A new ground motion prediction model for Northeast India (NEI) shallow crustal

T Rahman¹ and Bindesh Nunia²

¹Associate Professor, ²Research scholar,
Dept. of Civil Engineering, NIT Silchar, Assam, India.

E-mail: Tauhid_srm@yahoo.com, bindeshchouhan@gmail.com

Abstract. In this paper, a new ground-motion prediction model (GMPE) for North-eastern India (NEI) is developed based on the available recorded events. NEI has already faced several high magnitude earthquakes (moment magnitude \( M_w \) > 7.0) during the period 1200 to 2018. It is difficult to develop GMPE and estimating the seismic hazard of NEI, due to sparse recorded strong motion database. To date, seismic hazard maps for NEI have not been prepared. All developed countries have developed seismic hazard maps for their cities using region-specific GMPE. So, to prepare the seismic hazard maps of NEI, a ground motion prediction model will be required. The success of earthquake hazard mitigation depends to a large extent on how accurately the ground motion hazard can be estimated at a vulnerable site. The GMPE developed in this study has been compared with other ground-motion models as well as with the available limited recorded strong motion database. Based on the comparison, it is observed that the new model is reasonably correct as the model is unbiased with respect to both magnitude and hypocentral distance. This model needs to be upgraded as and when more recorded strong ground motion database is available for this region.

1. Introduction

Many other researchers have developed region-specific GMPE based on the recorded strong motion data. The model developed will be reliable if the number of recorded data for different magnitude and hypocentral distance are available. Gupta et al., [1] have also developed a ground motion model for NEI based on the existing recorded data and his relationship is not based on the bedrock level PGA. A ground motion model is also developed for the Eastern Himalayan region by Sharma [2], based on the recorded events in NEI and other parts of Eastern Himalayan. In deriving the model, Sharma [2] has considered only four recorded events from the NEI out of the available 18 recorded events for the region. He also considered together both the active and subduction zone earthquakes for the entire Himalayan region in developing the ground motion model. Skarlatoudis et al., [3] proposed new predictive relations for the peak values of the horizontal components of ground acceleration, velocity, and displacement, using 619 strong-motion recordings from shallow earthquakes in the broader Aegean area. Bragato and Slejko [4] used a large data set of seismometric and accelerometric recordings (3168 vertical and 1402 for each of the horizontal components) collected by various networks in the eastern Alps to estimate empirical ground-motion attenuation relation. Their ground motion relation is valid in the magnitude range 2.5–6.3 for distances up to 130 km. Mc Garr and Fletcher [5] developed GMPEs using data recorded by a seismic network, established and operated by
the University of Utah Seismograph Stations. This ground motion model provides a basis for assessing the seismic hazard to the Joes Valley Dam due to future coal mining in the nearby Cottonwood Tract in central Utah. Liu and Tsai [6] used strong ground-motion data obtained by the Taiwan Strong Motion Instrumentation Program and Central Mountain Strong Motion Array to derive new attenuation relationships for the vertical and horizontal PGA and PGV for crustal earthquakes in Taiwan. Akkar and Bommer [7] derived new equations using the strong-motion database for the seismically active areas of Europe and the Middle East. Bommer et al., [8] presented new empirical predictive equations for a number of definitions of strong-motion duration using the records from the NGA global database of accelerograms from shallow crustal earthquakes. Bradley and Misko [9] have studied the ground motion characteristics for a near-source strong ground motion observed in the 22nd February 2011 Christchurch earthquake. Ogweno and Cramer [10] have compared the central and eastern North America GMPEs using the NGA-East ground motion database. Atkinson [11] developed a GMPE that accounts correctly for point-source scaling in both magnitude and distance space for events of $M_w$ 3 to 6 at hypocentral distances less than 40 km, drawn from the NGA-West 2 database.

So, it is being well-practiced by the earthquake engineers to developed ground motion models based on past recorded events specific to a region. But in actual practice, It is really very difficult to determine a suitable GMPE for a region having a large variability of the strong-motion database. Correlation of regression coefficients in the ground motion models solely depends on the variability of strong motion records, because the strong coupling of variables in a prediction model and the statistical power of the data is often not large enough to determine the necessity of these parameters. To overcome this difficulty, in this study, the model has been developed based on three variables namely earthquake magnitude, the shortest distance to the seismic fault plane (Hypocentral/Epicentral distance) and focal depth.

In this study, the model which we used is an interim updated seismic hazard model, as it does not treat all uncertainties comprehensively; rather we address the impact of key uncertainties. Based on the updated interim seismic hazard model, uniform hazard spectra for the entire NEI can be prepared for the different return periods. In this study, we have also checked our model biases about the three key uncertainties namely magnitude, epicentral distance, and focal depth by performing sensitivity analysis.

2. Seismicity of NEI

NEI has experienced strong earthquakes since ancient times. However, prior to 1400 A.D., no earthquake event has been properly recorded in the literature. This region has experienced more than 2700 earthquakes of magnitude ($M_w$≥3.0) in a period of 605 (1100-2018) years.

As per Archeological Department, Govt. of Assam a damaging earthquake occurred in 1406 A.D. in the Shillong Plateau region. It seems to have caused severe damage in Shillong and its surrounding area. Another devastating earthquake occurred in Assam Valley in 1417 A.D. The intensity of the ground shaking of this earthquake was so high that clean water in a small lake became turbid and fish came out of the lake on to the ground. No reporting of damage is available in the literature. Iyengar et al. [12] have studied the history of earthquakes of medieval India in detail. As per their work, in 1548 A.D., a violent earthquake took place in Assam at Garhgoan which is South-East of Sibsagar. The epicenter of this earthquake was 26°45'N, 94°50'N. Pebbles, sand, and ash came out bursting the surface of the earth. The Modified Mercalli Intensity (MMI) of this earthquake has been estimated to be IX. Another devastating earthquake occurred at Gajala in 1596 A.D. Again hot water, sand and ash were thrown up from below. This earthquake was during the reign of Sukhampha alias Khora (Lame) Raja. During this earthquake, the King’s palace collapsed and some of the men guarding the place were also crushed to death. The MMI of this earthquake has been estimated to be IX. Another earthquake took place in the upper Assam in the year 1642 A.D. during the reign of king Suramppha alias Bhaga Raja alias Jayaditya. There is no information about the damage due to this earthquake and the MMI intensity of this earthquake has been estimated to be III. In the year 1649 A.D., three more
earthquakes occurred in upper Assam. The earthquakes are reported as felt and hence the intensity of these earthquakes might not have exceeded III. In the year 1663 A.D., a mild earthquake occurred and the intensity of this earthquake might be V.

3. Strong Ground Motion Acceleration Data
The recorded strong motion database for crustal earthquakes is presented in Table 1. Strong motion records are available in Sharma (2000) [13], Sharma and Bungum (2006) [14], Sharma et al. (2009) [15] and Rahman (2012) [16]. The distribution of Peak Ground Acceleration (PGA) with respect to magnitude and hypocentral is shown in Figure 2 (a) and 2(b). In this study, we used the strong ground motion database for the crustal earthquakes in NEI to develop the GMPE for NEI.

3.1. Ground Motion Model for the Active Region at C type site
Most of the recorded crustal earthquakes in NEI are located on the C type site and few of them are located in the firm stiff soil (Rahman, 2012). In this study, we have developed our model base on site-specific recorded events in NEI, so the proposed model is valid for C type sites.

In the present study, the following functional form used by Iyengar and Raghukanth (2004), Atkinson and Silva (2000) and Singh et al (2016) for the ground motion prediction model has been used for C type site

$$\ln(Y_{br}) = c_1 + c_2(M_w - 6) + c_3(M_w - 6)^2 - \ln R - c_4 R + \epsilon_{br} \tag{1}$$

where $c_1$, $c_2$, $c_3$, and $c_4$ are the regression coefficients.

Here $Y_{br}$ represents $S_a$ at rock level, $M_w$ is the moment magnitude and $R$ is the hypocentral distance, respectively. The ground motion model will not differ in the site condition is different. The

| Tectonic block   | Event                      | Location          | $M_w$ | Focal depth (km) |
|------------------|----------------------------|-------------------|-------|------------------|
|                  | Date(yy-mm-dd)             | Latitude/°N       | Longitude/°E |         |                 |
| Surma Valley     | 1988-02-06                 | 24.65             | 91.52          | 6.0    | 15              |
|                  | 1997-05-08                 | 24.89             | 92.25          | 5.9    | 35              |
|                  | 2006-08-12                 | 24.66             | 92.71          | 5.0    | 42.8            |
|                  | 2007-11-07                 | 22.15             | 92.39          | 5.5    | 28.7            |
| Shillong Plateau | 1986-09-10                 | 25.43             | 92.08          | 5.3    | 43              |
| Eastern Himalaya Region | 2006-02-11 | 27.23             | 92.14          | 4.8    | 49.3            |
|                  | 2006-02-14                 | 27.34             | 88.39          | 5.5    | 30              |
|                  | 2008-10-08                 | 29.76             | 90.33          | 5.5    | 10              |
|                  | 2011-09-18                 | 27.72             | 88.06          | 6.9    | 50              |
| Assam Valley     | 2006-02-23                 | 26.91             | 91.71          | 6.0    | 10              |
Table 2: Regression coefficients and standard deviation (σ) for the horizontal components.

| Period(s) | C₁  | C₂  | C₃  | C₄  | Σ  |
|-----------|-----|-----|-----|-----|----|
| 10.0      | 0.806 | 0.954 | 0.0450 | 0.0 | 0.36 |
| 6.66      | 1.195 | 0.856 | 0.0651 | 0.0 | 0.37 |
| 5.0       | 1.431 | 0.903 | 0.0746 | 0.0 | 0.40 |
| 4.0       | 1.479 | 0.865 | 0.079  | 0.0 | 0.39 |
| 3.33      | 1.548 | 0.875 | 0.0809 | 0.0 | 0.31 |
| 2.5       | 1.756 | 0.854 | 0.095  | 0.0 | 0.37 |
| 2.0       | 1.978 | 0.815 | 0.0107 | 0.0 | 0.35 |
| 1.66      | 2.015 | 0.784 | 0.019  | 0.0 | 0.36 |
| 1.42      | 2.135 | 0.715 | 0.015  | 0.0 | 0.37 |
| 1.25      | 2.353 | 0.709 | 0.019  | 0.0 | 0.40 |
| 1.11      | 2.551 | 0.700 | 0.020  | 0.0 | 0.39 |
| 1.0       | 2.750 | 0.691 | 0.1250 | 0.0004 | 0.31 |
| 0.66      | 2.951 | 0.595 | 0.092  | 0.0005 | 0.35 |
| 0.50      | 3.05  | 0.528 | 0.0650 | 0.0007 | 0.36 |
| 0.40      | 3.09  | 0.491 | 0.062  | 0.0011 | 0.36 |
| 0.31      | 3.11  | 0.450 | 0.0610 | 0.0015 | 0.37 |
| 0.28      | 3.19  | 0.425 | 0.0521 | 0.0016 | 0.30 |
| 0.25      | 3.204 | 0.406 | 0.0502 | 0.0021 | 0.39 |
| 0.22      | 3.251 | 0.400 | 0.0455 | 0.0029 | 0.31 |
| 0.20      | 3.305 | 0.395 | 0.0430 | 0.0034 | 0.34 |
| 0.18      | 3.365 | 0.383 | 0.0410 | 0.0036 | 0.36 |
| 0.16      | 3.395 | 0.379 | 0.0391 | 0.0038 | 0.36 |
| 0.15      | 3.399 | 0.368 | 0.0361 | 0.00395| 0.37 |
| 0.14      | 3.403 | 0.360 | 0.0352 | 0.00406| 0.40 |
| 0.13      | 3.406 | 0.353 | 0.0345 | 0.0041 | 0.39 |
| 0.125     | 3.409 | 0.359 | 0.0339 | 0.00425| 0.31 |
| 0.117     | 3.410 | 0.350 | 0.0331 | 0.00429| 0.37 |
| 0.11      | 3.425 | 0.341 | 0.0315 | 0.00435| 0.36 |
| 0.105     | 3.429 | 0.342 | 0.0309 | 0.0044 | 0.36 |
| 0.1       | 3.45  | 0.345 | 0.0300 | 0.0045 | 0.37 |
| 0.05      | 3.10  | 0.400 | 0.0350 | 0.0039 | 0.34 |
| 0.0       | 3.286 | 0.349 | 0.0651 | 0.0025 | 0.39 |

The present ground motion model can be used for different site conditions by multiplying the site amplification coefficients for a site class to the bedrock acceleration (Y_{br}). The hypocentral distance, R is calculated as

\[ R = \sqrt{R_e^2 + h^2} \]

where R_e and h are the epicentral distance and focal depth, respectively.

Since Y_{br} follows a lognormal distribution with \( \epsilon_{br} = 1 \), equation (1) represents the mean of the ground motion. In this study, to calculate the different regression coefficients in (1), we have carried out a two-stage regression analysis on the recorded database (Joyner and Boore, 1981). The advantage of this method is that it decouples the determination of magnitude dependence from the determination of distance dependence. In calculating the regression coefficients in the ground motion model, equation (1) can be written as

\[ \ln(Y_{br}) = -\ln R - c_4 R + \sum_{i}^{n} E_i l_i + \epsilon_d \]
where \( n \) is the number of recorded crustal earthquakes of NEI, \( E_i \) is the constant for the \( i \)th earthquake and \( l_i \) is a dummy variable which takes value 1 for the \( i \)th earthquake and 0 otherwise. \( \varepsilon_d \) is the error in the regression associated with distance dependence. The unknowns \( c_4 \) and \( E_i \) in the above equation are determined from a linear regression analysis. Once the distance coefficient \( c_4 \) is known, the other coefficients \( c_1, c_2, \) and \( c_3 \) are determined from \( E_i \) as

\[
E_i = c_1 + c_2 (M - 6) + c_3 (M - 6)^2 + \varepsilon_m
\]

(4)

Where \( \varepsilon_m \) is the error in the regression which is magnitude dependent.

The regression constants \( c_1, c_2, c_3, \) and \( c_4 \) are reported in Table 2. The standard deviation of the ground motion which is required in seismic hazard analysis can be expressed as

\[
\sigma(\ln \varepsilon_{br}) = \sqrt{\sigma(\varepsilon_d)^2 + \sigma(\varepsilon_m)^2}
\]

(5)

The value of \( \sigma(\ln \varepsilon_{br}) \) is also reported in Table 2.

The local site effects, an elastic attenuation; geometric attenuation; site coefficient considered in developing GMPE for NEI crustal earthquakes by Singh et al (2016) based on point source seismological model has also been used in our study.

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**Figure: 1** Seismotectonic map of NEI with earthquakes of magnitude \((M_w \geq 5.0)\) (AF is the Atherkat Fault, DF is Dhubri Fault).
Figure 2: Distribution of (a) strong-motion records versus magnitude and (b) strong-motion records versus hypocentral distance.

Figure 3 (a) Comparison of the model from recorded data for PGA with the stochastic model at C site class. (b) Comparison of the model from recorded data at 0.1 s with the stochastic model at the C site class.
Figure 4. (a) Comparison of spectral acceleration vs period for different magnitudes at C site class. (b) Distribution of PGA residuals versus magnitude ($M_w$).

Here, squares are residuals of individual data for each earthquake and vertical lines with three horizontal bars show ranges of the average ± standard deviation of residuals.

Figure 5 (a) Distribution of PGA residuals with respect to hypocentral distance (km). (b) Distribution of the residuals of 0.5 s $S_a$ with respect to hypocentral distance (km).

4. Sensitivity analysis of NEI

In this study, GMPE for the crustal earthquakes on C type has been developed based on the crustal earthquakes which were recorded in NEI. Ground motion parameters $Y_{br}$ is described in equation (1) is dependent on various input parameters namely magnitude, epicentral distance, focal depth and site
type on which recorded events are recorded. So, the robustness of the proposed GMPE developed based on these input parameters has to be checked through sensitivity analysis.

Sensitivity analyses are carried out to test the biasness of the model results in the presence of the input parameters such as magnitude, epicentral distance, focal depth, and site type. Drouet and Cotton (2015) and Singh et al (2016) have performed sensitivity analysis in deriving their ground motion prediction model for France and NEI. In the model, there can be wide variations in the ground motions due to simultaneous changes in the input parameters. So, we have checked the impact of each input parameter in our model through sensitivity analyses by estimating the standard deviation.

The parametric input parameters of focal depth; anelastic attenuation; geometric attenuation; site coefficient; and total uncertainties were evaluated.

The regression coefficients in our present model in equation (1) can be calculated with each of these input parameters by performing the sensitivity analysis and it is observed that their variation is almost the same. We have calculated the standard deviation of our model for these input parameters for different time periods and calculated maximum standard deviation for each time period which is presented in Table 3. Drouet and Cotton (2015) have described that the spread of standard deviations is considerable from 0.6 to 1.0 in natural logarithm units. In our model, the spread of standard deviations varies from 0.11 to 0.45 as reported in Table 3. It is clear from Table 3 that standard deviations due to parameters magnitude, focal depth, anelastic attenuation, geometric spreading and site coefficient are nearly the same.

| Serial no | Model input parameters | Standard Deviation |
|-----------|-------------------------|--------------------|
| 1         | Focal depth             | ±0.11              |
| 2         | Anelastic attenuation   | ±0.15              |
| 3         | Geometric attenuation   | ±0.14              |
| 4         | Site coefficient        | ±0.45              |
| 5         | Total uncertainties     | ±0.85              |

### 5. Comparison of the model

For In this study, we have compared our GMPE developed based on recorded strong motion database for crustal earthquakes with the stochastic model developed by Singh et al. (2016) for the crustal earthquakes of NEI. Our proposed model in this study is valid for the C type site class. We have incorporated the soil factor for C site class in the stochastic model developed by Singh et al (2016) at the hard rock level. We have compared PGA calculated with our model with the stochastic model in Figure 3(a). It is observed that PGA values obtained by using our present model are higher than those obtained by using the stochastic model. We have also compared the spectral acceleration ($S_a$) at 0.1 s obtained by our model with the stochastic model which is shown in Figure 3(b). It is also observed that in Figure 3(b), the value of spectral acceleration is higher than the stochastic model. We have also compared the spectral acceleration for $M_w$ 5 to 8 estimated from our model for the different time periods in Figure 4(a). It is clear from Figure 4(a) that our model is consistent for different magnitude at different time periods and it compared well and shows a good fit between the present model and stochastic model.

The ground motion parameters estimated from our present model are directly based on the C type site. But the ground motion model developed by Singh et al (2016) by the stochastic model is on the hard rock level based on many seismic input parameters. We have compared our present model on C type site with the stochastic model developed by Singh et al. (2016) by scaling with the site coefficient for C type. The errors associated with C type site for the typical soil profile of C type site vary from
0.021 to 0.06 (Singh et al, 2016). These errors provide a lower value of ground motion parameters in the stochastic model as compared to the present model based on the C type site in our study.

6. Validation of the present model using recorded database
The validation of the proposed model has been done by carrying out the residual analysis. The residual error of PGA or $S_a$ of the recorded strong motion database along with the predicted value obtained from our present model is calculated. We have plotted the ranges of the average and average ± standard deviation of residuals by vertical lines with three horizontal bars for each magnitude in Figure 4(b). It is observed from Figure 4(b) that the distributions of the PGA residuals with respect to different magnitudes are unbiased. The calculated PGA residuals of the recorded database in NEI and the predicted value from our model have been plotted for the various range of hypocentral distances which is shown in Figure 5(a). It is clear from Figure 5(a) that the PGA residuals are unbiased with respect to the hypocentral distances. Similarly, the residual errors of $S_a$ for 0.5 s have been plotted with respect to the hypocentral distances in Figure 5(b). It is seen from Figure 5(b) that the residuals of $S_a$ are also unbiased with respect to the hypocentral distances. This indicates that the proposed model provides reasonable PGA and $S_a$ for NEI with respect to both magnitudes as well as hypocentral distances. We have also performed the sensitivity analysis for calculating the regression coefficients in equation (1) based on the input parameters namely magnitude, focal depth, anelastic attenuation, and geometric attenuation. The standard deviation calculated in the sensitivity analysis varies from 0.11 to 0.45 which is within the limit as described by Drouet and Cotton (2015) and Singh et al (2016).

7. Conclusions
In this study, a new ground-motion prediction model for crustal earthquakes is developed for NEI based on available strong motion records. The present model developed on C type site has been compared with the stochastic model developed by Singh et al. (2016) on the Hard rock level. The site coefficient for the C type site has been calculated for NEI (Singh et al 2016). The stochastic model of Singh et al 2016 on the hard rock level ground motion model has been scaled to the C type site by multiplying site coefficient. It is seen that our model is well compared with the stochastic model scaled to the C type site. Most of the developed countries in the world have come up with region-specific GMPEs, which are successively used to estimate the probabilistic seismic hazard to a finer scale i.e. in a smaller grid point which is known as earthquake hazard microzonation. This type of earthquake hazard microzonation map has not been prepared to date for NEI. Based on the high seismic threat, probabilistic seismic hazard and earthquake hazard microzonation map for NEI is very much desirable. The GMPE developed for crustal earthquakes in the present study based on the recorded strong motion database in NEI can be conveniently used in preparing a seismic hazard map for NEI.

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