has found wide acceptance\textsuperscript{17,18}. But for its higher melting point (70.6°C), which necessitates quick dispensing\textsuperscript{9}, isubgol is a cost-effective gelling agent with desirable properties\textsuperscript{9}. Gum Katira, like ficoll, does not form a firm gel at 3%, but the explants remain on the surface if left undisturbed. In transparency, Gum Katira-gelled medium is comparable to the liquid medium. Therefore, it can be an excellent gelling agent for experiments requiring regular observations of cells, tissues or organs growing inside the medium\textsuperscript{9}.

As cost of isubgol and guar gum per litre of the medium is about 2.5–13 times less than different brands of agar (Table 2), these are two highly cost-effective gelling agents, which could be used for reducing the cost of in vitro-propagated orchid plants. Both being of plant origin, are biodegradable and do not pose any threat to the environment on being dispensed-off after use. Moreover, both P. ovata and Cyamopsis tetragonoloba, sources of isubgol and guar gum respectively, are easily cultivated and therefore, their increased demands can be easily met. However, media gelled with isubgol or guar gum, require quick adjustment of pH and dispensing because of their higher gelling point.


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Spectral attenuation models in the Sikkim Himalaya from the observed and simulated strong motion events in the region

Sankar Kumar Nath*, Madhav Vyas, Indrajit Pal, Avinash Kumar Singh, Sudeshna Mukherjee and Probab Sengupta
Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur 721 302, India

Strong motion recordings by the Sikkim Strong Motion Array (SSMA) of 80 events with good signal-to-background noise ratio (≥3) for magnitude between 3 to 5.6, have enabled estimation of source model and site response, and also the simulation of spectral acceleration for moderate-to-large earthquakes with 6 ≤ M\textsubscript{w} ≤ 8.3. A combined simulated and recorded data set have ultimately been utilized for deriving the spectral attenuation laws incorporating the local site conditions, namely, topographic effect and site response, with and without shear wave velocity in addition to the normal earthquake parameters, viz. moment magnitude (M\textsubscript{w}) and source-to-site distance (r). The spectral attenuation laws developed in this study have been found to be appropriate for predicting free-field horizontal Peak Ground Acceleration (PGA) for earthquakes of 3 ≤ M\textsubscript{w} ≤ 8.3 and for the sites with distances up to 100 km from the source in the Sikkim Himalaya. The estimated spectral acceleration through these attenuation laws mimic the mean spectral acceleration simulated using Brune’s source model.

The Sikkim Himalaya located in the northeastern Indian Peninsula, is seismically one of the six most active regions

*For correspondence. (e-mail: nath@gg.ittkgp.ernet.in)
of the world, being placed at the boundary of seismic zone V (PGA > 0.4 g), the highest region of the seismic zonation map of India (IS1893-2002). The high seismicity in the region is attributed to the collision tectonics between the Indian plate and the Eurasian plate to the north and Indo-Myanmar range to the east. There can be different methods of quantifying risk and hazard in a region, one of those being the estimation of Peak Ground Acceleration (PGA) through empirically developed attenuation relationships for the prediction of design ground motions that is often controlled by a hypothesized occurrence of a large earthquake on a nearby fault. Among the studies that characterize the Himalayan region of the country, the works that demand mention are those of the attenuation relationship based on multiple regression approach of Sharma\(^1\) and the one derived by Parvez et al.\(^2\) through combination of observations with theoretically based attenuation laws. Both Sharma\(^1\) and Parvez et al.\(^2\) used the strong motion array installed in the Himalayan region. The present study describes a set of attenuation relationships that we specifically developed to predict horizontal component of PGA and the spectral acceleration (SA) in the near source region using strong motion recordings of 80 events with magnitude (\(M_h\)) between 3 to 5.6 and large events through spectral simulation assuming Brune’s source model with magnitude between 6 and Maximum Credible Earthquake [MCE from Global Seismic Hazard Assessment Program (GSHAP) considerations]\(^3\) of magnitude 8.3. Initially a local relationship was established wherein we considered PGA to be a function of magnitude and distance only starting with a generalized attenuation law\(^4\). It has been considered prudent to ameliorate the relationship by incorporating corresponding terms for elevation, site response and shear wave velocity. Over the last two decades many researchers studied ground motion attenuation relationships that are, in essence, multiple regression models permitting predictions of a target parameter by means of an empirical relationship established on the basis of available strong motion data from a particular region. The engineering models that directly predict ground motion amplitude or that predict the modulation of this amplitude from such effects as fault geometry, source directivity and local site conditions in the form of a single coherent set of attenuation relationships are kept in mind while attempting the present analysis. The attenuation models of Joyner and Boore\(^5,6\), Campbell\(^7\) and Fukushima and Tanaka\(^8\) have been considered for establishing the attenuation relationship for the horizontal component of PGA. The strong motion parameters considered here include the horizontal PGA, spectral acceleration (SA), earthquake magnitude (\(M_h\)), source-to-site distance (\(r\)), local site condition (\(S_v\) and \(S_s\)) and station elevation or topography (\(h\)). Moment magnitude (\(M_w\)), a better measure of the true size\(^9\) of an earthquake is used to define earthquake magnitude in the present study. Source-to-site distance (\(r\)) is defined as the shortest distance between the recording site and the presumed zone of seismogenic rupture on the fault; the same is also referred to as hypocentral distance in case of a point source assumption.

To quantify the effects of local site conditions we have used two parameters namely Shear Wave Velocity (\(S_v\)) and Site Response (\(S_R\)). The soil thickness at different sites was estimated through seismic refraction profiling using a 24-channel engineering seismograph. Site classification is done on the basis of shear wave velocity\(^10\), which has been computed through the correlation of soil taxonomy map at 1 : 50,000 scale from National Bureau of Soil Survey\(^1\) and couple of litho-logs. Being situated in a hilly terrain, the Sikkim region is found through seismic refraction survey to be devoid of a thick sediment cover and hence no term incorporating the thickness of the soil has been used in the present analysis. Instead, \(S_v\) and \(S_R\) are used to represent and account for local site amplifications.

Topography plays a vital role for sites situated in a hilly terrain. In such areas, apart from incident wave we are expected to record diffracted and scattered waves that emanate from different parts of the hill which are hit upon by the incident waves. In regimes where constructive interference between incident and diffracted waves takes place, we observe site amplification and wherever destructive interference takes place amplitude gets reduced. This topographic effect, however, follows the frequency content of the signal as exhibited later in the site response analysis. A term for topography is, therefore, introduced in our attenuation models.

A semi-permanent 9-station strong motion array in Sikkim established by IIT, Kharagpur, India has been operative since 1998. One Kinematics Altus K2 and 8 Kinematics Altus ETNA high dynamic range strong motion accelerographs have been installed to continuously monitor the signals that satisfy event detection criteria. A trigger level of 0.02% of the full-scale (2 g) and a sampling of 200 samples per second are set for the data recording. The dynamic range of the systems is 108 dB at 200 samples/s with 18-bit resolution. The data for 80 local earthquakes (\(M_h\) 5.6) have been recorded during 1998-2003 shown in Figure 1 a with a N-S depth section on GIS platform in Figure 1 b. The depth section exhibits major clustering of events along Main Boundary Thrust (MBT) and in its proximity. The composite fault plane solution from the strong motion events along MBT suggests thrust faulting with strike slip component with a dip of 35° NNE striking at 310 (USGS convention) (Figure 1 b). Since the fault types are similar due to clustering along MBT, no fault term has been introduced in our attenuation models. In Figure 2 a-c the Butterworth band-pass filtered accelerograms at station Mangan are presented for the event 0010181422 (\(M_h\) = 4.9). The Fourier spectra of S-envelope (S) and the background/pre-event trace (B) windows are displayed in Figure 2 d-f in log-log scale in order to depict the quality of the data used in the analysis.

Following Andrews\(^11\) the amplitude spectrum of the \(i\)th event recorded at the \(j\)th station for the \(k\)th frequency,
Figure 1. a. Eighty earthquakes located in the Sikkim–Darjeeling area recorded by the Sikkim Strong Motion Array (SSMA) with 3.0 ≤ M ≤ 5.6. b. N–S depth-section on GIS platform showing the subsurface distribution of these earthquakes along with the composite fault plane solution that exhibits thrust faulting with strike-slip component.

\[ A(r_0, f_k) = \text{SO}_i(f_k) \cdot \text{SI}_j(f_k) \cdot P(r_0, f_k) \]

(1)

where \( G(r_0) \) accounts for geometrical spreading, \( Q_s(f_k) \) and \( \beta \) are S-wave frequency-dependent quality factor of the medium in the study region and velocity, respectively. We assumed \( \beta = 4.0 \text{ km/s} \) as an average shear-velocity on the basis of the velocity models for the Sikkim Himalaya and \( \alpha \beta = 1.73 \), where \( \alpha \) is the P-wave velocity\(^{16}\). We considered\(^{17,18}\),

\[ G(r_0) = \frac{1}{r_0} \quad \text{for} \ r < 100 \text{ km}, \]

or,
Figure 2. Butterworth band-pass filtered accelerograms of three components at Mangan station for the event 0010181422 (M_L = 4.9). a, NS; b, Vertical; and c, EW. Fourier spectra of S-envelope (S) and Background (B) for d, NS, e, Vertical and f, EW. Site response at Mangan computed through g, HVSR and h, GINV.

\[ G(r) = (n_y + 100)^{0.5} \]  \quad \text{for } r > 100 \text{ km}, \quad (3)

to take into account possible arrival of surface waves in the windowed data.

We have determined \( Q_s \) and its dependence on frequency in the form of a power law through regression analysis of the direct S-wave data recorded by SSMA as shown in Figure 3. The power law can be expressed as given below

\[ Q_s = (167.69\pm28.25)f^{(0.47\pm0.06)} \]  \quad (4)

Site response has been estimated through Generalized Inversion (GINV) approach and HVSR technique, these techniques are considered apt in the absence of a reference site. The sample site response curves by HVSR and GINV at Mangan for the source azimuth of 197.13°N are presented in Figure 2 g and h respectively. In order to illustrate spatial distribution of site response in the Sikkim Himalaya, we subdivided HVSR values in three frequency bands, namely, low frequency band, LFB (<5 Hz) with a geometric
central frequency 2.5 Hz, moderate frequency band, MFB (5–10 Hz) with a geometric central frequency 7.5 Hz and high frequency band, HFB (10–20 Hz) with a geometric central frequency 15 Hz. The averaged site response values at these frequencies are plotted, contoured and presented in Figure 4a–c respectively. It is observed that high site response contours at LFB are at the foothills of the Himalayas in the Siwalik soft rock terrain. Maximum site amplification to the tune of 3.4 is observed near Singtam that is at an elevation of 500 m above mean sea level. It is further evident from Figure 4a that as the altitude increases towards the northern districts of Sikkim, namely, Mangan, Chungthang and Lachen with the elevations of 1000, 2200 and 3800 m respectively, the site response diminishes. For
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the MFB with the geometrical central frequency of 7.5 Hz we observe in Figure 4b a different scenario of spatial variation of site amplification in contrast to that at low frequency band. Here, the higher HVSR values peak near Mangan at an elevation of 1000 m. In this region the hill slope is much steeper, the maximum site amplification observed in this case is 4.6. In the HFB with geometric central frequency 15 Hz the spatial variation pattern of site amplification shifts further northeast towards Chungthang with an altitude of 2200 m, site response peaking to a value of 5.8 on the high hill scarp between Mangan and Chungthang. It is noted that the Gangtok lineament is striking very close to Chungthang and is seismogenic in the area. This variation in the SR contour pattern at three distinct frequency bands seem to follow the topography for the moderate to high frequency regime and is in consistence with the findings of Bouchon and Barker\textsuperscript{2}, when they simulated an experiment to observe ground motion amplification at or near top of the hill depending on the slope and the resonance frequency of the respective morphometric signature of the terrain. We simulated source spectra assuming Brune’s source model\textsuperscript{22,23} that is given as,

\[ \overline{\text{SO}}(f_k) = \frac{[R_{00} F(2\pi f_k)^2]}{\sqrt{2(4\pi \beta)^3}} M_{0}(f_k), \] (5)

where \( R_{00} = 0.63 \) is the radiation pattern averaged over an appropriate range of azimuths and take-off angles, \( F = 2.0 \) accounts for the amplification of the seismic wave at the free surface, \( \rho \) is the crustal density of the continental crust at the focal depth, \( \beta \) is the shear-wave velocity at the source region and \( M_{0}(f_k) \) is the moment rate spectrum. The factor \( \sqrt{2} \) accounts for the partition of S-wave energy into transverse components. We have assumed \( \beta \) to be equal to 2.7 g/cc (crustal density) and \( \beta = 4.0 \text{ km/s} \).\textsuperscript{16} The moment rate spectrum \( M_{0}(f_k) \) can be expressed as,

\[ M_{0}(f_k) = \frac{M_{0}}{1+(f_k/f_{c1})^\gamma}, \] (6)

where \( M_{0}, f_{c1} \) and \( \gamma \), respectively are the scalar moment, corner frequency and the high frequency spectral fall-off associated with the \( i \)th earthquake. The value of corner frequency \( f_{c1} \) can be computed using the relation\textsuperscript{25},

\[ f_{c1} = 4.9 \times 10^{000} \times \beta (\frac{M_{0}}{\Delta \sigma})^{1/3}. \] (7)

Kanamori’s relation\textsuperscript{24} that is given below can be used to compute \( M_{0} \) from \( M_L \).

\[ M_{W} = 2/3 \text{log} (M_{0}) - 10.73, \text{ (} M_{0} \text{ in dyne-cm}). \] (8)

To estimate the value of stress drop (\( \Delta \sigma \)) we used the relation\textsuperscript{24},

\[ \text{log} (M_{0}) = 3/2 \text{log}(S) + \text{log}(16\Delta \sigma / 7\pi^{3/2}), \] (9)

where \( S \) represents the surface area, that can further be calculated using the relation\textsuperscript{25},

\[ \text{log}(S) = 1.21 M_{L} - 5.05 \text{ (S in square km)}. \] (10)

Since we have recorded \( M_{L} \), we convert it to surface wave magnitude (\( M_{S} \)) using the equation,

\[ 0.80 M_{L} - 0.60 M_{S} = 1.04. \] (11)

We can, therefore, establish an empirical relation between \( f_{c1} \) and \( M_{W} \) (since below 5.5, \( M_{W} \) and \( M_{L} \) are almost equal)\textsuperscript{4}. Frequencies thus estimated closely correspond to the frequencies obtained by inversion of the observed data, hence, considering it appropriate to obtain \( f_{c1} \) from above set of relations for the purpose of simulation. In the process of inversion we also obtained values of scalar moment \( M_{0} \) that were related to moment magnitude \( M_{W} \) through the following empirical relationship.

\[ \text{log} (M_{0}) = 2/3 M_{W} + (9.91 \pm 0.45) \text{ (} M_{0} \text{ in dyne-cm}). \] (12)

Having determined all the terms on the right hand side of eq. (1) we used the convolution model to generate the acceleration spectra.

An evaluation of seismic hazard requires an estimate of expected ground motion at the site of interest. In its most fundamental form, an attenuation relation\textsuperscript{9} can be described by its more common logarithmic form,

\[ \ln(Y) = C_1 + C_2 M - C_3 \ln(r) - C_4 r + C_5 F + C_6 S + \varepsilon, \] (13)

![Figure 5. Comparison between different attenuation relationships for \( M_{0} = 7 \) and hypocentral distances varying up to 100 km.](image)
where $Y$ is the strong motion parameter of interest (PGA in this case), $M$ is the earthquake magnitude, $r$ is a measure of source-to-site distance, $F$ a parameter characterizing type of faulting, $S$ the parameter characterizing local site condition, and $\varepsilon$ is the random error term. Ignoring the site and fault parameter, the generalized attenuation law takes the form,

$$\ln(Y) = C_1 + C_2 M - C_3 \ln(r) - C_4 r.$$  \hspace{1cm} (14)

We have used a semi-empirical approach by selecting to minimize the difference between observed and predicted values of ground motion, starting with eq. (14). Thus the first order attenuation relation takes the form:

$$\ln(Y) = -3.6 + 0.72 M - 1.08 \ln(r) + 0.007 r.$$  \hspace{1cm} (15)

This is a mean attenuation relationship without considering local site conditions and for hypocentral distances less than 100 km. A comparative plot between our 1st order relationship, Joyner–Boore relationship\textsuperscript{16}, Campbell’s relation\textsuperscript{19}, Fukushima–Tanaka relationship\textsuperscript{9}, relationship given by Sharma\textsuperscript{4} and Parvaz et al.\textsuperscript{2} for $M_W = 7$ and varying hypocentral distances from 0 to 100 km is shown in Figure 5. Our
1st order relation fits well into this set of attenuation laws. Since we have already observed in our previous analysis that the spectral acceleration depends on site amplification, topography, the source azimuth and the local site conditions, it became necessary for us to work out a local attenuation relation starting with the general form of equation given by Campbell’s Attenuation law for spectral acceleration,

$$\ln(S_A) = \ln(A) + c_1 + c_2 \tanh(c_3 (M - 4.7))$$
$$+ (c_4 + c_5 M) r + 0.5 c_6 S_R + c_7 \tanh(c_8 D)$$
$$+ (1 - S_{HR}) + f_{SA}(D) + \epsilon,$$

where $S_A$ is the horizontal spectral acceleration, $A$ is the PGA, $S_R$ and $S_{HR}$ are variables representing local site conditions for soft rock and hard rock respectively, $D$ is the depth to the basement rock and $f_{SA}$ is a function of $D$.

Since in our study region, the sediment cover is very thin, we neglected the terms corresponding to hard rock and soft rock, instead we introduced a term of site amplification to take into account local site conditions. Moreover, being situated in a hilly terrain dependence on topography is expected, and to account for this we have introduced a term for station elevation. Our established second order attenuation relation, therefore, takes the following shape,

$$\ln(\text{PGA}) = \ln(\text{SA}) - a_1 - (a_2 + a_3 M_W) r$$
$$- a_4 h - a_5 \ln(S_R),$$

where $h$ is the site elevation, $S_R$ the RMS site response and $S_A$ is the spectral acceleration at respective frequencies for which the relation holds well. A set of spectral attenuation relations for frequencies between 0.5 and 19 Hz has been determined at different source azimuths. It is to be noted that due to the paucity of data within the magnitude range 5.6 to 8.3 (MCE) we simulated the spectral acceleration at these magnitudes and clubbed with the recorded event spectra. As expected, the site amplification and spectral acceleration are balancing the azimuthal changes in the attenuation relations thereby stabilizing the coefficients to a large extent. We could further modify the relationship achieved in eq. (17) by appending a term $S_V$ for the shear wave velocity in spite of a thin soil cover. The equation thereupon took the following shape,

$$\ln(\text{PGA}) = \ln(\text{SA}) - a_1 - (a_2 + a_3 M_W) r$$
$$- a_4 h - a_5 \ln(S_R) - a_6 S_V.$$

Figure 6 shows the spline smoothed variation of different coefficients as a function of frequency. On comparison,
the coefficients of the attenuation relationship (17) show minor variation with respect to the ones of eq. (18) as are evident from Figure 6.

In order to judge the authenticity of these attenuation relations we attempted to simulate spectral acceleration using the Brune’s source model and also by using both the attenuation relations (17) and (18) within the frequency band 0.5–19 Hz at all the nine sites, the results at Mangan and Gangtok being presented in Figure 7. It is to be noted that the spectral simulation considered around 100 frequency samples while the attenuation relation considered 20 discrete samples within the same frequency band. As a result, the spectral acceleration computed through attenuation relations mimics the mean trend of that simulated by Brune’s source model as depicted in Figure 7, with and without shear wave velocity term in the spectral attenuation models. No major change is observed in the computed spectral acceleration curves with or without shear wave velocity term in the relationships.

It is, therefore, evident that the recommended spectral attenuation relations developed here are the characteristic spectral attenuation models in the Sikkim Himalaya for predicting free-field amplitudes of horizontal component of Peak Ground Acceleration for moderate to large earthquakes with a hypocentral distance less than 100 km.


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