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GENERATION OF SYNTHETIC ACCELEROGRAMS BY MODELLING OF RUPTURE PLANE

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ABSTRACT

Strong motion records of Uttarkashi earthquake have been modelled by using modified approach of Midorikawa (1993). The method of simulation gives total accelerogram at desired observation point for a model source of an earthquake. Synthetic accelerogram has been calculated by multiplying filtered white noise with the envelope of accelerogram at a particular observation point. Filters through which white noise passes include effect of geometrical spreading, effect of anelastic attenuation and near-site attenuation at high frequencies.

The method and its dependence on various modelling parameters are studied in detail which shows that property like directivity in strong ground motion is satisfied. Thirteen accelerograms are simulated for the source model of Uttarkashi earthquake and their quantitative comparison explains the utility of method and its applicability for Himalayan earthquakes for simulation of strong ground motions.

KEYWORDS: Strong Motion, Filter, Directivity, Attenuation

INTRODUCTION

Strong motion prediction can be performed with the help of the knowledge of the source of seismic waves, the medium through which the waves propagate, the local geology of the site and the structure located at the site (Campbell, 1985). One of the most common strong motion parameters that is predicted is the peak ground acceleration. The peak ground acceleration is however not adequate to characterize the seismic performance of structures (Sharpe, 1982; Campbell and Murphy, 1983; Kennedy et al., 1984).

In order to overcome this problem, a number of techniques have been proposed for the simulation of realistic strong motion time series. In one method, the time series is generated by using band-limited random signal to represent seismic radiation from earthquakes in the near field (e.g., Housner and Jennings, 1964; Hanks and McGuire, 1981; Boore, 1983; McGuire et al., 1984, Boore and Joyner, 1991; Shinozuka and Sato, 1967; Lai, 1982). The disadvantage of this method is that it does not include any representation of the earthquake source or wave propagation in the medium. Strong motion time series can also be generated using wave propagation theory together with the composite fault model (e.g., Zeng et al., 1994; Yu, 1994; Yu et al., 1995). Another method makes use of small event records as empirical Green's functions (Hartzell, 1978) for simulation of record of a large event. This method has been used by several workers (Hartzell, 1978, 1982; Kanamori, 1979; Hadley and Helmberger, 1980; Mikumo et al., 1981; Irikura and Muramatu, 1982; Hadley et al., 1982; Irikura, 1983; Coats et al., 1984; Houston and Kanamori, 1984; Imagawa et al., 1984; Mugnuia and Brune, 1984; Hutchings, 1985; and Heaton and Hartzell, 1986). The advantage of this method is that there is no need to calculate propagation effects (Fukuyama and Irikura, 1986). The small earthquakes needed in this method should ideally be located near the source and recorded at the site for which large event simulation is desired (Joyner and Boore, 1988). This is the most difficult condition to be met in real life and hence the method is of limited use.

In an approach presented by Midorikawa (1993) which is based on the semi-empirical Green's function method of Irikura (1986) but is simplified for engineering use, the envelope of the accelerogram for a large earthquake is obtained by superposing such envelopes for small earthquakes. The resulting envelope allows the estimation of the expected peak ground acceleration. Using this method, the peak accelerations were estimated for a central Chile earthquake $(M_a = 7.8)$ and the computed results were found to be in good agreement with the observed ones (Midorikawa, 1993). The final output of this method is envelope of the accelerogram which only gives the idea about peak ground acceleration at a particular site and the total duration of record but not the complete representation of the time series. A method is presented by Khattri (1998) wherein he makes use of the method of Midorikawa (1993) to obtain the envelope function and combines it with the source radiation represented by a band-limited white noise to obtain realistic accelerograms.

The method of Midorikawa for computing peak ground acceleration has been modified for its applicability in Himalayan region (Joshi, 1997 and Joshi and Patel, 1997) and the comparison of results establishes the efficacy of the approach. The present work deals with the generation of realistic time series using the concept of Khattri (1998) for case of the Uttarkashi earthquake of 20th October, 1991.

MODELLING OF RUPTURE PLANE

Parameters required for modelling of the rupture plane are: length (L), width (D), length and width of element (L_e, D_e), nucleation point, strike and dip of rupture plane (φ, δ), rupture velocity (V_r) and velocity of medium (V). These parameters may be deduced through empirical relations or through fault plane solution along with seismic studies of the region. These parameters and their method of calculation have already been explained by Joshi (1997) and Joshi and Patel (1997). Empirical relations for computing peak ground acceleration and duration of the acceleration record have been compared with those of field data before using those in the present technique. The empirical relation used for obtaining the peak ground acceleration is given by Abrahamson and Litehiser (1989), and its comparison with the Uttarkashi data shows a match in the trend of observed and calculated peak acceleration values (Joshi, 1997). Validity of this relation for predicting the Uttarkashi earthquake data is also found to be adequate by Kumar et al. (1997).

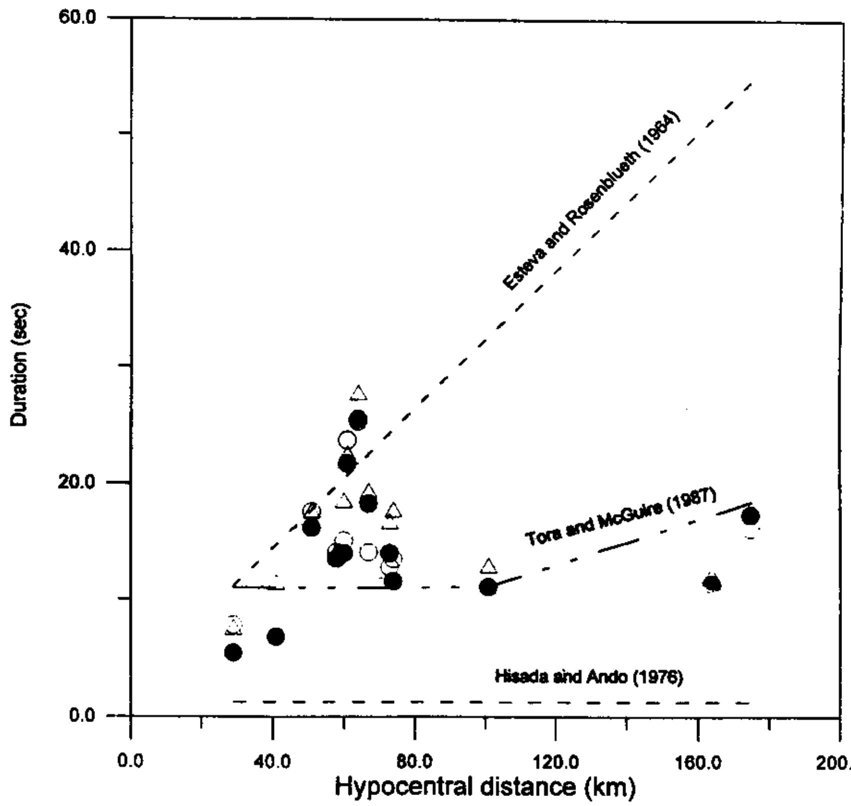

Fig. 1 Comparison of duration from field accelerogram with that from empirical relations of Esteva and Rosenblueth (1964); Midorikawa (1989), Toro and McGuire (1987) and Hisada and Ando (1976). The solid black circles represent duration from longitudinal components, empty circles represents duration from transverse components and triangles represent duration from vertical components.

In the earlier work (Joshi, 1997; Joshi, 1998; Joshi and Patel, 1997), duration of envelope function is calculated using Esteva and Rosenblueth (1964) relation. Several trial simulations show that the peak ground acceleration obtained by this technique is weakly affected by duration parameter while it is heavily dependent on the attenuation relation of peak ground acceleration used in the method (Joshi, 1997). However, the present method of simulation of accelerograms is dependent strongly on the empirical relation of duration. A comparison is made between the observed durations from the recorded accelerograms and the empirical relations of Esteva and Rosenblueth (1964), Toro and McGuire (1987) and Hisada and Ando (1976) in Figure 1. The criteria of Trifunac and Brady (1975) has been used for calculating durations of observed acceleration records. They have defined duration as the time in which significant contribution to the integral of square of acceleration referred as acceleration intensity takes place. Figure 1 shows that the relation by Toro and McGuire (1987) gives comparable match for nearly all observation points; the duration obtained from other relations is either too small or too large to be compared.

The rupture plane is assumed to be a rectangular one and is divided into several rectangular elements. Each element corresponds to a small earthquake event. Total number of elements within the rupture plane are n^2. An element within the rupture plane represents an earthquake of magnitude (M') which is smaller than the one to be modelled (M). For modelling Uttarkashi earthquake of magnitude $M_s = 7.0$, the values of M and M' have been used as 7.0 and 6.5 respectively. Once the rupture plane is divided into several elements, one element from which the rupture initiates is fixed. This point, considered as the nucleation point, can be assumed to coincide with the focus of the earthquake. However, this is not always true as the focus of an earthquake represents a point source and for a rectangular fault consisting of several elements, there are number of possibilities for the nucleation point.

The energy released by an earthquake rupture may be measured at a site in terms of particle acceleration time history. The envelope function of acceleration waveform defines the envelope of the accelerogram. The nucleation point is the first element to release the seismic energy. Rest of the elements release the energy whenever the rupture approaches the center of the other elements. The emitted acceleration waveform from different elements reaches the observation point with different time lags. The time lags depend on the time taken by the rupture to reach particular element from the nucleation point and on the time taken by the wave to reach the observation point from the particular element with the S wave velocity in the medium. The acceleration waveform envelope is a function which is based on the shape of the envelope of accelerogram at particular recording station. In this study, following acceleration waveform envelope function has been used (Kameda and Sugito, 1978; Midorikawa, 1993):

$$e(t) = \{(at)/d\}\exp(1 - t/d) \tag{1}$$

In this expression, a is the peak acceleration and d is the duration of accelerogram. The following empirical relation by Abrahamson and Litehiser (1989) has been used for computing the horizontal peak acceleration a in Equation (1):

$$\log_{10} a(g) = -0.62 + 0.177M - 0.982 \log_{10}\left(R + e^{0.284M}\right) + 0.132F - 0.0008ER \tag{2}$$

In this expression, M is the magnitude of the earthquake, R is the hypocentral distance in km, and $a(g)$ is the horizontal peak acceleration in cm/sec^2. E is a dummy variable and is 1 for interplate events and 0 for intraplate events. The dummy variable F is 1 for reverse or reverse oblique events and 0 otherwise. For Himalayan region, the local conditions favour using values $E = 1$ and $F = 1$ and hence, the same are used for calculating the acceleration by this expression.

The parameter d in Equation (1) represents the duration of acceleration waveform envelope in sec and is calculated by using following expression by Toro and McGuire (1987):

$$d = \begin{cases} 1/f_0 & \text{for} \quad R < 100\,\text{km} \\ 1/f_0 + 0.1\ (R - 100) & \text{for} \quad 100\ \text{km} < R < 200\,\text{km} \\ 1/f_0 + 0.05R & \text{for} \quad R > 200\,\text{km} \end{cases} \tag{3}$$

where f_0 represents the corner frequency and can be calculated by using following expression (Boore and Atkinson, 1987):

$$f_0 = 4.9 \times 10^6 \beta \left(\sigma / M_0\right)^{1/3} \tag{4}$$

where M_0 is seismic moment of an earthquake in dyne-cm, β is shear wave velocity in cm/sec, $\Delta\sigma$ is stress drop in dyne/cm^2, R is the hypocentral distance in cm. Assumptions used in Equation (3) are meant to describe ground motion due to direct shear wave arrivals, which are the dominant contribution to ground motion at small distances (Toro and McGuire, 1987).

Equation (3) is different from the relation used by Midorikawa (1993) for obtaining durations of strong motion records. Several trial simulations show that although peak ground acceleration is weakly affected by duration parameter (Joshi, 1997), the total time series is strongly dependent on the duration parameter. Role of Equation (3) in the entire simulation procedure will be to simulate a ground acceleration from a finite duration segment of stationary random process. Trial simulations were made for obtaining complete time series representing acceleration time history of Uttarkashi earthquake by present method using relations of duration by Esteva and Rosenblueth (1964), Midorikawa (1989), Toro and McGuire (1987) and Hisada and Ando (1976). It has been seen that among these, the relation by Toro and McGuire (1987) gives a record which is quite comparable with field records. Other relations give unexpectedly large duration acceleration time series. Further, a comparative study of each of these relations (see Figure 1) also supports the use of relation by Toro and McGuire (1987).

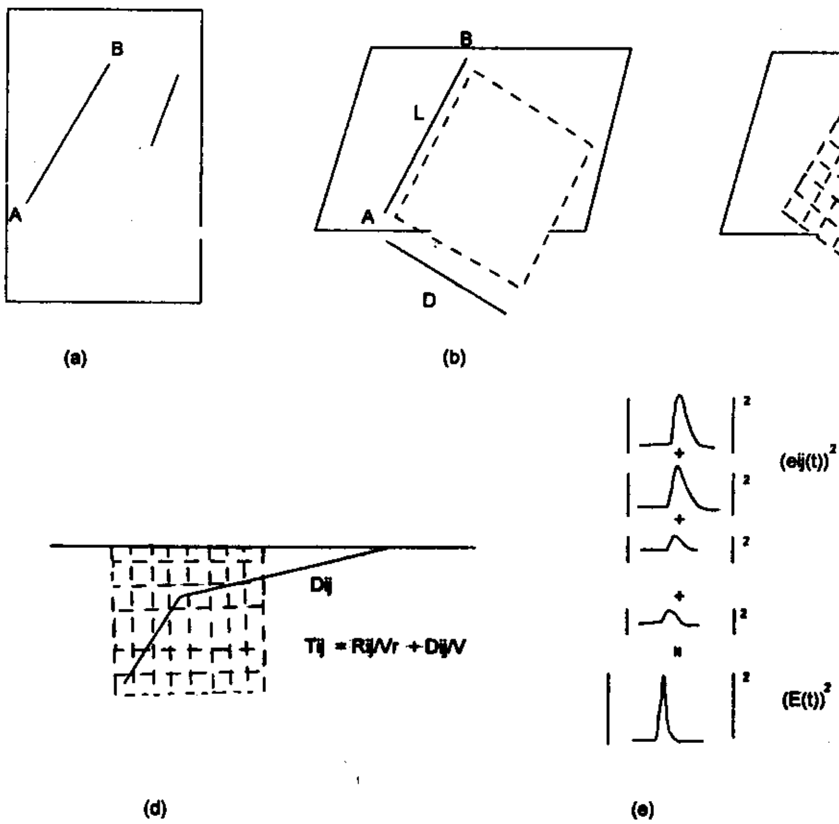

Fig. 2 (a) Map showing the causative fault 'AB' in the area of study for any hypothetical earthquake, (b) Rupture modelled along causative fault AB, (c) Representation of rupture plane into numbers of elements, (d) Arrival time T_{ij} of the wavefront at the observation point. R_{ij} is distance between nucleation point and *ij* th element. D_{ij} is distance between *ij* th element and observation point. V_r and V are velocities of rupture and wave propagation, respectively. (e) Summation of acceleration waveform envelopes $e_{ij}(t)$ released by different elements to obtain resultant acceleration waveform envelope function $E(t)$ at the observation point.

The waveform envelope functions $e_{ij}(t)$ of different peak accelerations and durations arrive at the observation points at different time lags t_{ij} from various elements within rupture plane. The envelope of acceleration $E(t)$ of the modelled earthquake is computed by summation of envelopes $e_{ij}(t_{ij})$ given as:

$$E(t)=\left(\sum_{i=1}^{n}\sum_{j=1}^{n} e_{ij}^{2}(t-t_{ij})\right)^{1/2} \tag{5}$$

Equation (5) gives the resultant acceleration envelope function at a particular site. The complete procedure for getting resultant envelope by modelling rupture plane along some identified causative fault on map is shown in Figure 2. For generation of accelerogram, following additional steps have been taken:

(i) A random time series, $m(t)$, of desired length and sampling interval is generated with the help of computer program. The random series of desired length is generated through a computer program. Baseline correction is applied in the obtained random series and is normalised for further use (see Figure 3(a)).

(ii) The amplitude spectrum, $RN(f)$, of the random time series, $m(t)$, is calculated using Fourier transform (see Figure 3(b)).

(iii) Both time and random process methods require specification of a basic spectral shape representing the radiation from the source. A number of other frequency-dependent functions are needed to specify the spectral shape at a given site. Following spectra have been used in this work as given by Kamae and Irikura (1992):

$$A(f)=S(f)P(f)e^{-\pi fR/Q\beta}/R \tag{6}$$

where,

$$S(f)=(2\pi f)^2/\left(1+(f/f_0)^2\right)$$
$$P(f)=1/(1+f/f_m)$$

Here, R denotes hypocentral distance, Q is material property known as the quality factor, $S(f)$ represents Brune's acceleration spectrum and f_0 is the corner frequency (where acceleration spectrum changes from being proportional to f^2 to being proportional to f_0). $P(f)$ represents near-site attenuation at high frequencies. The third quantity in the above equation represents the effect of anelastic attenuation. Corner frequency f_0 is calculated using Equation (4) and f_m is calculated using following empirical relation of Faccioli (1986):

$$f_m = 7.31 \times 10^3 M_0^{-0.12} \tag{7}$$

Spectrum $A(f)$ is shown in Figure 3(c).

(iv) The spectrum of the random series is passed through the final spectrum $A(f)$, therefore resulting in a spectrum of accelerogram $A'(f)$ at a given site:

$$A'(f)=RN(f)A(f) \tag{8}$$

where, $RN(f)$ is the spectrum of random time series. After taking inverse Fourier transform of $A'(f)$, desired random time series $a'(t)$ is obtained which represents accelerogram having basic spectral shape. The obtained random series $a(t)$ is shown in Figure 3(d).

(v) The random time series $a'(t)$ is multiplied with the resultant envelope of the accelerogram $E(t)$ (see Figure 3(e)) obtained earlier (Equation (5)) at a particular site to get the accelerogram $af(t)$ at that site. This is given by the following expression:

$$af(t)=a'(t)E(t) \tag{9}$$

The synthetic accelerogram $af(t)$ is shown in Figure 3(f).

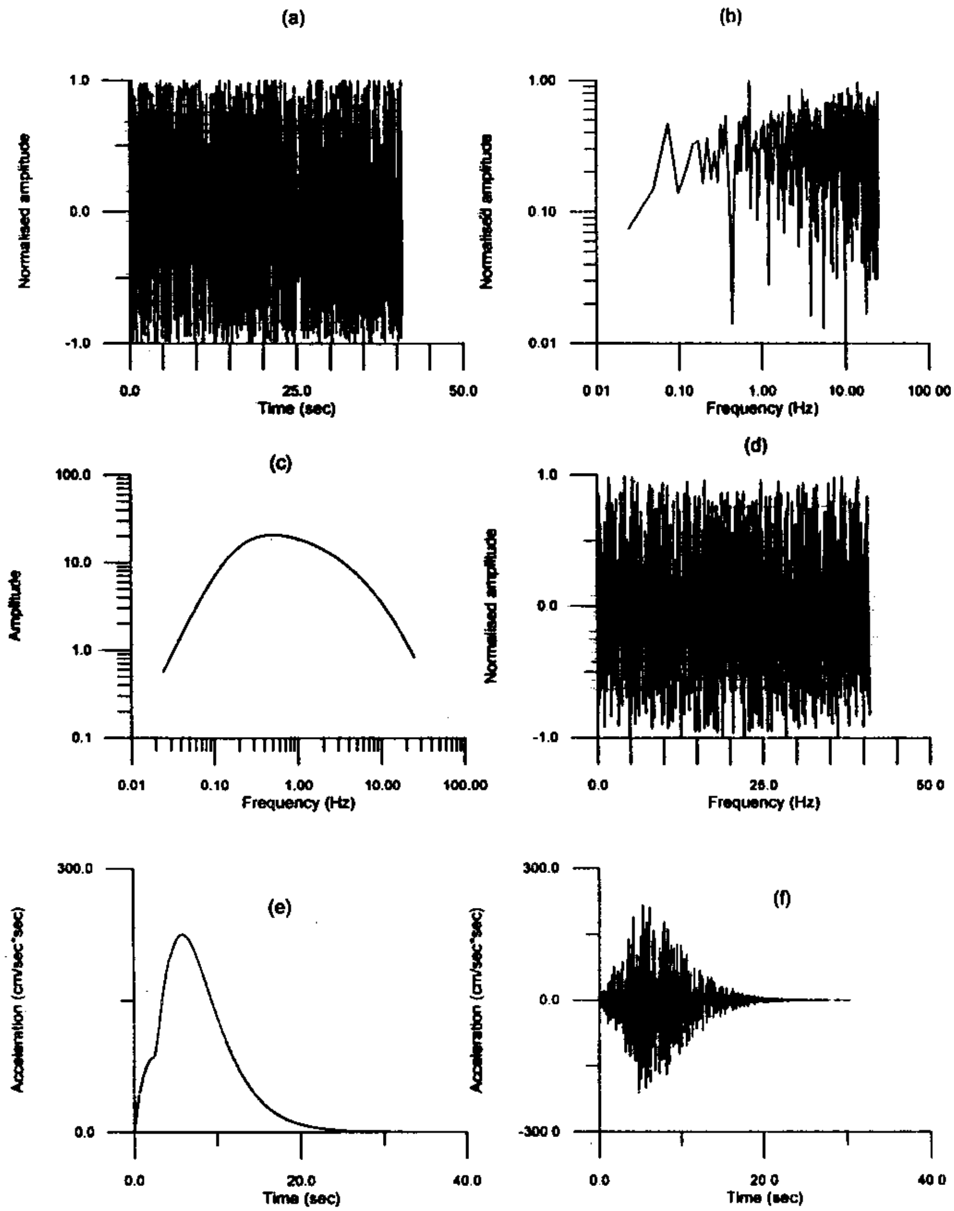

Fig 3. Normalised (a) Randomly generated sequence (b) Amplitude spectrum of random number (c) Amplitude spectrum of filter (d) Random number obtained after passing through theoretical filter (e) Resultant envelop function at given observation point (f) Synthetic accelerogram at given observation point. The sampling interval of random number is .02 sec.

ATTENUATION CURVES FOR DIFFERENT RUPTURE MODELS

To investigate the attenuation characteristics of peak ground accelerations, calculations were performed for earthquakes of magnitudes 6.5, 7.1 and 7.4, and having vertical as well as dipping rupture models. Those have been already discussed in detail by Joshi (1997) and Joshi and Patel (1997). The peak ground accelerations obtained for different rupture models are nearly the same as those obtained by the earlier approach (Joshi, 1997 and Joshi and Patel, 1997) since the resultant envelope function obtained in the present technique is same.

CASE STUDY: UTTARKASHI EARTHQUAKE OF 20TH OCTOBER, 1991

The Uttarkashi region which lies in the northern part of Indian subcontinent was rocked by a moderately strong earthquake (m_b = 6.5, M_s = 7.0) in the early hours of October 20, 1991. Parameters of this earthquake are given as:

Date	:	19 October, 1991
Origin Time	:	21 Hr 23 Min 14.3 sec
Epicenter	:	30.780°N, 78.774°E
Focal Depth	:	10 km
m_b	:	6.5
M_s	:	7.0
NP1	:	Strike: 317°, Dip: 14°, Slip: 115° (CMT; Harvard)
NP2	:	Strike: 112°, Dip: 78°, Slip: 84°
M_0	:	1.8 x 10^{26} dyne-cm (CMT; Harvard)

Under the project entitled "Strong Motion Array" of the Himalayan Seismicity Project, the Department of Earthquake Engineering, University of Roorkee has installed and operated a strong motion array in Uttarkashi and adjoining region. Thirteen stations had recorded strong motion data of this earthquake. Locations of those stations are given in Figure 4. Table 1 gives the values of the peak accelerations from recorded accelerograms at thirteen stations.

Table 1: Peak Acceleration from Recorded Accelerograms for Uttarkashi Earthquake. (Chandrasekaran and Das (1992)).

	Peak Acceleration in 10^{-2} m/sec^2		
Stations	**Log. Comp.**	**Trans. Comp.**	**Ver. Comp.**
Barkot	93	80	43
Bhatwari	248	241	288
Ghansiali	115	114	99
Karnprayag	60	77	25
Kosani	28	31	11
Koteshwar	98	65	74
Koti	20	40	14
Purola	73	91	51
Rudraprayag	52	50	44
Srinagar	65	49	44
Tehri	71	61	57
Uttarkashi	237	304	192

The most probable causative fault for this earthquake has been identified on the basis of isoseismal, isoacceleration, aftershocks locations and regional tectonic maps (Joshi, 1994) (Figure 5). Studies of all these maps indicate possibility of Munsiari thrust as the causative fault for this earthquake which has been verified by Jain and Chander (1995). The depth section in this region given by Seeber et al. (1981) indicates that the mainshock of this earthquake occurred at the juncture of the main central thrust and basement thrust (Kayal, 1994). The section further indicates that the cut-off depth of aftershocks was at 12-15 km, where plane of detachment is suggested by Seeber et al. (1981) and Ni and Barazangi (1984).

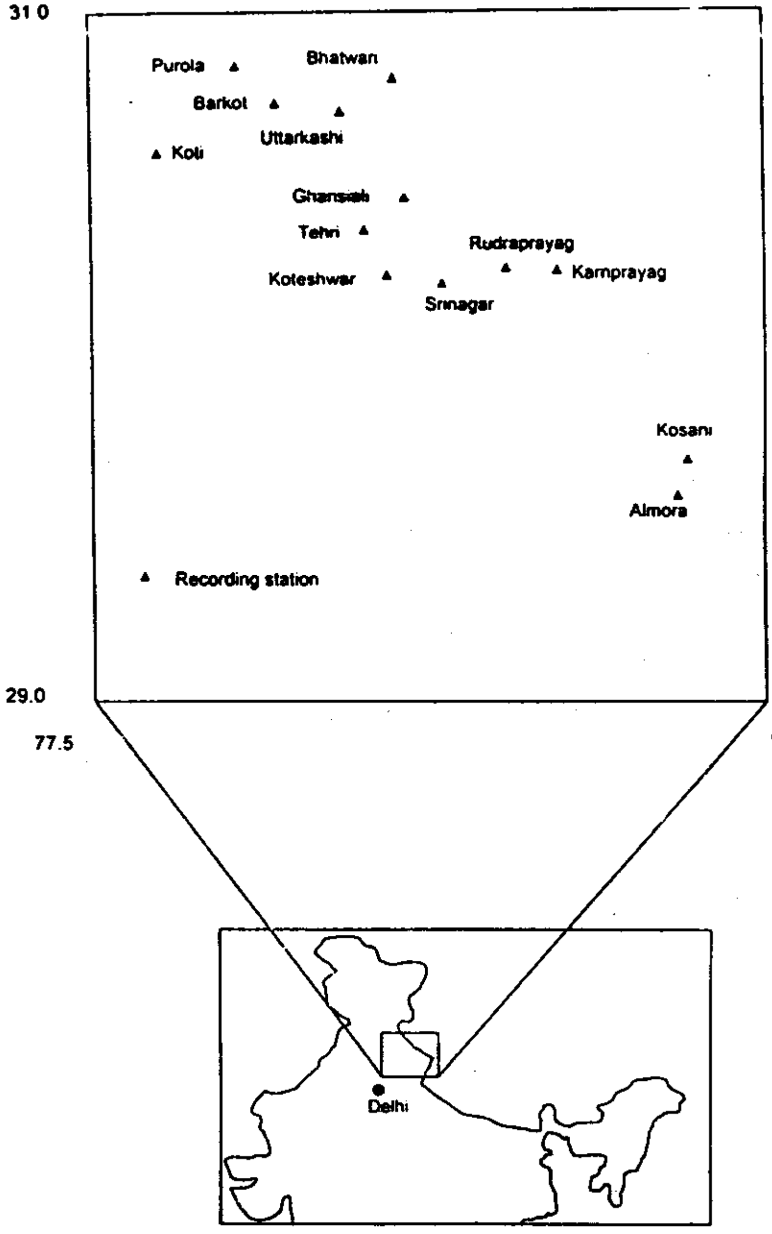

Fig 4. Location of strong motion stations that had recorded Uttarkashi earthquake of 20 th October, 1991 on strong motion array

Three dimensional coordinates of the recording stations are computed from tophosheet containing these stations. Parameters of rupture plane required for modelling the Uttarkashi earthquake of 20th October, 1991 are computed using the criteria explained by Joshi (1997) and Joshi and Patel (1997). The length of the aftershock distribution area for the Uttarkashi earthquake is about 40 km and this coincides with the rupture length of 42 km computed by using the relation by Araya and Kiureghian (1988). The dip and strike for this rupture model are based on the fault plane solution given by Dziewonski et al. (1992). The stress drop of 30 bars is taken from Yu et al. (1995). Model of rupture plane for Uttarkashi earthquake was prepared having parameters given in Table 2 (Joshi, 1997 and Joshi and Patel, 1997).

Table 2: Modelling Parameters of Rupture Plane for Uttarkashi Earthquake of 20th Oct, 1991 (The Magnitude of Elementary Earthquake for the Model is 6.5)

Modeling Parameters	Criteria of selection	Value for Uttarkashi Earthquake	Reference
L	$\text{Log}(L) = -2.77 + .619\ M_s$	42 km	Araya and Kiureghian (1988)
D	$\log(A) = 1.02\ M_s - 4.0$ Since $A = L \times D$ for rectangular Rupture, therefore, $D = A/L$	29 km	Kanamori and Anderson (1975)
ϕ and δ	Fault plane solution	$\delta = 14°$, $\phi = 317°$	Dziewonski et al. (1992)
V_r	$8 \times V_s$	2.6 km/sec	Mendoza and Hartzell (1988) and Reiter (1990)
V_p	Velocity structure	5.7 km/sec	Kamble (1992a, 1992b)
n	$= 10^{.5(M-M')}$	2	Sato (1989)
L_e D_e	$= L/n$ $= D/n$	21 km 8.5 km	
Depth of Rupture plane	Geological depth section	12 km	Kayal (1994)

L = Length of rupture plane
D = Width of rupture plane
M_s = Surface wave magnitude of earthquake
δ and ϕ = Dip and strike of rupture plane
V_r = Rupture velocity
V_s = S wave velocity in the medium
V_p = P wave velocity in the medium
n = Total number of elements along length or width of rupture plane

Table 3: Peak Acceleration Obtained from Field Records (Chandrasekaran and Das, 1992) and the Model of Rupture Plane for Uttarkashi Earthquake of 20th Oct, 1991 (The Peak Acceleration from Horizontal Component giving Maximum PGA is used for Comparison with Simulated Values)

Station	Largest Component of Peak Acceleration from Field Record (10^{-2} m/sec^2)	Peak Acceleration from Simulated Records (10^{-2} m/sec^2)
Almora	21	30
Barkot	93	142
Bhatwari	248	333
Ghansiali	115	142
Kampray	77	65
Kosani	31	32
Koteshwar	98	101
Koti	40	71
Purola	91	111
Rudrapray	52	99
Srinagar	65	104
Tehri	71	113
Uttarkashi	303	225

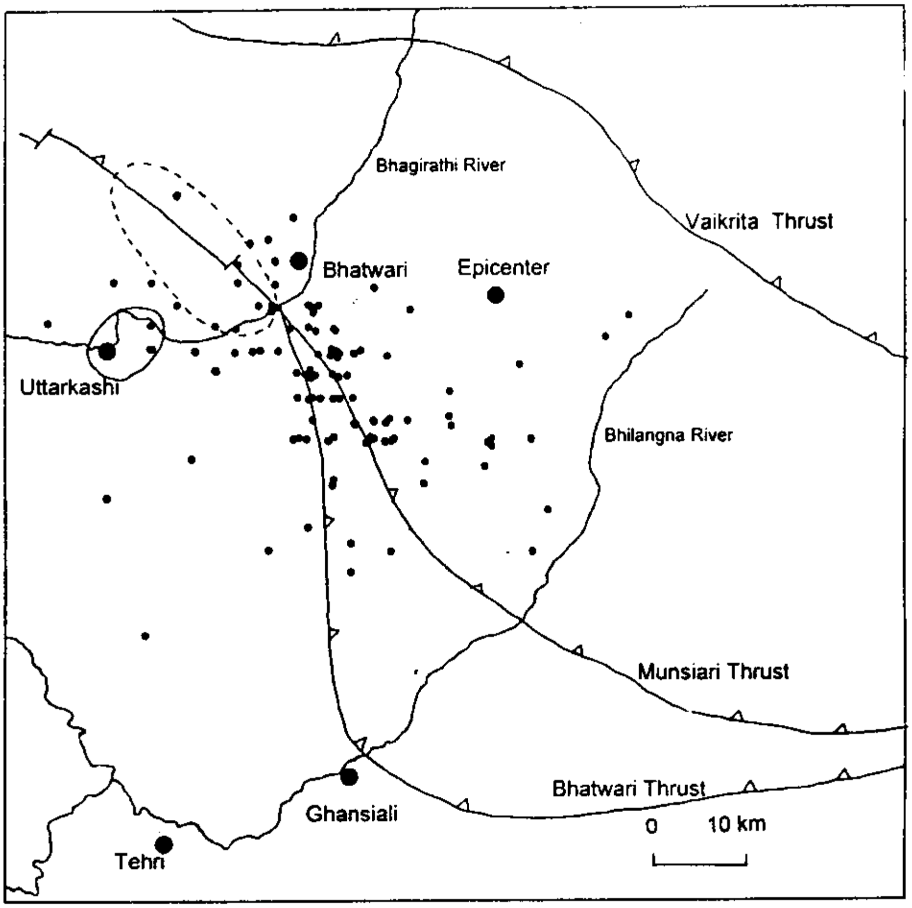

Fig. 5 Composite map of isoacceleration contours, aftershocks location, meizoseismal area of Uttarkashi earthquake of 20th October, 1991 and tectonics of the region. Chandrasekaran and Das (1991, 1992)), Kayal et al. (1992), Jain and Chander (1995), and Sinvhal et al. (1992). Solid curve represent isoacceleration contours of value 300 cm/sec^2. The curve with dashed line represents meisoseismal area of the Uttarkashi earthquake

MODEL OF RUPTURE PROPAGATION

For Uttarkashi earthquake rupture propagating in mostly updip direction has been modelled. The aftershocks distribution, meisoseismal area and region of maximum recorded peak ground acceleration of Uttarkashi earthquake lie in westward direction with respect to the epicenter. These effects are well explained only by updip propagating rupture (Figure 6). Position of nucleation point for this model is shown in Figure 6. For this model, nucleation point is placed at the center of extreme north-east corner element. Accelerograms at thirteen stations which recorded this earthquake are simulated and shown in Figure 7.

The peak accelerations obtained from simulated accelerograms were compared with those from field accelerograms. The resultant envelope of accelerogram depends on empirical relation of peak ground acceleration by Abrahamson and Litehiser (1989). The horizontal component of field record giving maximum ground acceleration is used for comparison. It is observed that the trend in peak ground acceleration is maintained in both field and simulated records, Table 3. The difference in this trend is less for stations at a hypocentral distance more than 60 km. Peak acceleration in the simulated record is less than that in the field record at stations like Karnprayag and Uttarkashi while it is high at eleven other stations.

The comparison of acceleration spectra of simulated and recorded accelerograms in Figure 8 shows that these two spectra match at intermediate frequency range between 1 to 10 Hz. The acceleration spectra of simulated accelerogram are richer in high frequencies for nearly all records. The simulated records at all stations except Koteshwar (Figure 7) show that their durations are higher than the observed ones. These discrepancies can be due to the unavailability of proper empirical relations for this region due to limited data base and various other factors including radiation pattern, propagation effect, local site geology, topographic effects and inhomogeneities in the earth model which are not included in the present technique.

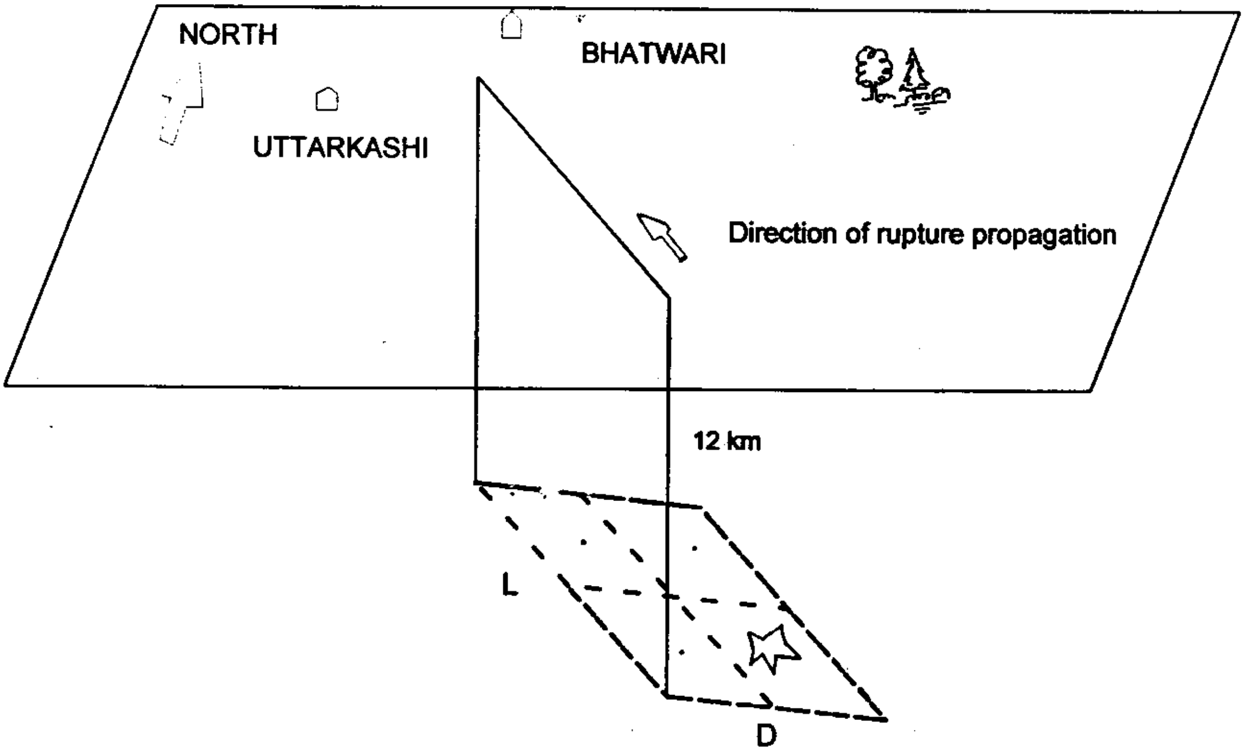

Fig. 6 Model of rupture plane for Uttarkashi earthquake assuming northward propagating rupture

CONCLUSIONS

Modifications have been made in the technique of Midorikawa (1993) for its applicability for Uttarkashi earthquake and method has been modified to simulate accelerograms at various observation points. Synthetic accelerogram has been calculated by multiplying filtered white noise with the envelope of accelerogram at a particular observation point. Filters through which white noise passes include the effects of geometrical spreading, anelastic attenuation and near-site attenuation at high frequencies.

The method and its dependency on various modelling parameters have been studied in detail. After selecting the rupture model for Uttarkashi earthquake, thirteen accelerograms have been simulated for the model of the Uttarkashi earthquake and their quantitative comparison explains the utility of the method and its applicability for Himalayan earthquake.

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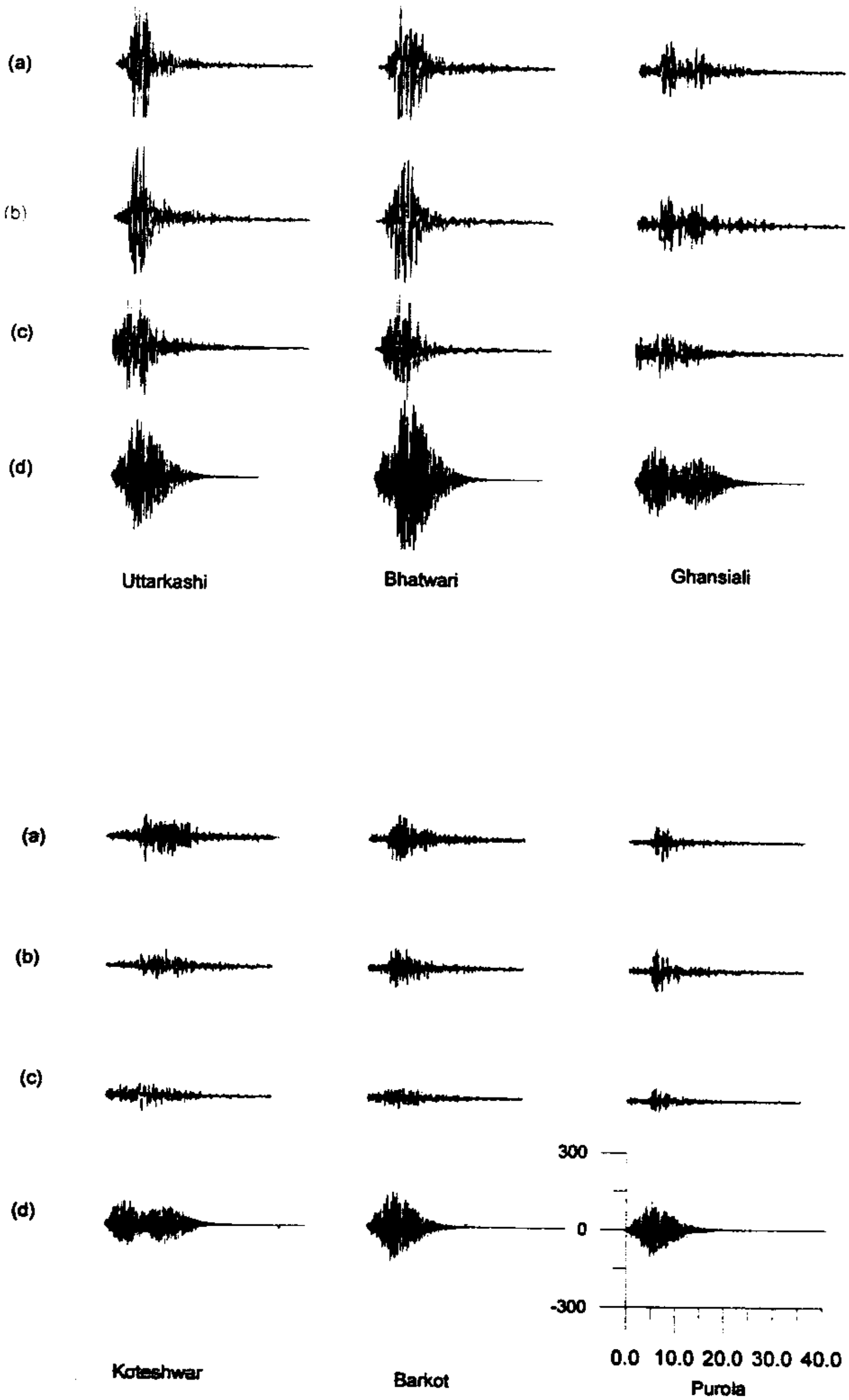

Fig. 7a Normalised (a) longitudinal, (b) transverse, (c) vertical and (d) simulated accelerograms of Uttarkashi earthquake at 13 different stations with same scale of time axis for all records (Chandrasekaran and Das (1991, 1992)).

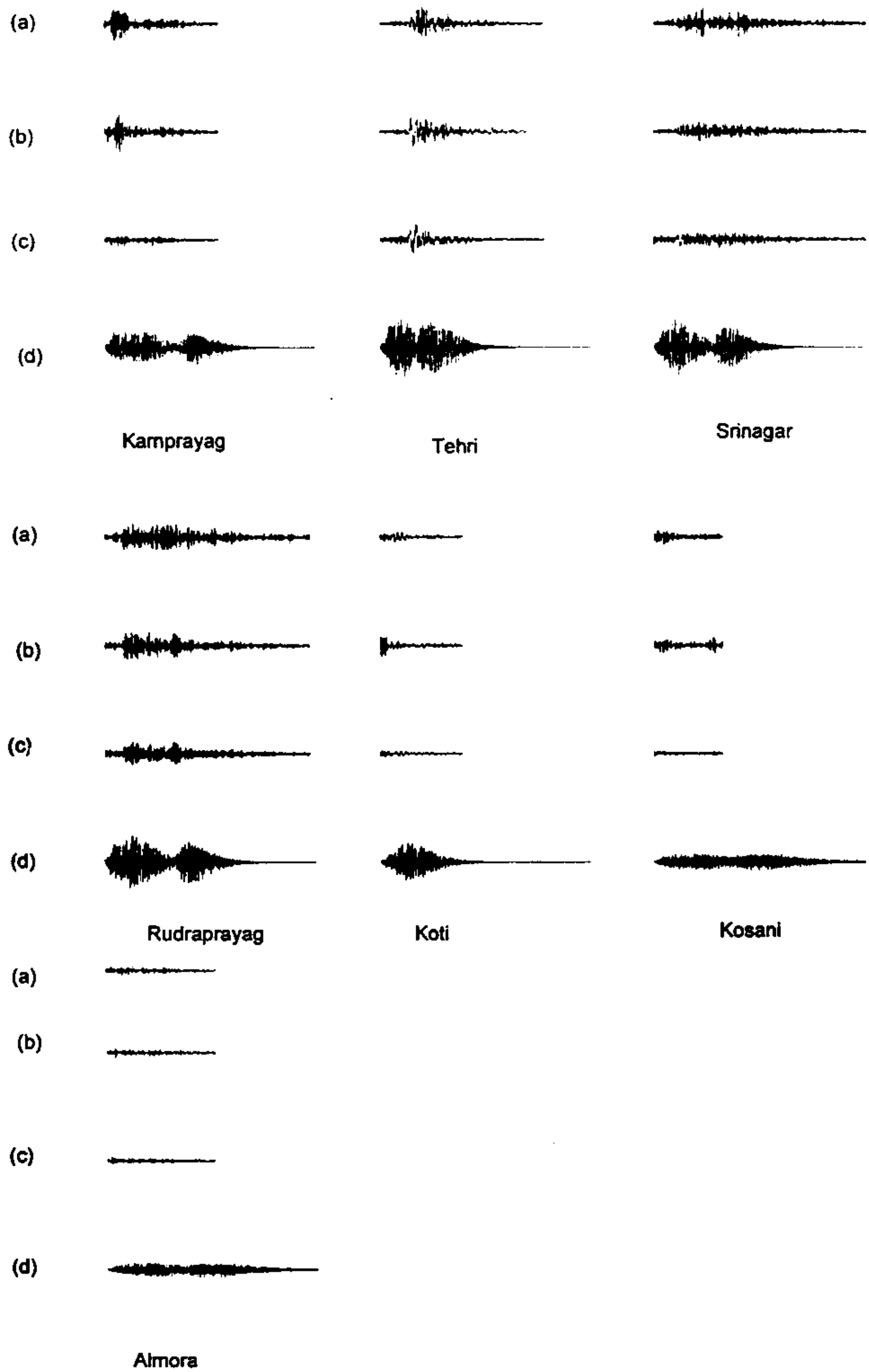

Fig. 7b Normalised (a) longitudinal, (b) transverse, (c) vertical and (d) simulated accelerograms of Uttarkashi earthquake at 13 different stations with same scale of time axis for all records (Chandrasekaran and Das (1991, 1992))

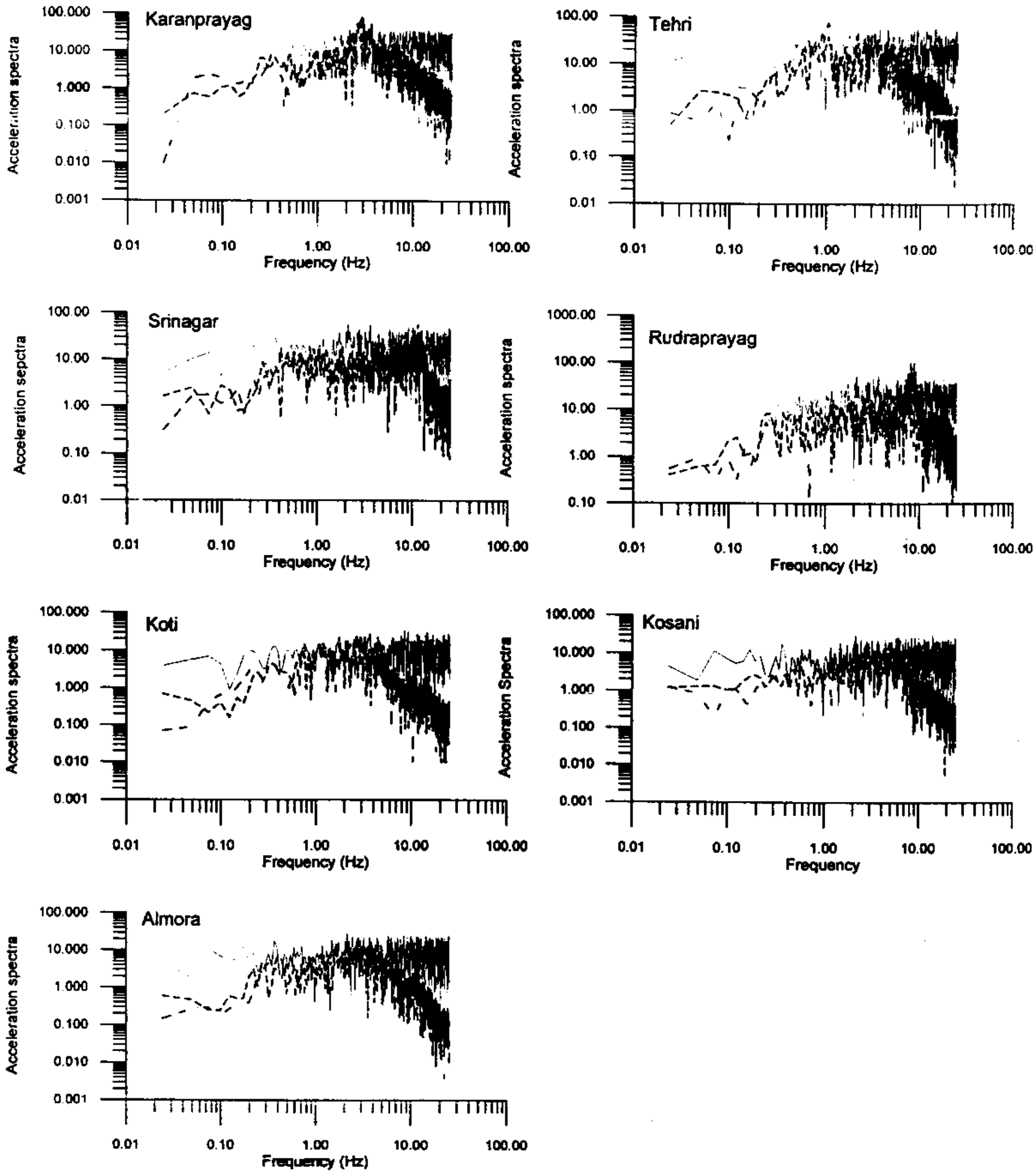

Fig. 8a Acceleration spectra of simulated and observed accelerograms (Chandrasekaran and Das (1991, 1992))

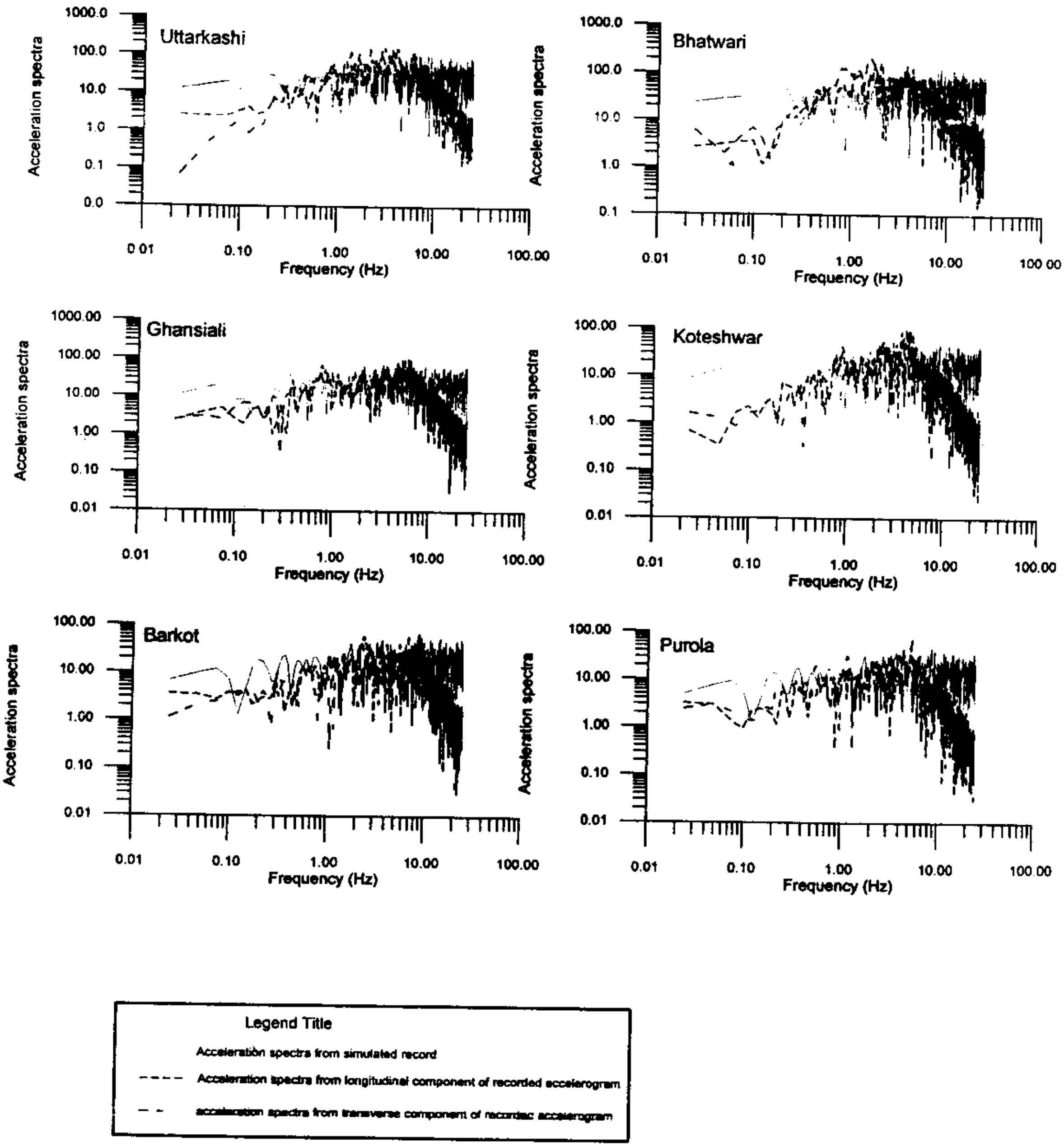

Fig. 8b Acceleration spectra of simulated and observed accelerograms (Chandrasekaran and Das (1991, 1992))

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