, (c) 6 February 1988, (d) 8 May 1997, (e) 9 December 2004 and (f) 3 January 2017 earthquakes.

Figure 4. Distribution for the attenuation parameters for VCGM of NEI interface earthquakes after applying bootstrapping method to the results and associated Gaussian models: (a) γ and (b) $\log_{10}(Q_0)$.

Figure 5. Predicted and recorded PGA values for VCGM at Site Class C for (a) 10 September 1986, (b) 18 May 1987, (c) 6 February 1988, (d) 8 May 1997, (e) 9 December 2004 and (f) 3 January 2017 earthquakes. Error/vertical bar represent the standard deviations for VCGM of GMM.

Figure 6. Distribution of PGA residuals for VCGM with respect to M_w . The residuals for each earthquake events are shown with black vertical line with three horizontal bars which indicate the ranges of average $\pm$ standard deviations of residuals.

Figure 7. Distribution of the residuals for VCGM of (a) PGA, (b) 2.0 s S_a with respect to hypocentral distance (km).

Figure 8. Comparison of Peak Ground Acceleration for VCGM of present GMM with Rahman and Chhangte (2021) and Abrahamson et al. (2016) for M_w (a) 6.5, (b) 7.5, (c) 8.5, and (d) 9.5 w.r.t. hypocentral distance (km) respectively.

Figure 9. Comparison of Spectral Acceleration for VCGM of present GMM with Rahman and Chhangte (2021) and Abrahamson et al. (2016) for M_w (a) 6.5, (b) 7.5, (c) 8.5, and (d) 9.5 at 0.25 s w.r.t. hypocentral distance (km) respectively.

Figure 10. Comparison of Spectral Acceleration for VCGM of present GMM with Rahman and Chhangte (2021) and Abrahamson et al (2016) for M_w (a) 6.5, (b) 7.5, (c) 8.5, and (d) 9.5 at a hypocentral distance of 50, 100, 150 and 200 km w.r.t time periods (0.01 to 5.0 s) respectively.