Strong-motion amplitudes in Himalayas and a pilot study for the deterministic first-order microzonation in a part of Delhi city

Imtiyaz A. Parvez[†,*,#,], G. F. Panza[*,#], A. A. Gusev[‡] and F. Vaccari[*,##]**

[†]CSIR Centre for Mathematical Modelling and Computer Simulation, NAL Belur Campus, Bangalore 560 037, India
*Department of Earth Sciences, University of Trieste, Via E. Weiss 4, 34127 Trieste, Italy
[‡]Institute of Volcanic Geology and Geochemistry, Russian Academy of Sciences, 9 Piip Blvd., Petropavlovsk-Kamchatsky, Russia 683 006
[#]The Abdus Salam International Centre for Theoretical Physics, SAND Group, Trieste, Italy
[##]INGeV, Instituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

The interdependence among the strong-motion amplitude, earthquake magnitude and hypocentral distance has been established[1] for the Himalayan region using the data set of six earthquakes, two from the Western Himalayas (WH) and four from the Eastern Himalayas (EH) ($M_w = 5.2$–7.2) recorded by strong-motion networks in the Himalayas. The level of the peak strong-motion amplitudes in the EH is three-fold larger than that in the WH, in terms of both peak acceleration and peak velocities. In the present study, we include the strong-motion data of Chamoli earthquake ($M_w = 6.5$) of 1999 from the western sub-region, to see whether this event supports the regional effects. New results fit well with our earlier prediction in WH. The minimum estimates of peak acceleration (A_{peak}) for the epicentral zone of $M_w = 7.5$–8.5 events is 0.25–0.4 g for the WH and 1.0–1.6 g for the EH. Similarly, the expected minimum epicentral values of peak velocity (V_{peak}) for $M_w = 8$ are 35 cm/s for WH and 112 cm/s for EH, respectively. The presence of unusually high levels of epicentral amplitudes for the eastern sub-region also agrees well with the macroseismic evidence[1]. Therefore, these results represent systematic regional effects, and may be considered as a basis for future regionalized seismic hazard assessment in the Himalayan region.

Many metropolitan and big cities of India are situated in the severe hazard zone just south of the Himalayas. A detailed microzonation study of these sprawling urban centres is therefore urgently required for a better understanding of ground-motion and site effects. An example of the study of site effects and microzonation of a part of metropolitan Delhi is presented based on a detailed modelling along a NS cross-section from the Inter State Bus Terminal to Sewanagar. Full synthetic strong-motion waveforms have been computed using the hybrid method, a combination of modal summation and finite difference techniques, for the earthquake source of 15 July 1720 (MMI = IX, $M = 7.4$), and mapped all along the cross-section. The response spectra ratio, i.e. the response spectra computed from the signals synthesized along the laterally varying section normalized by the response spectra computed from the corresponding signals, synthesized for the bedrock reference regional model, have been determined as well.

ESTIMATED values of the expected ground motion, as a function of hypocentral distance and earthquake magnitude constitute the fundamental quantities required for the quantitative assessment of earthquake hazard. Predictive relationships for parameters that decrease with increasing distance (such as peak acceleration and peak velocity) are often referred to as attenuation relationships. Over the last two decades, many researchers[2–10] have studied ground-motion attenuation relationships for various regions of the world. Chandrasekaran[11], Singh *et al.*[12] and Sharma[13] have proposed the attenuation relations for the Himalayan region. Most of these studies are, in essence, multiple regression models that permit prediction of a target parameter by means of an empirical relationship established on the basis of the available strong-motion data from a particular region. However, even for regions with a long history of strong-motion observations, data are often insufficient for obtaining completely reliable average trends. The probabilistic approach, being unavoidably based upon the above-mentioned generic attenuation laws, can be misleading as it cannot take into account, with satisfactory accuracy, some of the most important aspects which characterize the critical motion for base-isolated and standard structures (e.g. rupture process, directivity and site effects). Furthermore, the probabilistic analysis of seismic hazard is basically conditioned by the definition of the seismogenic zones. Within each of them the seismogenic process is assumed to be rather uniform, however the critical assumption of homogeneity

**For correspondence. (e-mail: parvez@cmmacs.ernet.in)

can introduce severe errors in the estimate of the seismic hazard in a given site.

In a very recent study, Parvez *et al.*[1] have estimated strong-motion amplitudes from an analysis of the Himalayan array data, using the approach of Gusev[14] and Gusev and Petukhin[15,16]. In this study, the limited amount of available observation was combined with theoretically grounded attenuation laws to determine the peak horizontal acceleration and velocity relationships with magnitude and distance, rather than seeking purely empirical relationships based on 'blind' multiple regression. The general approach that has been applied to the data includes the following steps: (i) reduction of the data to a common fixed distance, (ii) reduction of the result to a common fixed magnitude, and (iii) analysis of the effect of the ground, sub-region and station. In both reductions, a number of variants of the attenuation laws and magnitude trends have been investigated and the appropriate one, assumed to be near-optimal, was chosen. After accounting for the sub-regional effect, the attenuation relationships for two sub-regions, the EH and WH were derived. The results of Parvez *et al.*[1] were based on two events from WH and four events from EH. In the present study, we extend their results by including the strong-motion data of Chamoli earthquake ($M_w = 6.5$) of 1999 in the WH. This event gives us an opportunity to further check the prediction of Parvez *et al.*[1] for the WH. The new established attenuation curves for WH, obtained in the present study after including the Chamoli event, fit very well with our earlier prediction.

A growing number of large industrial cities and urban centres in India face severe earthquake hazard. The recent Bhuj earthquake of 26 January 2001 has left thousands dead, hundreds of thousands injured and a large number destitute. Damage to property apparently runs into billions of rupees. This was a shocking event that generated untold misery and captured media attention around the world. Although located about 300 km away from the epicentre of the earthquake, Ahmedabad, one of the largest cities in India, suffered severe damage due to this earthquake. Other megacities in India such as Delhi, Mumbai, Kolkata and Guwahati also face similar threats. The most effective way to safeguard these cities from the adverse ground shaking that may be caused by a future earthquake is to evaluate the risk to which they may be subject to, by carrying detailed deterministic site effects and microzonation studies, to obtain estimates of seismic ground motion at specific sites. Fortunately, such estimates can be made without having to wait for earthquakes to generate measurable ground motion, if we have the knowledge of the 3-dimensional structure of the region, obtained through independent geophysical investigations, and of the gross properties of the possible earthquake scenarios, defined on the basis of the known tectonics. We present here the results of a pilot study about site-effects and microzonation carried in a part of Delhi city, along the cross-section from the Inter State Bus Terminal (ISBT) to Sewanagar.

Strong-motion arrays and data

The Department of Earthquake Engineering, University of Roorkee[17] installed three arrays during 1985–86 in the Himalayas. Figure 1 gives the location of these arrays, namely (1) Shillong array (Assam and Meghalaya), (2) Uttar Pradesh hills (UP) array, Uttar Pradesh and (3) Kangra array, Himachal Pradesh. Forty-five analogue strong-motion accelerographs have been installed in the Shillong array with a spacing of 10–40 km. Fifty similar units form the Kangra array and forty are installed in the UP array, with spacing of 8 to 30 km. The instruments are three-component SMA-1 of Kinemetrics, USA. Figure 1 shows the location of stations with instruments that have been triggered at least once. The epicentres of the recorded events are shown as well. Four events with magnitude 5.2–7.2 have been recorded by the Shillong array between 1986 and 1988, and three earthquakes with magnitude 5.5 and 6.8 have been recorded separately by Kangra and UP arrays during 1986–1999, respectively. A total of 138 horizontal component peak accelerations and velocities (including NS and EW components) from the events recorded by the Shillong array and 64 horizontal component peak accelerations and velocities from Kangra and UP arrays have been used to obtain the attenuation laws in Himalayas.

Simple theory versus empirical formulae in strong-motion data analysis

In a region with a sufficiently large amount of strong-motion records, the average dependence of strong-

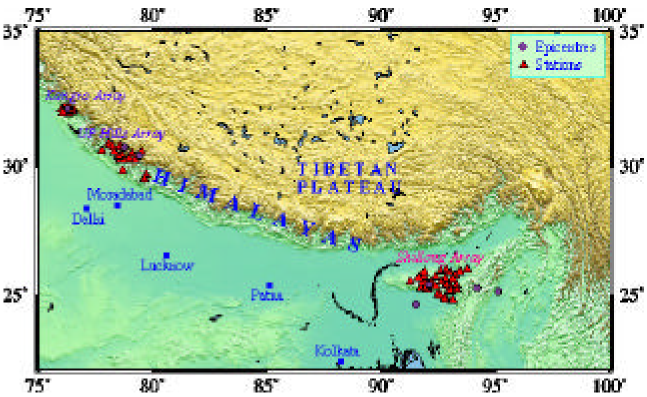

Figure 1. Generalized geological and topographical map along with the strong-motion arrays and location of the events in Himalayas recorded by the network.

motion values (e.g. peak acceleration) on distance, magnitude and other relevant parameters is usually determined on an empirical basis by means of multiple regression procedures. Such empirical formulae are then used for the approximate forecasting of various parameters of strong ground-motion related to a specific earthquake source, wave propagation path and site geology. One difficulty with such formulae, among others, is related to the discrepancies between simple forms of traditional empirical regression relationships for various ground-motion parameters on the one side, and the actual, often nonlinear, trends that are both seen in observations and may be expected even from a simple theory. For example, until 1985 the regression coefficient that defined amplitude attenuation was almost never (even implicitly) assumed to be magnitude-dependent; whereas such dependence is evident in the data, and it arises automatically in an adequate theoretical calculation. In many poorly studied and/or low-seismicity areas, the situation is frequently worsened by the very limited amount of observations. To formally describe non-linearities or interactions between factors, one needs a considerable number of regression coefficients; whereas available data may be hardly sufficient to determine two or three of them. To replace the use of formulae, a simplified practical algorithm has been designed which is capable of determining approximate mean trends of strong ground-motion parameters. To make these trends more reliable, we specify many properties of the medium and of earthquake sources (where possible) in a way independent from the sparse strong-motion data. The trends calculated in this manner may be used instead of formulae, both in the analysis of observed ground motions and in the construction of predictive schemes that interpolate or extrapolate the data. To implement this approach, a dedicated code has been developed and used by Parvez *et al.*[1] to estimate strong-motion amplitudes in the Himalayas. They determined, on a theoretical basis, the shape of the distance, *R*, dependence at a given magnitude and then only adjusted its absolute level to the data. To reach this purpose the equivalent procedure has been followed to reduce the data to a fixed distance and magnitude and then to average them.

Attenuation of strong-motion amplitudes in Himalayas

Parvez *et al*.[1] have analysed the strong-motion data from the Himalayan region and have also given step-by-step procedures. First, the data were analysed in a group for the whole Himalayan region after reducing to a chosen hypocentral distance of 100 km. The data turned out widely scattered when analysed in one group, but showed greater coherence when divided into a group of WH and EH. A similar situation is seen here when we include the strong-motion data of the Chamoli earthquake (see Table 1). As expected, the residual rms deviation shows that this event also belongs to the WH group of events. In Figure 2 *a*, our results for two families of A_{max} (*R*) curves for a set of M_w values have been presented. Thin solid curves are the predicted values for the EH and thin dashed ones represent WH[1]. Thin dotted curves are the result of the present study and represent the new attenuation relationship for WH. These curves are slightly above the earlier curves of Parvez *et al*.[1], for WH and once again confirm the adequate separation of WH and EH attenuation laws. Each event of our very modest database is represented by its centroid (dots) and by a segment describing the data range by thick continuous and dotted lines for WH and EH, respectively. The curves represent quite a reasonable description of observational data for peak acceleration from both regions.

In Figure 2 *b* our results for the expected A_{max} vs hypocentral distance are compared with the results obtained by other researchers, for fixed $M_w = 7$ (or $M_L = 6.7$). The thick solid line represents our results for EH and the thick dashed line for WH. The result from Chandrasekaran[11], Singh *et al.*[12] and Sharma[13] for Himalayas, Trifunac[2] and Joyner and Boore[3] for western US, Ambraseys[7] for Europe, Atkinson and Boore[8] for Eastern North America and Fukushima and Tanaka[6] for

Table 1. List of events used in the study of A_{max} and V_{max} attenuation laws

Region	Date	Time (UT)	Lat. (°N)	Long. (°E)	Depth, km (CMT)	Depth, km (NEIC)	M_w
Western Himalaya	26 April 1986	07:35:20.0	32.17	76.28	15	33	5.5
	19 October 1991	21:23:21.6	30.73	78.79	15	10	6.8
	28 March 1999	19: 05:11.03	30.41	79.42	15	15	6.5
Eastern Himalaya	10 September 1986	07:50:25.6	25.42	92.08	_	43	5.2
	18 May 1987	01:53:59.3	25.27	94.20	75	50	6.2
	6 February 1988	14:50:43.6	24.64	91.51	31	33	5.8
	6 August 1988	00:36:37.6	25.14	95.12	101	91	7.2

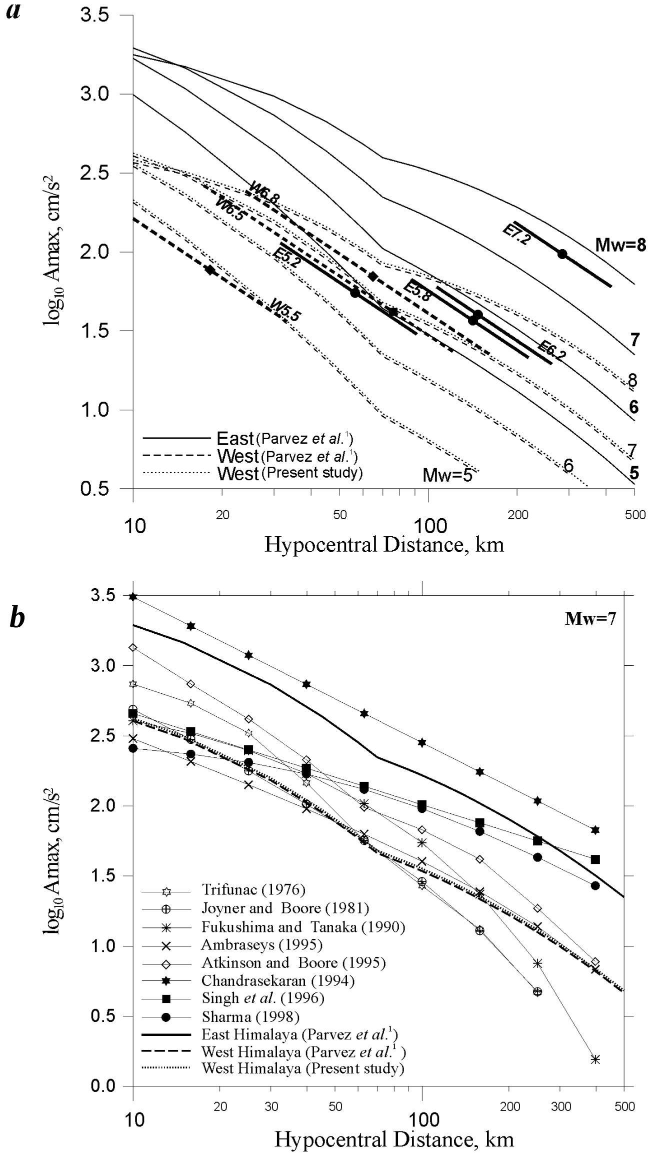

Figure 2. ***a***, Attenuation laws of $\log_{10}$ peak acceleration for small distances and large magnitude. The thin solid curves are the predicted values for the EH and the thin dashed curves are for the WH. The thick solid and dashed lines are the segments of the observed data with their centroid for EH and WH, respectively. ***b***, Comparison of our attenuation laws with those of other authors. Our results are represented by the thick solid lines for the EH and the thick dashed lines for the WH for $M_w = 7$. The thin curves with solid symbols are from the Himalayan region, while the thin curves with empty symbols are given by different authors for different regions of the world.

Japan have also been shown in the same figure. One can see from this figure that our result for EH is unusually high compared to all the others, except that of Chandrasekaran[11], whereas our results for WH are quite comparable to others. Singh *et al.*[12] and Sharma[13] have used the data from both the sub-regions jointly; their results for $M_w = 7$ are close to our EH results for distances above 150 km and to our WH results for distances below 50 km. We believe that the main reason behind the differences between these results and ours is the separation of the data set into two coherent groups. We therefore consider our results to be more reliable. Our results for WH are quite comparable to those of Ambraseys[7] for Europe and of Joyner and Boore[3] for California, at $R < 100$ km. However, at $R > 100$ km, the distance attenuation curve for California decays much faster than ours. At smaller distances, Fukushima and Tanaka's[6] results are slightly higher than ours for WH, and definitely lower than ours for EH. The distance decay of Fukushima and Tanaka[6] trend at $R > 100$ km is much faster than ours. The closest analogue of our EH result, both in terms of level and shape of attenuation curve, is the trend after Atkinson and Boore[8] for eastern United States.

In a similar fashion, the relationships of peak velocity with distance and magnitude have also been determined. The established semi-empirical relationships V_{max} (M_w, R) for EH and WH are represented in Figure 3*a* as two families of $V_{max}(R)$ curves for $M_w = 5$, 6, 7 and 8. The solid thin lines are the expected trends for EH, and the dashed thin lines are those for WH[1]. The thin dotted curves are the results of the present study for the WH, which fit very well with the earlier trend. The data centroids (dots) and the distance ranges (thick segments) are also shown in this figure. The difference in the absolute levels of the expected peak velocity between regional groups is prominent, though not as large as that for peak accelerations (Figure 2*a*). The agreement between the predicted lines and the observed peak velocity from each event is quite acceptable. We can now compare our expected V_{max} vs hypocentral distance relationship with other published trends for different regions, see Figure 3*b*, which completely follows the style of Figure 2*b* for A_{max}. We believe that the ground is of rock-type for WH stations, and mixed rock and hard soil for EH stations, in agreement with Sharma[13]. For comparison, we give curves of Trifunac[2] (average for rock and medium ground) and of Joyner and Boore[3] (hard soil) for western US, Atkinson and Boore[8] (typically rock type) for eastern North America, Kawashima *et al.*[4] (average for hard and medium ground) for Japan, and world average of Campbell[9] (presumably rock). We see that our result for EH is unusually high, above all the others at distances in excess of 50 km, whereas our results for WH look quite regular.

Microzonation and site-effect studies of megacities and large urban areas

One of the basic problems associated with the study of seismic zonation/microzonation is to determine the seismic ground motion, at a given site, due to an earthquake with a given magnitude (or moment) and epicentral distance. The ideal solution for such a problem could be to use a wide database of recorded strong motions and to group those accelerograms that have similar source, path and site-effects. In practice however, such a database is not available. Actually, the number of recorded signals is relatively low and the installation of local arrays in each zone with a high level of seismicity is too expensive an operation that requires a long time interval to gather statistically significant data sets. While waiting for data accumulation, a preventive tool is supplied by the realistic modelling, based on computer codes developed from the knowledge of the seismic source and of the propagation of seismic waves associated with the given earthquake scenario. Fäh *et al.*[18,19] developed a hybrid method that combines the modal summation technique[20–23], finite differences[24–26], and that exploits both methods to their best.

In the framework of the UNESCO-IUGS-IGCP Project 414, 'Realistic Modelling of Seismic Input for Megacities and Large Urban Areas'[27], this hybrid approach has been successfully applied, for the purpose of deterministic seismic microzoning, in several urban areas: Beijing[28], Benevento[29,30], Bucharest[31,32], Catania[33,34], Mexico City[35], Rome[19,36], Naples[37] and Santago de Cuba[38].

With this approach, source, path and site-effects are all taken into account and a detailed study of the wavefield that propagates at large distances from the epicentre is possible. Several techniques have been proposed to empirically estimate the site-effects using observations. As pointed out by Panza *et al.*[23], those techniques supply reliable information about the site response to non-interfering seismic phases, but they are not adequate in most real cases when the seismic sequel is formed by several interfering waves. Recently, Lokmer *et al*[39] demonstrated that the focal mechanism can play a much more important role in the local amplification of ground motion than the local structure itself. Given the complexity of the problem of site response estimation, the realistic modelling can be considered the only way to assess the hazard, by means of considering several scenario earthquakes and taking envelopes of averages and of upper extremes of the parameters describing the hazard itself.

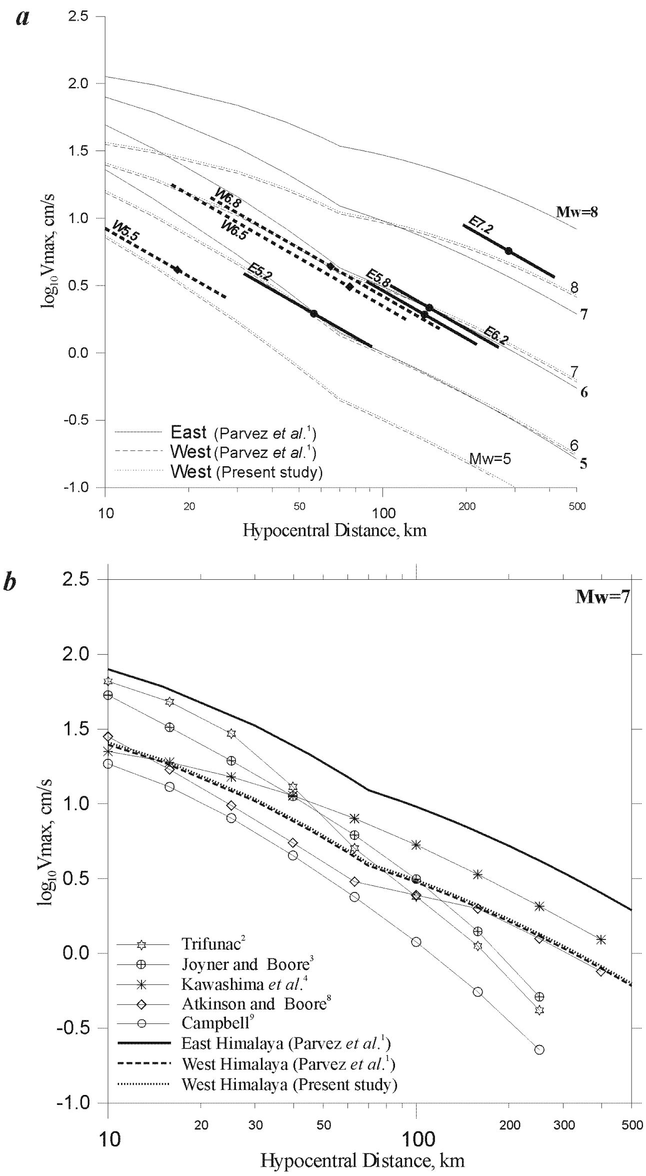

Figure 3. ***a***, Same as Figure 2 *a* but for $\log_{10}$ peak velocity. ***b***, Comparison of our results with those of other authors. Our results are represented by the thick solid lines for the EH and the thick dashed lines for the WH for $M_w = 7$. Thin curves with empty symbols are given by different authors for different regions of the world.

First-order microzonation and site-effect studies of Delhi city

Delhi – the capital of India – is a fast-growing megacity that influences the economic and industrial developments of much of the country. The estimated population of urban Delhi is now around 12.2 million. Figure 4 *a* shows the epicentres of some moderate and large earthquakes, which occurred in the Delhi region, as well as the events which occurred in the Himalayan region, along the Main Boundary Thrusts (MBT) and Main Central Thrusts (MCT), that have been felt in Delhi. The Himalayan thrust zone, just 250–350 km north of the megacity, has been identified as a significant seismic gap in the Central Himalayas[40,41]; thus it can be presently considered one of the most hazardous megacities of the world. Delhi is therefore quite vulnerable to Himalayan earthquakes and its burgeoning population and industrial works face increasing risk from seismic hazard. To mitigate the seismic hazard, it is necessary to define a correct response in terms of both the peak ground acceleration and spectral amplification. These factors are highly dependent on the local soil conditions and on the source characterization of the expected earthquakes.

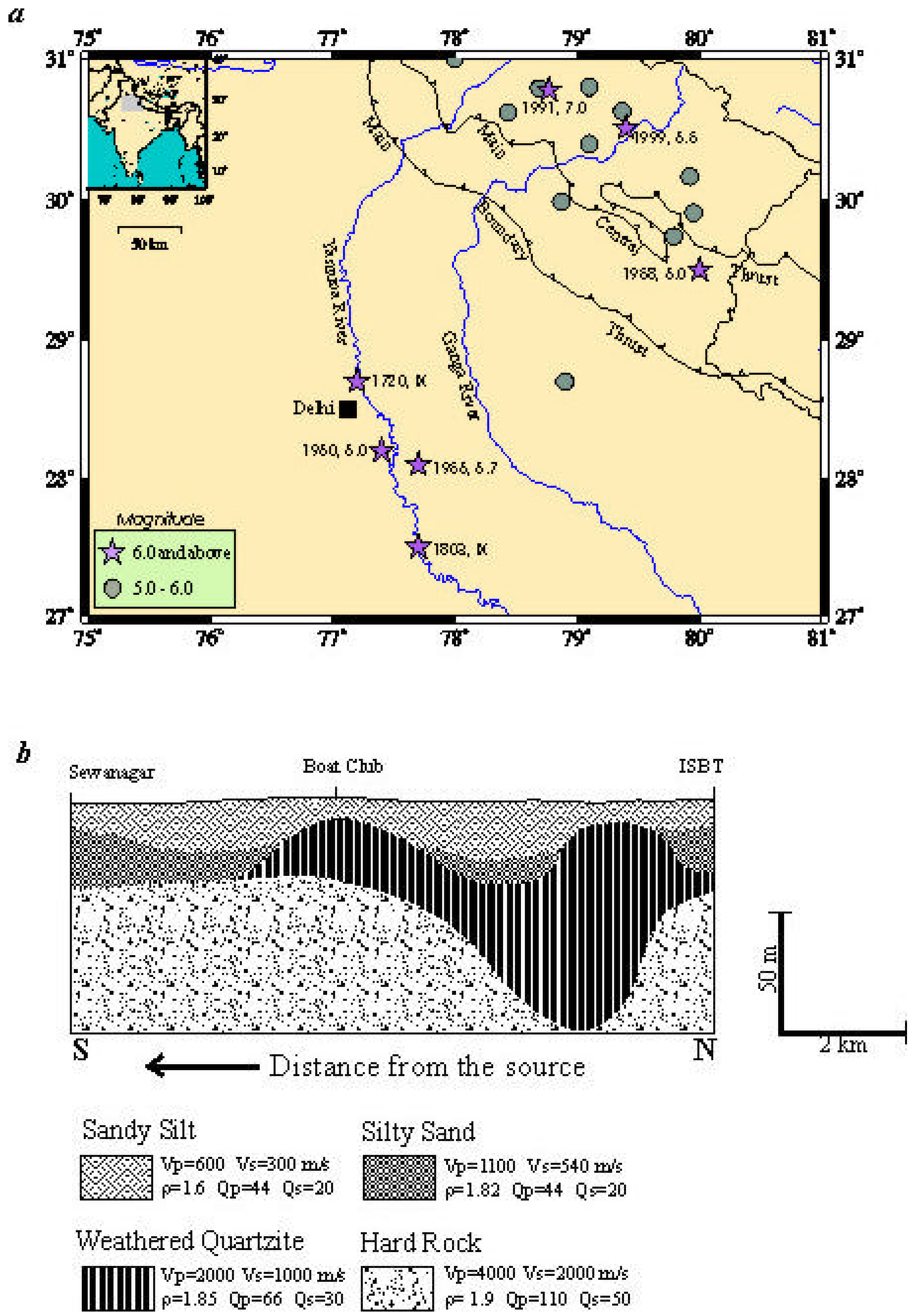

Figure 4. ***a***, Geological map of Delhi and surrounding areas with the epicentres of the earthquakes that occurred in the region. ***b***, Soil properties of the NS cross-section model from ISBT to Sewanagar. The original model[42] gives *S*-wave velocity (V_s) and density (ρ); to be conservative we have assumed p-wave velocity (V_p) = $2V_s$. The quality factor (Q) values for the different soils are taken from standard compilation.

We think that it is time to learn lessons from the Bhuj earthquake, and to go for a detailed seismic ground-motion modelling for microzonation studies of Delhi city. A first step to mitigate the seismic hazard is to correctly define a response in terms of two factors that are highly dependent on the local soil conditions and on the seismic source characteristics: the peak ground acceleration and the spectral amplification.

Numerical modelling of seismic ground motion

We estimate the seismic ground motion along NS cross-section of Delhi city from ISBT to Sewanagar. The input data, necessary for the ground-motion simulation, consist of the two-dimensional structural model, the regional bedrock structures and the focal mechanism solution. Figure 4*b* shows the north-south cross-section from ISBT to Sewanagar, which includes the structural

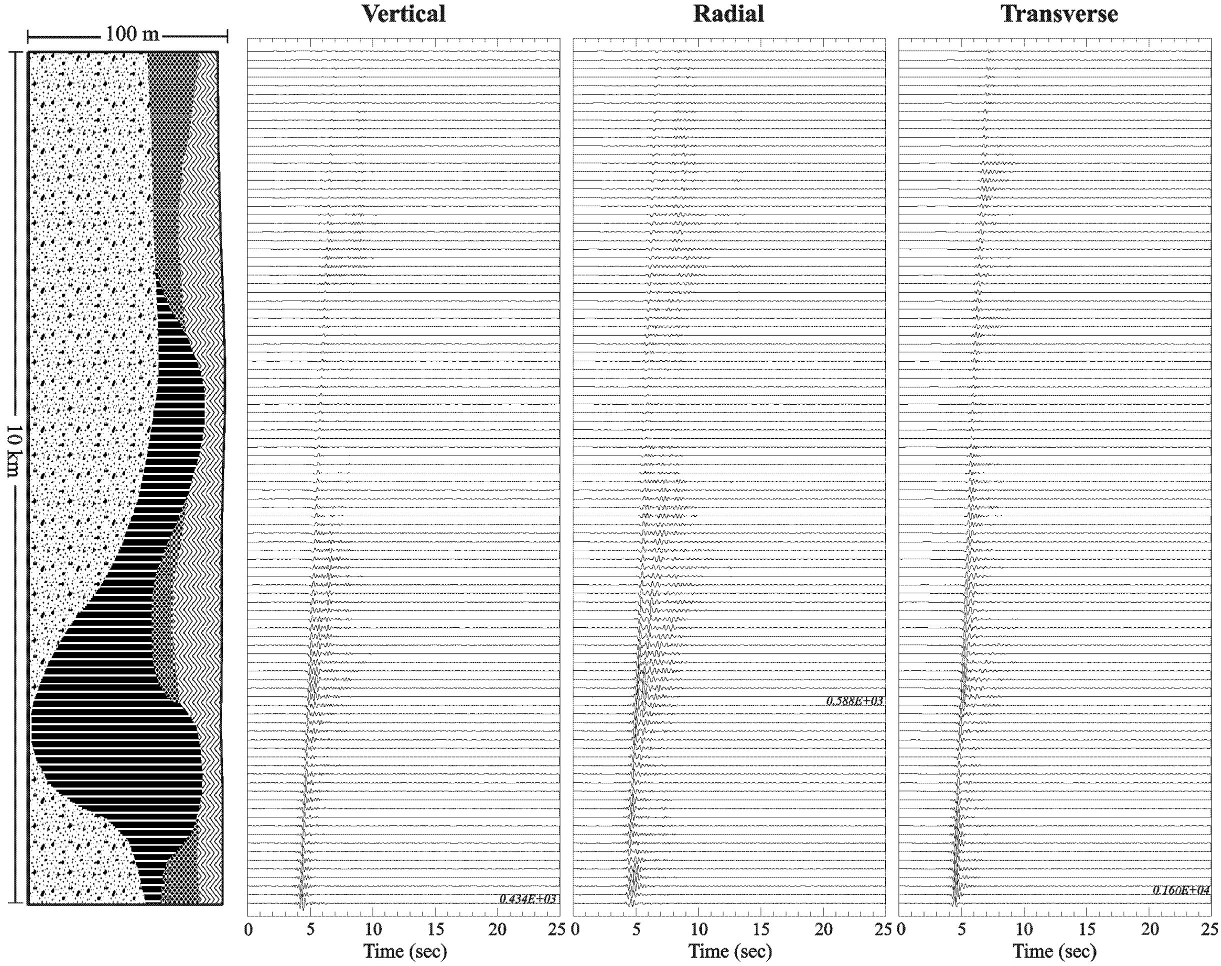

Figure 5. Cross-section and corresponding synthetic strong-motion records computed every 100 m.

parameters of the local soft soils above the bedrock. This cross-section has been taken from Iyengar[42]. This model initially available up to 30–35 m of depth has been further extended up to approximate bedrock depth level from Iyengar[42]. A major event of intensity IX (MMI) that occurred on 15 July 1720 has been used as seismic source in the modelling. The epicentre (28.7N, 77.20E) and magnitude ($M = 7.4$) of this event are taken from Global Seismic Hazard Assessment Programme (GSHAP) catalogue.

The synthetic seismograms (SH and P-SV waves) have been computed with the hybrid method for an array of 100 receivers regularly spaced (every 100 m) along the cross-section. The three-component accelerograms shown in Figure 5 clearly define the trend of the amplification effects and well reflect the geometry of cross-section model, used in the computations. A peak acceleration (AMAX) of 1.6 g is estimated in the transverse component, at the receiver nearest to the source, at an epicentral distance of 10 km. This is a quite large value and represents a severe seismic hazard, as it can be expected at the epicentral area of an event of magnitude 7.4. We believe that the peak values within 10 km of epicentral distance are saturated for a large event in terms of damage/ground motion observed at the epicentre. Such high values of AMAX validate the reports of the damage caused by the 1720 earthquake[42]. The other components of ground motion exhibit peak values in the range of 0.5 to 0.6 g.

The response spectra ratio (RSR), i.e. the response spectra computed from the signals synthesized along the heterogeneous medium normalized by the response spectra computed from the corresponding signals synthesized for the regional model, is another parameter relevant for earthquake engineering purposes. The distribution of RSR as a function of frequency and epicentral distance along the profile, up to a maximum frequency of 5 Hz, is shown in Figure 6 for the three components. The amplification reaches the largest values for frequencies above 2 Hz, and the maximum is seen in the transverse component (nearly 7), whereas for the vertical and radial components, the amplification is in the range from 4 to 6. All this indicates that, due to the local effects, one may expect local intensity increments of about two units with respect to the average value observed in the area[43].

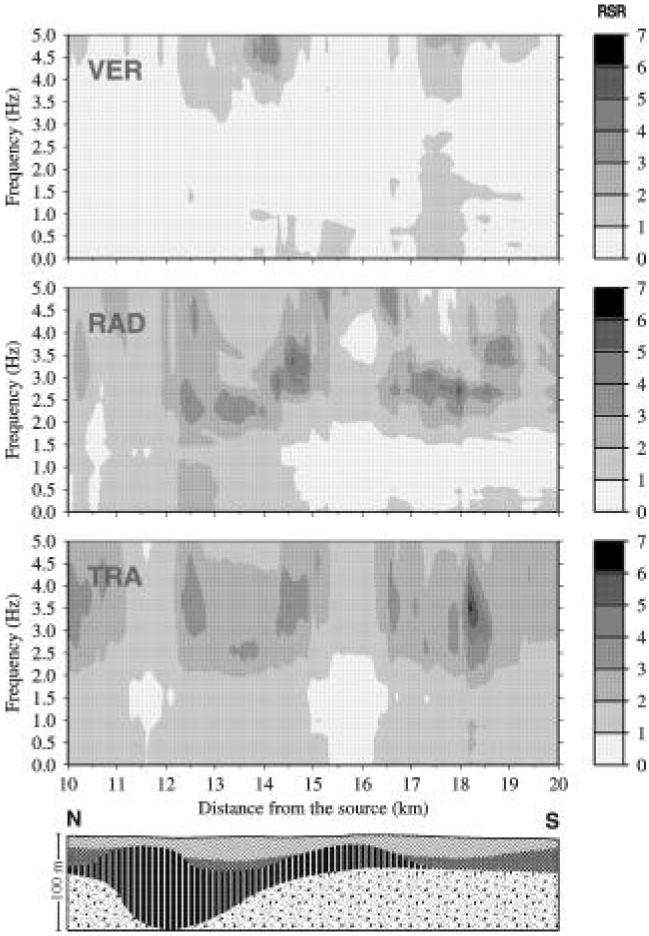

Figure 6. Cross-section and corresponding plot of response spectra ratio (RSR) with frequency.

Conclusions

Using the strong-motion data available for Himalayan earthquakes, the relationships between strong-motion amplitudes, hypocentral distance and magnitude have been established. A theoretical magnitude-dependent distance attenuation law is used for data analysis instead of the empirical regression, and data reduced at a standard distance of 100 km and of magnitude 7 are fixed accordingly. The most important outcome of the present study is the separation of the data into two sub-regions, the EH and WH regions. Of these, the WH region is comparable in terms of near-source amplitudes, to the Japanese region, whereas the amplitudes in the EH are three times larger, and have no known direct analogues amongst other seismically-active regions of the globe. Horizontal epicentral accelerations in excess of 1–1.5 g are typical here.

Given a certain earthquake scenario, and an appropriate structural model, based on detailed geological, geophysical and geotechnical data, it is possible to realistically evaluate the local amplification in the frequency range of interest for civil engineering, and to obtain valuable parameters for the realistic microzonation. This is possible by applying detailed numerical modelling that takes into account source, propagation and local site-effects. An example of the first-order ground-motion modelling in the part of Delhi city, in terms of both the peak ground acceleration and spectral amplification, carried on along the NS profile from ISBT to Sewanagar shows that the response spectra ratios are as large as about 7. Therefore, for any earthquake, one can expect local increments of the macroseismic intensities of about two units, with respect to the average observed value.

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