# Strong Ground Motion Prediction Equation for Northwest Himalayan Region based on Stochastic Approach

**M. L. Sharma & A. Harbindu**
*Department of Earthquake Engineering, Indian Institute of Technology Roorkee*

**Kamal**
*Department of Earth Sciences, Indian Institute of Technology Roorkee*

**SUMMARY:**
Understanding spatial variations of ground motion due to earthquakes is an important problem. This is particularly so in assuring safety of important structures such as dams, bridges and nuclear power plants. This problem is not tractable from purely instrumental record in the regions with scarcity of strong-motion data as in Indian subcontinent. In this study, predictive relation are developed for ground motions from NW Himalayan earthquakes of $3.5 \leq \mathbf{M} \leq 6.5$ at distances of $1 \leq R \leq 75$ km. The predicted parameters are 5% damped response spectra at periods of 0.1 to 10 Hz, and peak ground accelerations. The predictions are derived from empirically based stochastic ground motion model. The source, path and site parameters are derived from the available earthquake records of the region. The stochastic model is tested against available recorded motions and shows an adequate match with the recorded ground motion for the magnitude range of interest. The derived prediction equation is in demonstrable agreement with the observed data and shows a reasonable consistency with the other predictive relations currently in use for the region.

*Keyword: stochastic model, ground-motion predictive equation , response spectra, NW Himalaya*

## 1. INTRODUCTION

One of the important issues for reliable seismic hazard analysis is the accurate prediction of ground motion at a site as a function of magnitude and distance. This can be obtained by deriving ground motion predictive equation (GMPE) using a large set of observed data. There are several equations available across the globe, especially in the regions with abundance of strong-motion data. But availability of GMPEs based on observed data is always questionable for a region with scarcity of observed strong-motion data such as India. However in such a case, synthetic data generation by simulations based on regional seismic parameters can be used as an alternative for deriving GMPEs. Such GMPEs have been derived successfully by some researchers in the past and are in use for engineering purposes (Atkinson and Boore, 1995; Toro et al. 1997)

In the present paper, we formulate the ground-motion equations for Himachal region of Northwest Himalaya, which is well known for its seismic activities. The predictive equations are developed for ground motions for magnitude range $3.5 \leq \mathbf{M} \leq 6.5$ at distances of $1 \leq R \leq 75$ km. The predicted parameters are 5% damped response spectra at periods of 0.1 to 10 Hz, and peak ground accelerations. The predictions are derived from empirically based stochastic ground motion model. Harbindu et al., (2012) derived source, path and site parameters from the available earthquake records of the region. The stochastic model is tested against available recorded motions and shows an adequate match with the recorded ground motion for the magnitude range of interest. The derived prediction equation is in agreement with the observed data and shows a consistency with other predictive relations currently in use for the region.

## 2. STUDY AREA AND SEISMOTECTONIC BACKGROUND

The Himachal region is located between 30.3$^0$ - 33.0$^0$ N latitude and 75.6$^0$ - 79.0$^0$ E longitude in the NW Himalaya. Seismically, it lies in the 2500 Km long great Himalayan seismic belt. The region has experienced a number of devastating earthquakes causing enormous damage in the past. A catalogue prepared by Szeliga et. *al.*, (2010) on intensity, magnitude, location and attenuation of felt earthquakes in India since 1762 to 2009 contains at least 7 earthquakes ranging from magnitude 7.8 to 4.5 which have occurred in Kangra region only. The epicenter of most earthquakes is in the Himachal region and is distributed in three major zones namely, the north western zone, eastern zone and central zone. The study area falls in the north western zone and central zone which comprises of Chamba, Kangra and Mandi districts. The study area consists of two main tectonic features: Main Boundary thrust (MBT) and the Himalayan Frontal Fold (HFF). Fig. 1. shows major tectonic features in the study area. Three main tectonic features namely Main Boundary Thrust (MBT), Main Central Thrust (MCT) and Main Frontal Thrust (MFT) have been delineated due to continuous movement of Indian plate towards Eurasian plate. The continuous northward movement of Indian plate causing enormous seismic activities along the entire Himalayan arc.

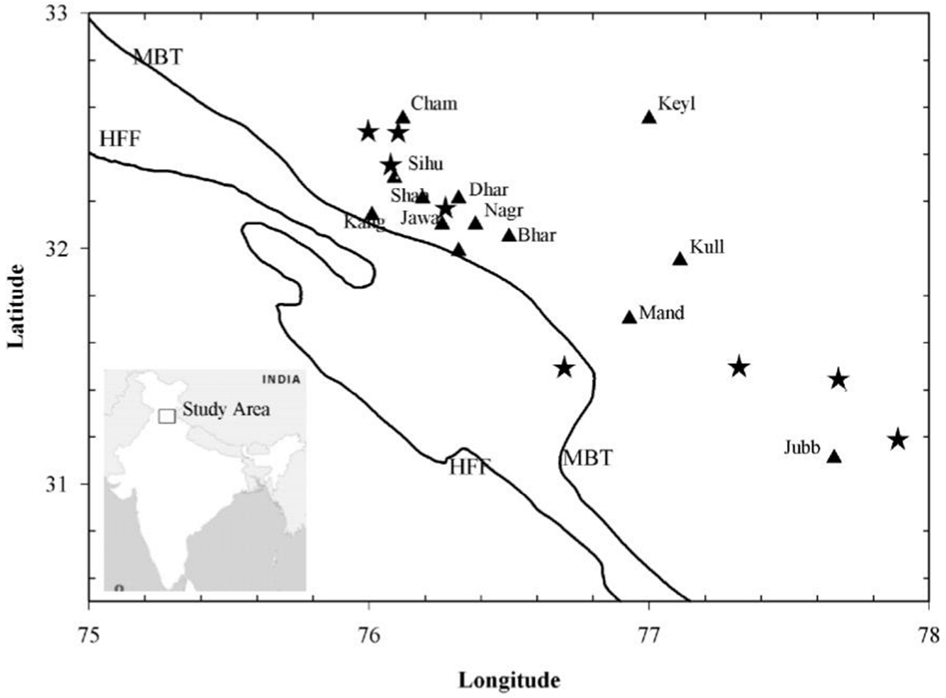


**Figure 1.** Map showing tectonic frame work of study area in NW Himalaya. Solid triangles represent the strong-motion stations and stars represent the epicenters of the events listed in Table 1. HFF is Himalayan frontal Fold, and MBT is Main boundary thrust.

## 3. DATABASE

The data used in this study has been compiled from Indian dataset (PESMOS), a strong-motion instrumentation network of Indian Institute of Technology, Roorkee (IITR) which consists data from 284 strong-motion accelerographs installed in North and Northeast India. The average station-to-station distance of the network is about 50 km. Each station has digital strong-motion accelerographs with a wide frequency and dynamic range. The information of all the participating earthquakes used in the present study are given in Table 1. The details of all recording stations are presented in Table 1. The 1986 Dharmsala earthquake $M_w$ 5.4 (event 1 in Table 1) has been recorded by earlier strong-motion network of IITR which used SMA1 analog accelerograms with triggering set at 0.01 cm/sec$^2$. The analog accelerographs were manually digitized at a sampling frequency of 50 Hz and band pass filtered (0.17-0.20; 25-27 Hz) using Ormsby filter (Chandrasekaran and Das, 1992). This earthquake was recorded at 8 stations of Himachal region.

**Table 1.** Details of the Earthquakes

| Serial Number | Date | Latitude ($^0$ N) | Longitude ($^0$ E) | Magnitude | Recording station code | Distance range (km) |
|---|---|---|---|---|---|---|
| 1 | 26/04/1986 | 32.1 | 76.2 | 5.4 | Baroh, Bharwana, Dharmsala, Jawali, Kangra, Nagrota, Shahpur, Sihunta, | 9-26 |
| 2 | 10/12/2006 | 31.5 | 76.7 | 3.5 | Mandi | 31 |
| 3 | 04/10/2007 | 32.5 | 76.0 | 3.8 | Chamba | 9 |
| 4 | 21/10/2008 | 31.5 | 77.3 | 4.5 | Kullu, Mandi | 44-48 |
| 5 | 31/1/2009 | 32.5 | 76.1 | 3.7 | Chamba, Dharmsala , Keylang | 16-33 |
| 6 | 17/07/2009 | 32.3 | 76.1 | 3.7 | Chamba, Dharmsala, Keylang | 23-30 |
| 7 | 28/5/2010 | 31.2 | 77.9 | 4.8 | Jubbal | 25 |
| 8 | 13/8/2010 | 31.4 | 77.7 | 3.4 | Jubbal | 32 |

## 4. APPROACH

### 4.1. Brief Review of Basic Method

Following Boore (2003), the stochastic method of ground motion modeling (also referred as Band-Limited-White-Noise or BLWN) is based on assumption that the radiated energy is randomly distributed over a specified duration of time. The method involves two main steps, (i) generation of a windowed time series of band-limited random white Gaussian noise with zero mean amplitude and (ii) development of theoretically derived target Fourier amplitude spectrum. The details of the methodology can be found at Boore (2003). The acceleration Fourier amplitude spectrum *A(R,f)* at any station located at distance *R* can we written as:

$$A(R,f) = \underbrace{C\,\frac{(2\pi f)^2 M_o}{[1+(f/f_c)^2]}}_{Source\ term} * \underbrace{G(R)e^{-\frac{\pi f R}{\beta Q_\beta}}}_{Path\ term} * \underbrace{P(f).D(f)}_{Site\ term} \tag{4.1}$$

*G(R)* is geometrical spreading of seismic energy travelling from source-to-site and P*(f)* is the site amplification and *D(f)* is de-amplification or diminution function (Anderson and Hough,1984). *R* is the hypocentral distance, asterisk (*) represents multiplication and *C* is a constant computed as ($R_{\theta\varphi}FH/4\pi\rho\beta^3$ )where $R_{\theta\varphi}$ (0.55) is a parameter to account for the average radiation over a range of azimuths $\theta$ and take off angles $\varphi$. *F* (2) is the parameter for free surface amplification. *H* (0.71) is the parameter to account for partitioning of energy into two horizontal components. $\rho$ (2.8 gm/cm$^3$) and $\beta$ (3.3 km/s) is the regional density and shear wave velocity in the vicinity of the source.

### 4.2. Model Parameters

The input parameters for the method include all the terms of Eqn. 4.1. and the duration of the motion. The $\omega^2$ model is particularly adequate for the present study because of its simplicity and ability to predict spectral amplitudes and shapes over wide range of magnitudes, distances and frequencies as well as wide tectonic regimes. Recently Harbindu et al., (2012) has computed the source, path, and site parameter of Himachal region using the database reported in Table 1.The source parameters includes estimation of source spectra for each mainshock and stress drop, corner frequency and seismic moments of each event reported in Table 1. The site amplification *P(f)* has been computed using horizontal-to vertical (*H/V*) spectral ratio technique and *for D(f)*, high frequency diminution function kappa estimated as 0.005 s. All stations are located on hard rock sites. The frequency dependent anelastic attenuation factor (Q-value) is computed using direct regression on observed shear-wave Fourier amplitude as $103f^{\,0.66}$. In the present study, the geometrical spreading term accounted as follows (Singh *et al.*, 1999):

$$G(R) = \begin{cases} 1/R & R \le 100\ km \\ 1/(100R)^{1/2} & R > 100\ km \end{cases} \tag{4.2}$$

Apart from the source, path and site parameters for database reported in Table 1., the final input in stochastic simulation of ground motion required is the duration model. It represents the length of synthetic time history to be considered for simulation. The duration model is generally expressed as $T = T_0 + bR$, where $T_0$ is the source duration and $bR$ represent the distance dependent term that account for dispersion. For the source duration, we assume a source duration as $1/f_c$ where $f_c$ is corner frequency and b = 0.05 (Boore and Atkinson, 1987). A summary of all input used for simulation are summarized in Table 2.

### 4.3. Model Validation

The important aspect of any numerical modeling approach is a demonstration of the model's ability to predict recorded strong ground motions. In this section, the ground motions are modeled and compared to the actual recordings of all the events reported in Table 1. Table 2 presents the model parameters for variability calculation for the stochastic ground motion model. For event 1 (Dharmsala earthquake), the model predicts a very demonstrable match of response spectra for all seven recording stations and shown in Fig. 2.

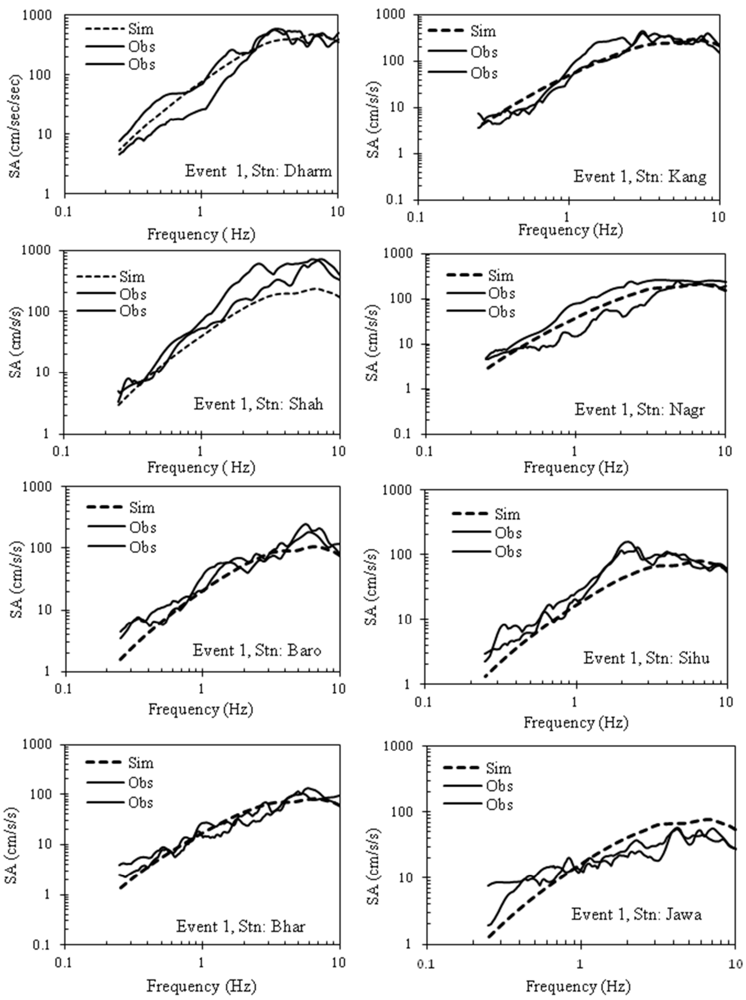


**Figure 2.** Comparison of observed and modeled 5% damped acceleration response spectra for 1986 Dharmsala earthquake and other events. Model results are from the stochastic ground motion model. The dashed line represents the simulated ground motion and solid lines represent the observed horizontal components of ground motion.

**Table 2.** List of modeling parameters: (moment magnitude ($M_w$),seismic moment ($M_o$), quality factor, site amplification and kappa) for variability calculation for the stochastic ground motion model.

| Event No. | $M_w$ | $\Delta\sigma$ (bars) | $Q_0$ | Amplification factor | kappa, $\kappa$ |
|---|---|---|---|---|---|
| 1 | 5.4 | 35 | | | |
| 2 | 3.5 | 121 | | | |
| 3 | 3.8 | 32 | | | |
| 4 | 4.5 | 10 | $103\,f^{0.66}$ | *H/V* | 0.005 |
| 5 | 3.7 | 11 | | | |
| 6 | 3.7 | 44 | | | |
| 7 | 4.8 | 40 | | | |
| 8 | 3.4 | 98 | | | |

The Response spectra of the other events are presented in Fig. 2. and it show a reasonable match with the model-predicted response spectra except for event 4 and 7. For event 4 and 7, the model has over predicted in lower frequency from 0.1 to 4 Hz. The overall agreement between the recorded ground motions and modeled ground motions are in good agreement in frequency range of engineering interest.

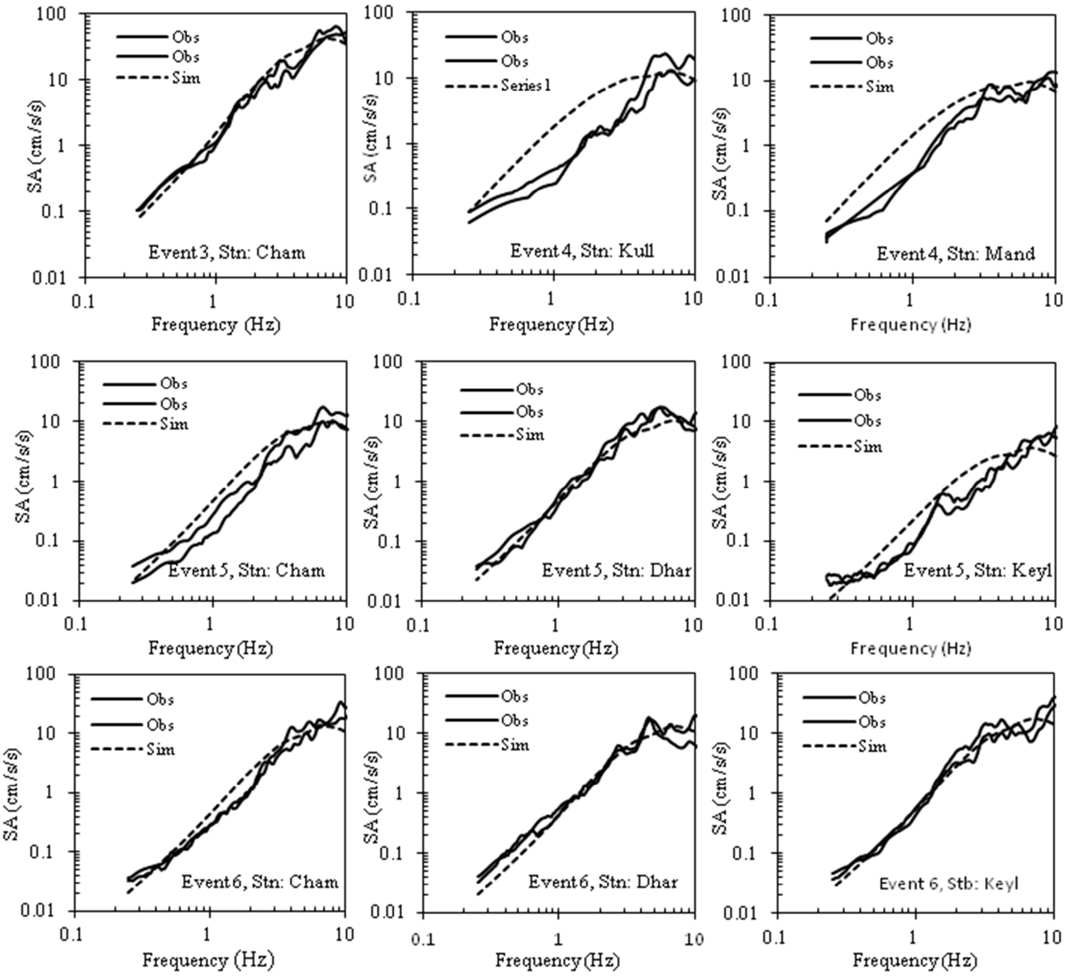


**Figure 2.** Continued

## 4.4. Modeling Uncertainty

To provide quantitative measure of the uncertainties in the ground motion predictions, a simple goodness-of-fit was performed at each frequency. The modeling uncertainty is the average at each frequency of the difference of the natural logarithm of the observed ground motions and the model predicted ground motions. Fig. 3. shows the modeling uncertainty computed from the combined data from the all the events. For frequencies greater than about 2 Hz, the total modeling uncertainty ($\sigma_{ln}$) is quite low, generally about 0.2.The modeling bias has been estimated using procedure describe by Abrahamson et al. (1990) and shown in Fig. 3. for combined data for all events along with ±1 standard deviation (dotted lines). The model bias is essentially close to zero for frequencies above 2 Hz. A small negative model bias is observed in frequency range 0.5 to 2 Hz indicates a small over prediction of the ground motions by the model compared to the recorded ground motions. Following Abrahamson et al. (1990), if any model bias exists in the process, it may be used to correct (lower) the modeling uncertainty. The bias-corrected modeling uncertainty is presented in Fig. 3 by dashed lines.

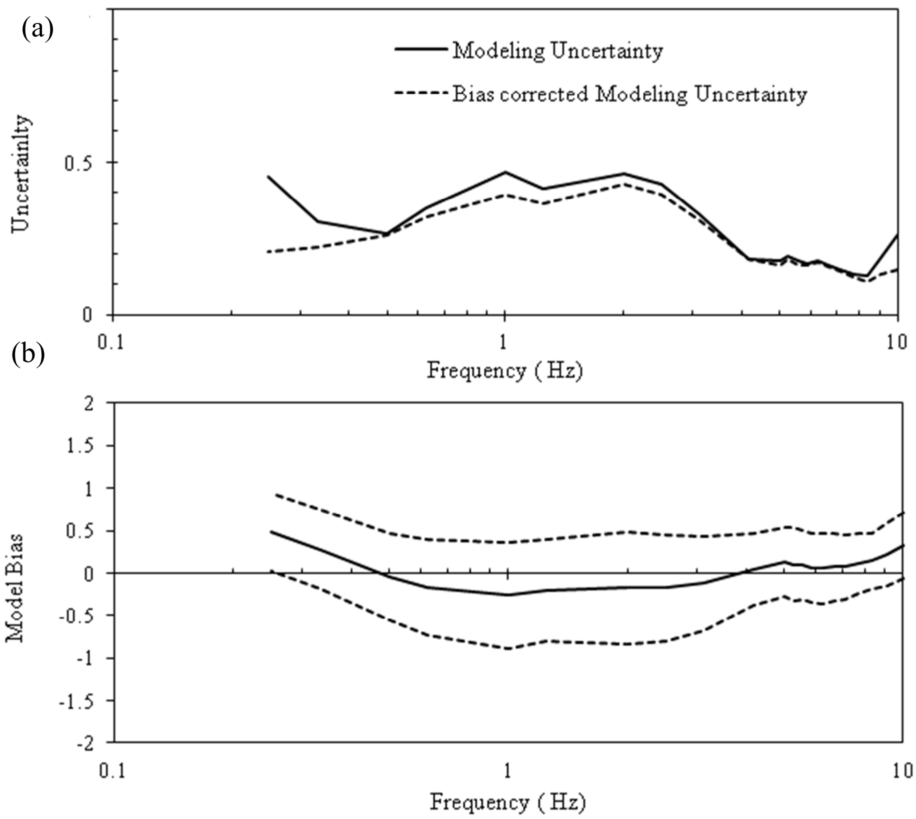


**Figure 3.** (a)Modeling uncertainty (solid) and bias-corrected modeling uncertainty (dashed)(both $\sigma_{ln}$) and (b) Model bias with ±1 standard deviation (dashed) computed for combined data from all the events considered.

## 6. DEVELOPMENT OF PREDICTIVE EQUATION

### 6.1. Functional Form of Ground Motion Predictive Equation

In view of practical application of ground motion prediction equations for engineering design and seismic hazard assessment, the ground motion equation must be in the simple functional form in terms of magnitude and distances. These sets of attenuation functions commonly called as engineering model. Atkinson and Boore (1995) tested simple quadratic functional form of ground motion prediction equation by performing some example of hazard calculation and investigated that simple quadratic form predict sufficiently accurate in magnitude ranges that are most significant to seismic hazard analysis. We adopted same functional form of predictive equation for present analysis which is as follows:

$$\log(SA) = c_1 + c_2(M-6) + c_3(M-6)^2 - \log R - c_4 R \qquad (6.1)$$

where SA is the spectral acceleration (cm/s$^2$) and $c_1$ through $c_4$ are constant to be determined from modeling results. $M$ is the moment magnitude and $R$ is the fault rupture distance (km).

### 6.2. Fit to Model Predictions

The stochastic ground model was used to calculate ground motion amplitudes for a number of magnitude, distance, and model parameters bins, covering the ranges of engineering interest. Table 3. summarizes the parameters variations considered to generate scenarios. The ground motion amplitudes were obtained for all parameter combinations. We used 20 trials for each magnitude and distance combinations. Thus, a total $(13\ x\ 7x\ 8\ x\ 12x\ 1\ x\ 1\ x\ 1\ x\ 20)$174720 number of simulations have been performed for complete analysis. This large set of results embodies all possible ground motion predictions by the model of wave propagation, seismic source and crustal structure. Since all of the recording stations are located in rock site, random parameter *Q(f)* is same in all simulations. The only random parameter can be varied is stress drop in order to get model scenarios. Each combination of random parameter (stress drop) in Table 3. assigned equal weight based on distribution of stress drops reported in Table 2. One fit (i.e. one set of coefficients) is obtained for each combination of ground motion measure, site amplification, and quality factor. A total 174720 of fit obtained to develop ground motion prediction equation for this study.

**Table 3.** Parameter Variations

| Category | Quantity | Number | Values | Median |
|---|---|---|---|---|
| Dependent Variables | Ground-Motion Amplitude | 13 | PGA, spectral acceleration 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0 | |
| Independent Variables | Magnitude (M) | 7 | 3.5, 4.0 ,4.5, 5.0, 5.5, 6.0, 6.5 | |
| | Distance (km) | 8 | 5,10,15,20,30,40,50,75 | |
| Random Parameters | Stress drop (bars) | 12 | 5,10,15,20, 30, 35, 40, 45, 50, 75, 100, 120 | 37.5 |
| | Quality factor, *Q(f)* | 1 | $103f^{0.66}$ | $103f^{0.66}$ |
| | Amplification function | 1 | *H/V* | *H/V* |
| | Kappa, κ | 1 | 0.005 | 0.005 |
| | Total Number of run 174720 | | | |

## 7. RESULTS

Table 4 lists the regression coefficients $c_1$ through $c_4$ and the standard deviation of the engineering model, which were obtained by fitting Eqn. 6.1. The present study has used all the updated list of the earthquakes records of the region which ranges in magnitude M 3.4 to 5.4 and distance 5 to 100 km. All the source, site and path parameters listed in Table 3 are estimated using these observed earthquake records. Thus we restricted the ground motions predicted by engineering model derived in this study in magnitude range of 3.4 to 6.5 and distance 10 to 100 km. Extrapolation beyond this magnitude and distance range causes a large uncertainty in the ground motion prediction. The derived engineering model has been compared with other available GMPEs across the globe against observed peak ground acceleration (PGA) of 1986 Dharmsala earthquake of the study region. Fig. 4. shows the most available GMPE display a good fit upto 15km and overestimate beyond 15 km except the one by Peng et al. (1985) for Northeast China. This show that the study region has faster attenuation characteristic than estimated by the worldwide GMPEs . The presently derived equation shows a good fit to observed data in for all distance range.

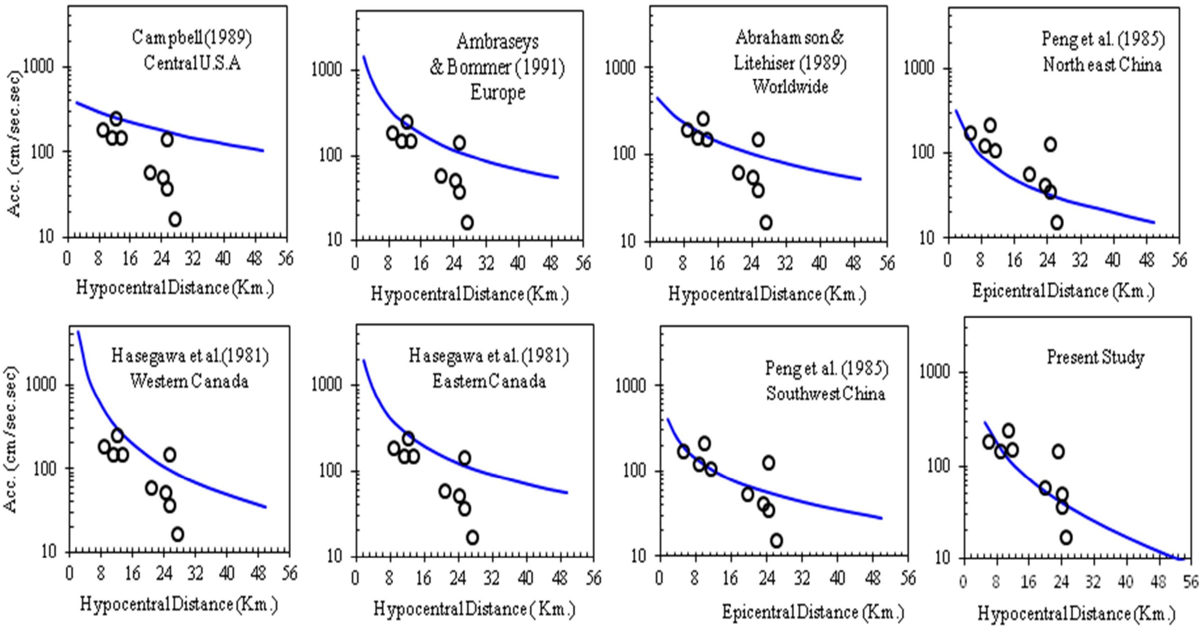


**Figure 4.** Proposed engineering model plotted along the observed peak ground accelerations of 1986 Dharmsala earthquake.

**Table 4.** Regression coefficients and standard error for Rock-Site conditions

| Period (sec) | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $\sigma_{ln}$ |
|---|---|---|---|---|---|
| PGA | 3.374 | 0.3503 | -0.0698 | 0.00919 | 0.0488 |
| 0.1 | 3.653 | 0.3492 | -0.0556 | 0.01001 | 0.0335 |
| 0.15 | 3.787 | 0.3612 | -0.0632 | 0.00907 | 0.0238 |
| 0.2 | 3.723 | 0.3546 | -0.0804 | 0.00839 | 0.0258 |
| 0.3 | 3.690 | 0.3632 | -0.1077 | 0.00718 | 0.0271 |
| 0.4 | 3.580 | 0.3722 | -0.1294 | 0.00618 | 0.0280 |
| 0.5 | 3.473 | 0.3855 | -0.1459 | 0.00531 | 0.0266 |
| 0.8 | 3.244 | 0.4392 | -0.1635 | 0.00402 | 0.0234 |
| 1.0 | 3.073 | 0.5040 | -0.1629 | 0.00342 | 0.0267 |
| 1.5 | 2.830 | 0.6280 | -0.1441 | 0.00296 | 0.0404 |
| 2.0 | 2.651 | 0.7299 | -0.1198 | 0.00287 | 0.0503 |
| 3.0 | 2.382 | 0.8720 | -0.0787 | 0.00294 | 0.0595 |
| 4.0 | 2.161 | 0.9559 | -0.0494 | 0.00302 | 0.0640 |

Recently Sharma et al., (2009) have derived a GMPE for the Himalayan region using records of Himalayan earthquakes. Fig. 5. compares model predicted PGAs with those estimated by Sharma et al., (2009) and Boore and Atkinson (2008) for magnitudes 5.0, 5.5, 6.0, and 6.5. We observe that the present engineering model predicts roughly similar PGA values. and show comparatively faster attenuation characteristic.

In Fig. 6., we compared the derived model with the ground motion equations by other authors for Himalayan region or similar tectonic environments. The comparison is made for magnitude M 5.0 and M 6.0 and distances 10 and 50 km. The standard deviations of presently derived model are comparatively lesser than Sharma et al. (2009) in all period ranges. The smaller deviations have significant impact on assessed ground motion from probabilistic seismic hazard analysis especially at longer return periods.

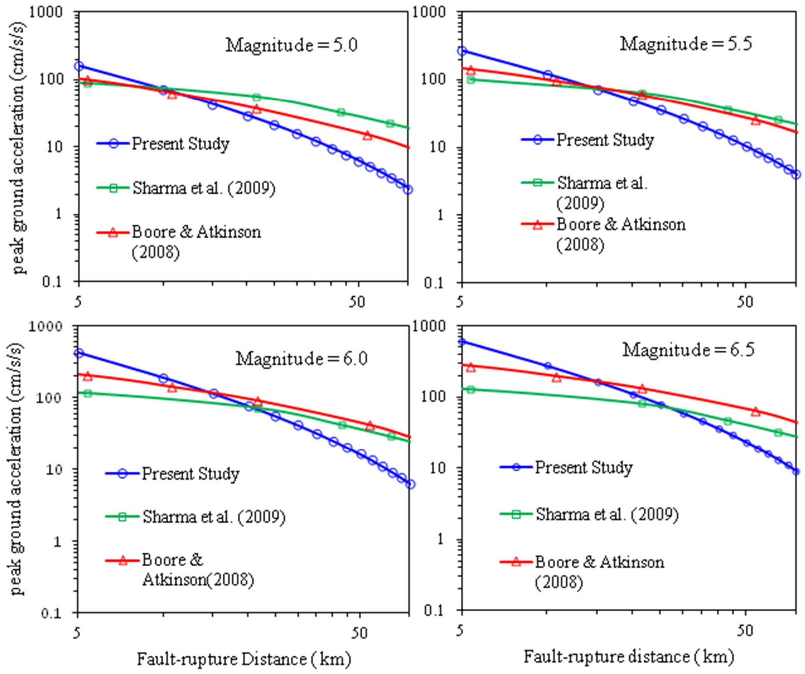


**Figure 5.** Comparison of present engineering model with the ground motion predictive equations given by Sharma et. al., (2009) and Boore and Atkinson (2008) for Magnitude 5.0, 5.5, 6.0, and 6.5.

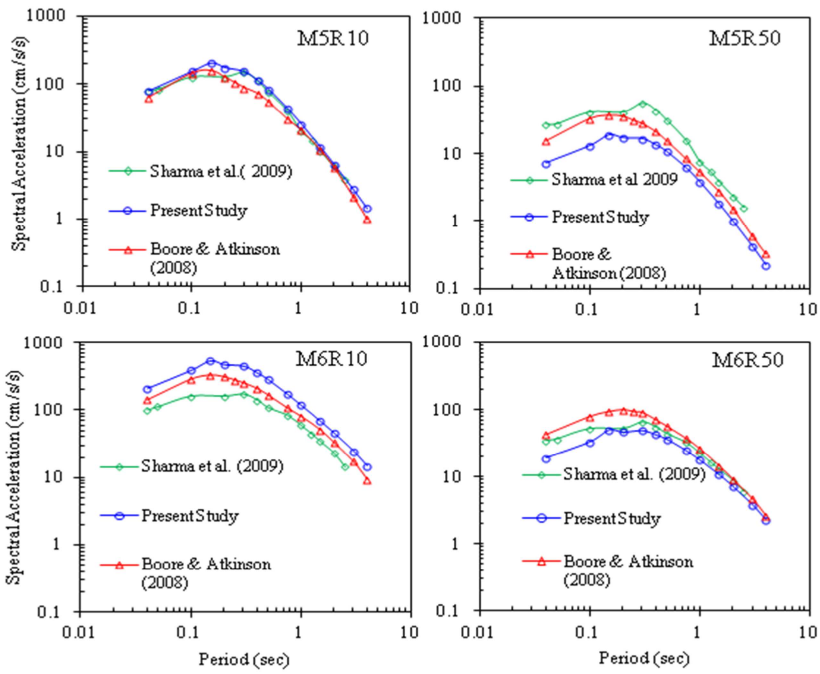


**Figure 6.** Comparison of 5 % damped response spectra from stochastic ground motion model with Sharma et. al., (2009) and Boore and Atkinson (2008) for magnitude M 5.0 and M 6.0 and distances 10 and 50 km.

## 8. CONCLUSIONS

The new ground-motion relations provides a good description of peak ground motions and response spectra for Himachal region's earthquakes of small-to-moderate magnitude (M 3.5-6.5) for shorter distance (R 5-75 km). The equations for strong ground motion estimation are consistent with the instrumental observations of earthquake ground shaking in Himachal, and are roughly consistent with previous prediction relations. Difference with the observations are not statistically significant (except at low frequencies where they over estimate ground response) and attributable to the limited samples of earthquakes with magnitude and distance of engineering interest. The important conclusion that could be drawn from the study is the faster attenuation characteristic of acceleration as compare to other predictive relations. This characteristic of the region have been reported other authors also (e.g. Sriram et al. 2005).There are insufficient instrumental data to adequately judge the relations at larger magnitude. The underlying model parameters, such as source spectrum and attenuation, are constrained by observed data for events of M 3.4 to M 5.4. Even with this constrained on the model parameters, the model has demonstrated reasonable prediction of strong ground motion for small-to-moderate events

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