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MODELLING OF PEAK GROUND ACCELERATIONS FOR UTTARKASHI EARTHQUAKE OF 20TH OCTOBER, 1991

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Abstract

Using modified technique of Midorikawa (1993) a method of estimating peak ground acceleration from the model of rupture plane has been proposed in this work. The technique has been tested for Uttarkashi earthquake of 20th Oct, 1991 which was well recorded on strong motion array. After identification of causative fault, rupture has been modelled and peak accelerations were simulated at those thirteen stations which had already recorded this earthquake. Peak accelerations obtained after modelling are compared with that from the field records and consistency in the comparison confirm the efficacy of the approach. Simulations from several models were made to study the dependency of present methodology on various empirical relations and modelling parameters. The study confirm the utility of this method for predicting peak ground acceleration over the conventional method of using attenuation relation for this purpose.

INTRODUCTION

Prediction of strong ground motion is one of the most important subjects in earthquake engineering and engineering seismology (Midorikawa, 1993). For this reason attenuation relation plays important role, however their applicability is of limited use because of limited data base. Recently a method for predicting ground motions for an earthquake is popular among seismologist which make use of summations of recordings of small earthquakes, considered as Green's functions (Joyner and Boore, 1988). This method has been used by several workers (Hartzell, 1978, 1982; Kanamori, 1979; Hadley, and Helmberger, 1980; Mikumo et al., 1981;

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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 scheme is that there is no need to remove propagation effects (Fukuyama and Irikura, 1986) The small earthquakes needed in this method are located ideally near the source and recorded at site for which large event simulation is desired (Joyner and Boore, 1988). This is the most difficult condition to be met in real problem and hence the method is of limited use.

This difficulty is removed in an approach presented by Midorikawa (1993) which is based on semi empirical Green's function method of Irikura (1986), but is simplified for engineering use. This method had already been tested and peak accelerations were simulated for Central Chile earthquake (M_s 7.8) and computed results are found to be in good agreement with observed one (Midorikawa, 1993). This method has been used in present work after incorporating scaling relations that are suitable for Himalayan earthquake. The main objectives of the work presented in this paper are : to calculate peak ground acceleration due to the model of rupture plane for Uttarkashi earthquake and establish the efficacy of the approach.

ATTENUATION LAWS IN THE REGION

In the methodology presented for modelling of rupture plane, attenuation relation has been used for computing peak ground acceleration. The methodology has been applied for Uttarkashi earthquake which was well recorded on strong motion array at thirteen stations (Chandrasekaran and Das, 1992). Peak acceleration data at various station are given in Table 1. It was reported by Chandrasekaran and Das (1992) that peak acceleration from field data is reasonably predicted by the relationship given by McGuire (1978). However, this relation has been obtained by the data of western United States. Recorded peak ground accelerations from Uttarkashi earthquake has also been compared by Yu et al. (1995) with the regression relation given by Boore et al. (1993). Although comparison is consistent, the relation by Boore et al. has been obtained by using primarily strike slip earthquakes in California and western United states. Peak acceleration computed from the empirical relation given by Abrahamson and Litehiser (1989) has been compared with field data (Fig 1) and it was observed that calculated values although smaller at near field stations, shows an overall consistency with field data. This relation is based on worldwide earthquake data and can be used for earthquakes having thrust as source mechanism.

This relation has been compared with empirical relations of McGuire (1977) and Campbell (1981) and is shown in Fig. 2. It was seen that peak ground acceleration obtained by McGuire (1977) and Campbell (1981) is larger and smaller, respectively, with field values. However, the values obtained by Abrahamson and Litehiser (1989) are close to the observed values at many stations.

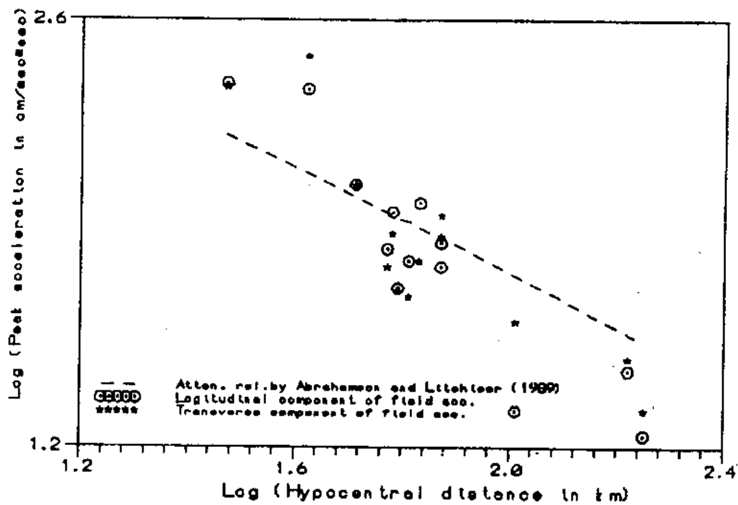

Fig 1 Comparison of peak ground acceleration recorded for Uttarkashi earthquake with that calculated from attenuation relation of Abrahamson and Litehiser (1989). For use in attenuation relation hypocenter of this earthquake is taken from PDE (1991).

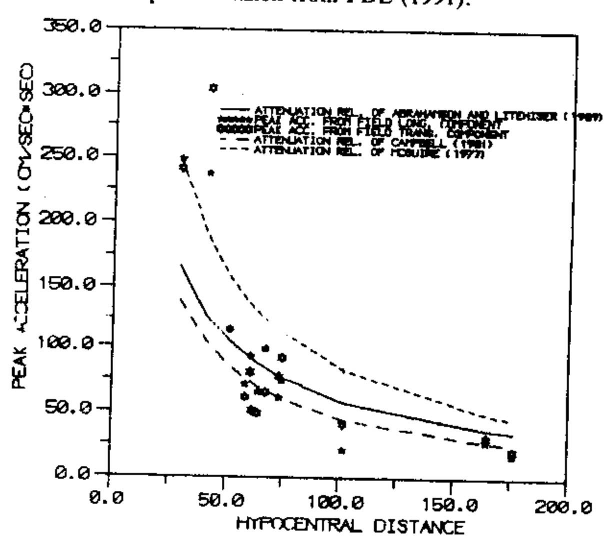

Fig 2 Comparison of peak ground acceleration from field data for Uttarkashi earthquake of 20th Oct, 1991 with that obtained from attenuation relation of Abrahamson and Litehiser (1989), Campbell (1981) and McGuire (1977).

Beside peak acceleration, duration can also been computed from the empirical relations. Duration from the field records can be calculated by using Trifunac and Brady (1975) criteria. They have defined duration as the time in which significant contribution to the integral of square of acceleration referred as acceleration intensity takes place. Using this criteria duration has been calculated from two horizontal components of all 13 stations that has recorded Uttarkashi earthquake. The regression relation by Esteva and Rosenblueth (1964) is used for comparing duration obtained from field horizontal records for Uttarkashi earthquake (Fig 3). The calculated duration is close to that of field records at those near field stations which lie at hypocentral distance less than 100 km and is larger at some few far field stations.

Table 1 Peak acceleration from recorded accelerograms for Uttarkashi earthquake. Data taken from Chandrasekaran and Das (1992).

	Peak acceleration in cm/sec^2			
Stations	Log. comp.	Trans. comp.	Vertical comp.	Hypocentral distance in km
Almora	17	21	18	175
Barkot	93	80	43	60
Bhatwari	248	241	288	29
Ghansiali	115	114	99	51
Karnprayag	60	77	25	73
Kosani	28	31	11	164
Koteshwar	98	65	74	67
Koti	20	40	14	101
Purola	73	91	51	74
Rudraprayag	52	50	44	61
Srinagar	65	49	44	64
Tehri	71	61	57	58
Uttarkashi	237	304	192	41

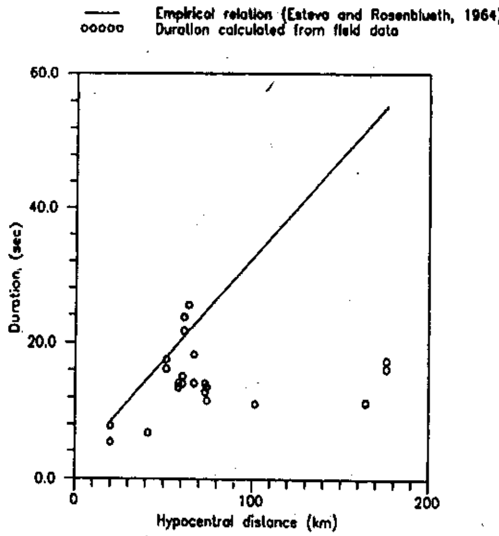

Fig 3 Comparison of duration of acceleration records for Uttarkashi earthquake with that calculated from relation of Esteva and Rosenblueth (1964).

MODELLING PARAMETERS OF RUPTURE PLANE

In the present approach rupture plane has been modelled as a rectangular plane embedded in a homogeneous half space. The length (L) and width (D) of the rectangular plane define its dimension. Empirical relations between rupture length (L) and the magnitude of the earthquake given by Araya and Kiureghian (1988) has been derived on the basis of worldwide data and is given below as :

$$\log L = -2.77 + .619\, M_s \quad \text{.... (1)}$$

In this expression L is the length of rupture in km and M_s is surface wave magnitude of the earthquake. Area of ruptured plane (A) can be calculated by using relation given by Kanamori and Anderson (1975):

$$\log(A) = M_s - 4 \quad \text{.... (2)}$$

In this expression A is the area of ruptured fault $(km)^2$ and M_s is surface wave magnitude of the earthquake. This relation is derived for earthquake having surface wave magnitude greater than or equal to 6. For a rectangular rupture plane of dimension L and D, area (A) can be expressed as :

$$A = L \times D \quad \text{and} \quad D = A / L \quad \text{.... (3)}$$

In the present methodology entire rupture plane is divided into several elements. The condition which has to be satisfied is that the number of elements along length and downward extension must remain same. The total numbers of elements within the rupture plane are calculated as :

$$N = (L \times D)/(L_e \times D_e) \qquad .... (4)$$

In this expression $L_e = L/n$ and $D_e = D/n$. Parameter n represents total number of elements along length or downward extension and is calculated by using following empirical relation given by (Sato, 1989) :

$$n = 10^{.5(M - M')} \qquad .... (5)$$

In this expression M is the magnitude of earthquake to be modelled and M' is the magnitude of earthquake represented by an element. Once the rupture plane is divided into several elements, an element is decided from which rupture initiates. This is termed as initial point, nucleation point or starting point of the rupture.

The velocity of the medium (V) in which the rupture plane is lying is assumed from the seismic section available for the region. Velocity of the medium depends on the rock type in the region, hence different regions having different rock type will have different velocity of the medium.

The velocity of propagation of rupture with in the rupture plane (V_r) is assumed as 80% of S wave velocity in region surrounding the earthquake source (Mendozo and Hartzell, 1988, Reiter, 1990). Rupture within the rupture plane propagates according to the assumed geometry of rupture propagation from the nucleation point. Radial type of geometry is among the simplest type of rupture geometry and this geometry have been used in the present study.

METHOD OF MODELLING OF THE RUPTURE PLANE

Rupture plane is divided into several rectangular elements, each element corresponds to a small event earthquake. Total number of elements within the rupture plane are n^2. Element within the rupture plane represent an earthquake of magnitude (M') smaller than that of to be modelled (M). The magnitude M' is calculated from the expression (5) given by Sato (1989).

For the purpose of modelling, entire rupture plane has been mapped in a three dimensional coordinate system. The origin of the coordinate system is assumed to lie at a point coinciding with the center of one of the topmost element at the extreme corners of the rupture plane. The X axis is assumed along the strike of the rupture plane, Y axis is perpendicular to the X axis and is positive in the dip direction and Z axis is positive vertically downward. The nucleation point is the point within the rupture plane coinciding with the hypocenter of the earthquake.

Acceleration waveform envelop function is released from each element when rupture from the nucleation point approaches its center. The acceleration envelope from each element reaches the observation point with different time lags. The time lags depends on the time taken by the rupture to reach particular element from the nucleation point and the time taken by the envelope function to reach the observation point with the velocity of the medium. The acceleration waveform envelope function, used by Kameda and Sugito (1978) has been used in the present study. This function is given as :

$$e_{ij}(t) = (a_{ij} * t/d_{ij}) \exp(1 - t/d_{ij}) \quad .... (6)$$

In this expression a is the peak value of $e_{ij}(t)$ and d_{ij} is the duration parameter. Value of a_{ij} is computed using empirical relation of peak ground acceleration. Subscript 'ij' in these expression are meant for different elements. Following relation given by Abrahamson and Litehiser (1989) has been used for computing horizontal peak acceleration :

$$\text{Log}_{10}\, a(g) = -.62 + .177M - .982\, \text{Log}_{10}\,(R + e^{.284M}) + .132F - .0008ER \quad .... (7)$$

In this expression M is the magnitude of the earthquake, R is the hypocentral distance and a(g) is the horizontal peak acceleration. The variable 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 favor using values E = 1 and F = 1 and hence the same are used for calculating the acceleration by this expression. The parameter 'd' in expression 1 represent the duration of acceleration waveform envelope and is calculated using following relation (Esteva and Rosenblueth, 1964)

$$d = .02 \exp(.74M) + .3 R \quad .... (8)$$

Where M is magnitude of earthquake and R is the hypocentral distance. Substituting the values of R and M' in expressions (7) and (8), waveform envelopes of different peak acceleration and durations are released from different elements (eq. 6). Depending upon geometry of rupture propagation and the coordinates of observation points these different envelopes arrive at the observation points at different time lags t_{ij}. The resultant envelope E(t) of the modelled earthquake is computed by summation of envelopes $e_{ij}(t)$ by using following expression :

$$E(t) = |\Sigma\, e^2_{ij}(t - t_{ij})|^{1/2} \quad .... (9)$$

The complete procedure of modelling is shown in Fig 4.

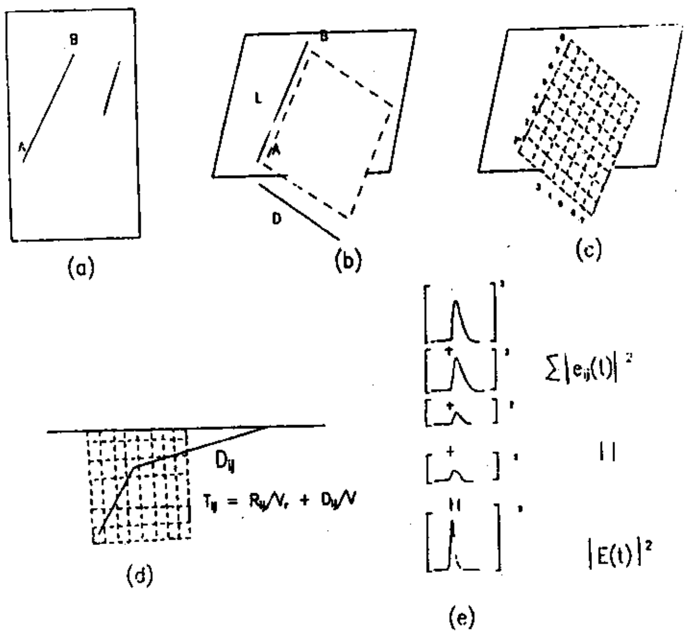

Fig 4 (a) map showing the causative fault AB' in the area of study for any hypothetical earthquake, (b) Rupture modelled along causative fault AB', (c) Representation of rupture plane into numbers of elements. each element within the rupture plane is represented by 'ij' where i and j are total number of element along width and length, respectively (d) Arrival time T_{ij} of the wavefront at the observation point. R_{ij} is distance between nucleation point and ijth element. D_{ij} is distance between ijth 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.

CASE STUDY : UTTARKASHI EARTHQUAKE OF 20TH OCT, 1991

The Uttarkashi region was rocked by a moderately strong earthquake (m_b = 6.5, M_s = 7.1) in the early hours of October 20, 1991. Parameters of this earthquake are given in Table 2. 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 the Uttarkashi and adjoining region. Strong motion records at 13 stations had been recorded for the Uttarkashi earthquake of 20th October, 1991 (Chandrasekaran and Das, 1992). Location of these stations is given in Fig 5.

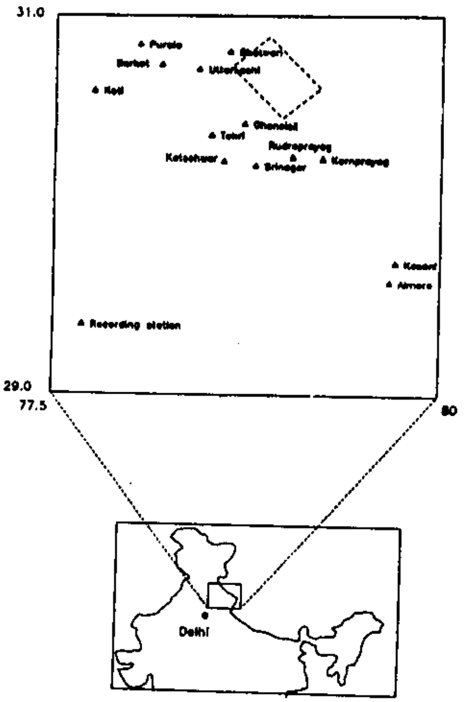

Fig 5 Location of stations that had recorded Uttarkashi earthquake of 20th October, 1991 on strong motion array. Rectangle in dash lines shows the projection of rupture modelled for Uttarkashi earthquake.

Table 2 Parameters of Uttarkashi earthquake as reported by PDE (1991).

Date	20 October, 1991
Origin Time:	02 Hr 30 Min 15.1 sec
Epicenter	30.73°N, 78.79°E
Focal Depth	19 Km
M_b	6.5
M_s	7.1
NP1	Strike 332°, Dip: 19°, Slip: 133°
NP2	Strike 108°, Dip: 76°, Slip: 77°
M_o	1.0 x 10^{25} dyne-cm

For checking the efficacy of the approach peak acceleration at thirteen stations were simulated by the procedure of modelling. The three dimensional coordinates of the recording stations in assumed system are computed from map. The parameters of the rupture plane for modelling the Uttarkashi earthquake of 20th Oct 1991 are given in Table 3.

Table 3 Criteria of selection of modelling parameters of rupture plane. The value of modelling parameters are given for Uttarkashi earthquake of 20th Oct, 1991. The magnitude of elementary earthquake for the model is 6.5.

Modelling 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	$\text{Log}(A) = M_s - 4.0$ As A = LxD for rectangular rupture therefore, D = A/L	29 km	Kanamori and Anderson (1975)
δ and ϕ	Fault plane solution	$\delta = 14°$ and $\phi = 317°$	Dziewonski et al. (1992)
V_r	$V_r = .8 * V_s$	2.6 km/sec	Mendoza and Hartzell (1988) and Reiter (1990)
V_p	Velocity structure	5.7 km/sec	Kamble (1992a, 1992b)
n	$n = 10^{.5(M-M')}$	2	Sato (1989)

L_e	$L_e = L/n$	21 km	
D_e	$D_e = D/n$	14.5 km	
Depth of rupture plane	Geological depth section	12 km	Kayal (1994)

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

The most probable causative fault for this earthquake has been identified on the basis of isoseismal map, isoacceleration map, aftershocks location map and tectonic map (Joshi, 1994). The composite map is shown in Fig 6. Study of all these maps indicate possibility of Munsiari thrust as causative fault for this earthquake which has already been verified by Jain and Chander (1995). The depth section in this region (Seeber et al., 1981) indicates that the mainshock of this earthquake occurred at the Juncture of 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 (Seeber et al., 1981 and Ni and Barazangi, 1984).

Peak acceleration at thirteen stations were simulated after preparing a model of rupture plane. 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 Oct 1991, are computed by the pre explained criteria. Some of these parameters (e.g. L, D, δ, ϕ, location of rupture plane and nucleation point) have already been finalized after simulating strong motion records from several models by Joshi (1994). The length of aftershock distribution area for the Uttarkashi earthquake (Fig 5) is about 40 km and this coincides with the rupture length of 42 km computed by using relation by Araya and Kiureghian (1988). The dip and strike for this rupture model is based on the fault plane solution given by Dziewonski et al. (1992).

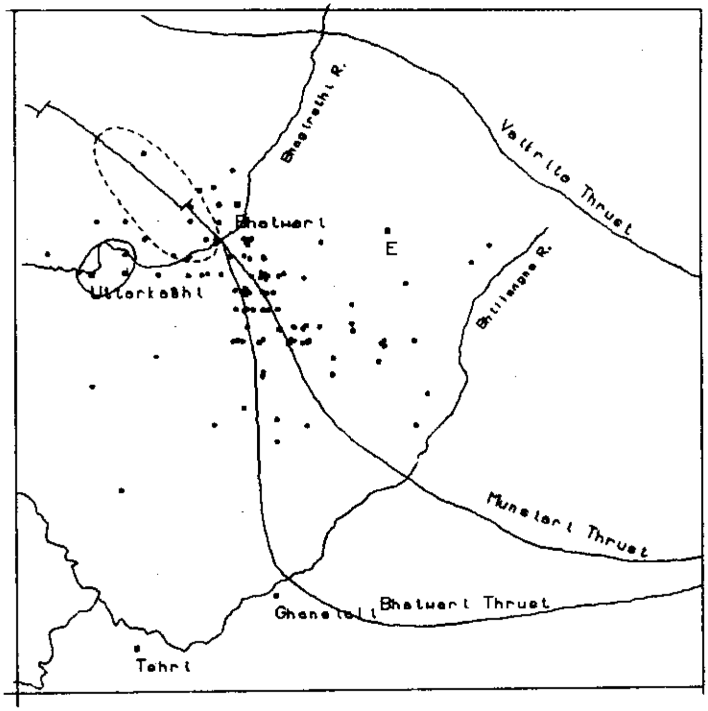

Fig 6 Composite map of isoacceleration contours, aftershocks location, meizoseismal area of Uttarkashi earthquake of 20th October, 1991 and tectonics of the region. Data taken from Chandrasekaran and Das (1992), Kayal et al. (1992), Jain and Chander (1995), and Sinvhal et al. (1992). The ellipse in dashed line shows the meisoseismal area while the solid line curve shows 300 cm/sec^2 isoacceleration contour prepared from resultant peak acceleration of field data. E denotes the epicenter of Uttarkashi earthquake.

Peak acceleration was simulated at 13 stations (Table 4). Trend of peak acceleration at 13 different stations for this model is shown in Fig 7. The computed peak accelerations at thirteen stations according to the above model of the rupture plane for this earthquake are compared with the larger peak acceleration among two horizontal component of the recorded accelerations (Table 4). The comparison shows a difference of less than 30% at Bhatwari and Uttarkashi stations. These stations are nearest to the modelled source of earthquake. Except for Uttarkashi which is close to the modelled source of this earthquake, peak acceleration overestimates the peak ground acceleration at other stations it can be accounted due to radiation pattern, propagation effect, local site geology, topographic effects and inhomogeneities in the earth model. There is a match in the trend of values of peak acceleration at various stations.

Table 4 Peak acceleration obtained from the model of rupture plane and field records (Chandrasekarana nd Das, 1992) for Uttarkashi earthquake of 20th Oct, 1991.

No.	Station	Peak acceleration from model cm/sec²	Peak acceleration from field record cm/sec²	Hypocentral Distance in km
1	Almora	55	21	175
2	Barkot	163	93	60
3	Bhatwari	324	248	29
4	Ghansiali	180	115	51
5	Karnprayag	110	77	73
6	Kosani	52	31	164
7	Koteshwar	134	98	67
8	Koti	121	40	101
9	Purola	120	91	74
10	Rudraprayag	109	52	61
11	Srinagar	132	65	64
12	Tehri	157	71	58
13	Uttarkashi	247	304	41

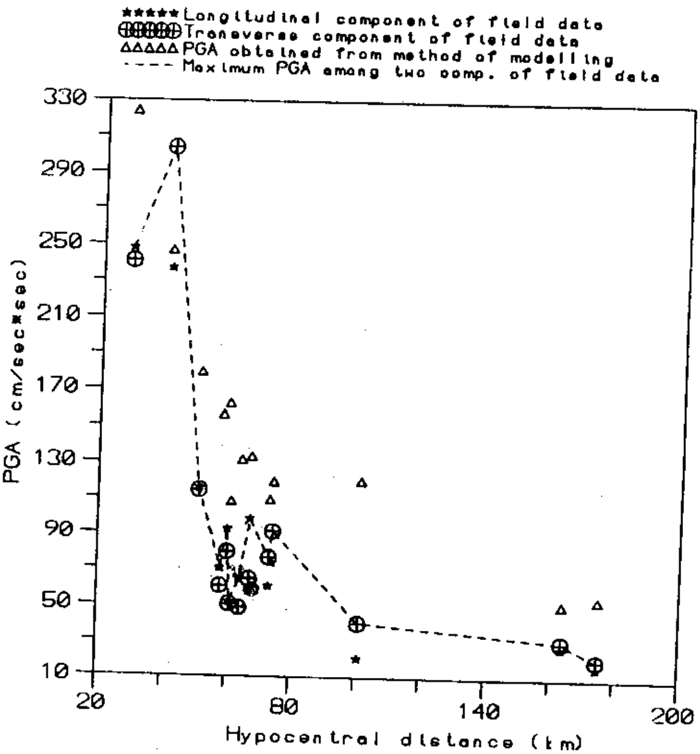

Fig 7 Comparison of peak acceleration obtained after modelling of the rupture process for Uttarkashi earthquake. Field record acceleration data has been taken after Chandrasekaran and Das (1992) and reproduced in table 1.

PROPOSED METHODOLOGY : A DISCUSSION

Since the method presented depends heavily on the empirical relations therefore a complete study regarding its dependency on empirical relations needs to be testified. Fig 8 shows distribution of peak ground acceleration for unilateral and bilateral rupture propagations for M 7.1 earthquake having vertical rupture. It is seen that for bilateral rupture propagation acceleration attenuates uniformly on both sides of rupture model while for unilateral propagation acceleration is higher in the direction rupture propagation compared to other direction. This observation is consistent with the results of Midorikawa (1993) and are termed as directivity effects.

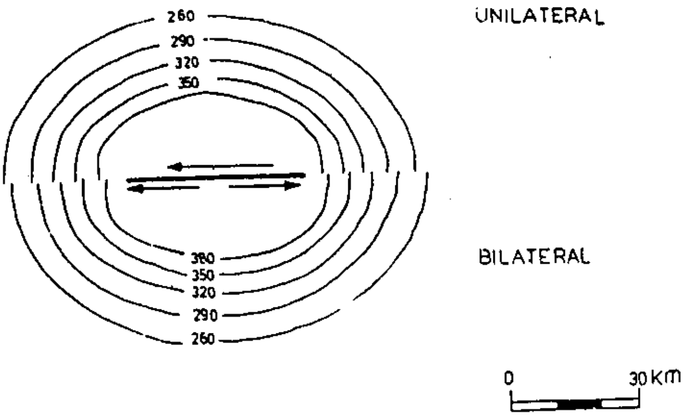

Fig 8 Distribution of peak ground acceleration for vertical rupture model for M 7.1 earthquake for unilateral and bilateral rupture propagation.

Earthquake of magnitude 6.5, 7.1 and 7.4 has been modelled with vertical as well as dipping ruptures having parameters given in Table 5. The parameters concerning the medium properties i.e., velocity of medium and rupture velocity are same as used for Uttarkashi earthquake. Simulated peak accelerations were compared with that obtained from attenuation relations. For all of these and subsequent models bilateral rupture propagation has been considered.

Table 5 Modelling parameters of magnitude 6.5, 7.1 and 7.4 earthquakes. The magnitude of elementary earthquake in each of these model is kept as 6.0.

Magnitude	L (km)	D (km)	N	L_e (km)	D_e (km)
6.5	18	17	4	9	8.5
7.1	42	29	16	10.5	7.2
7.4	64	39	25	12.8	7.8

Symbols : L = Length of rupture plane; D = Width of rupture plane; N = Total number of elements within rupture plane; L_e = Length of element and D_e = Width of element

Attenuation curves are obtained by using present approach for M 6.5, M 7.1 and M 7.4 earthquakes for vertical rupture models having bilateral faulting and are compared with the attenuation curve prepared from empirical relation of Abrahamson and Litehiser (1988). This comparison is shown in Fig 9, 10 and 11. The observation points are selected along the strike of the modelled fault. It was seen from these curves that at large distance from the model of rupture the attenuation curve calculated by using present approach matches well with that from empirical relation indicating that calculated value depends heavily on empirical relation of peak acceleration used. However, at close distances, difference of peak accelerations from present approach and empirical relation is markable.

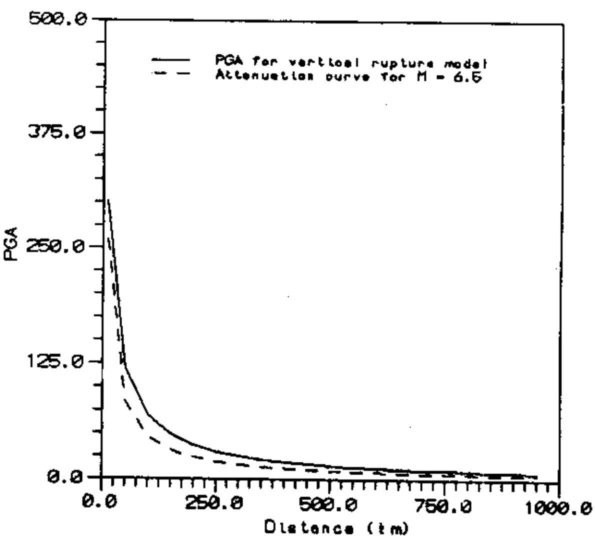

Fig 9 Attenuation curve for M = 6.5 earthquake having vertical rupture plane with bilateral rupture propagation and its comparison with that of attenuation relation of Abrahamson and Litehiser (1989).

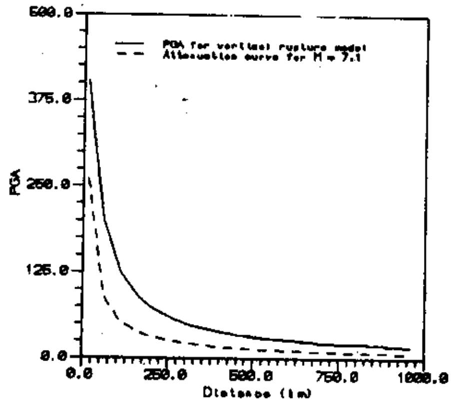

Fig 10 Attenuation curve for M = 7.1 earthquake having vertical rupture plane with bilateral rupture propagation and its comparison with that of attenuation relation of Abrahamson and Litehiser (1989).

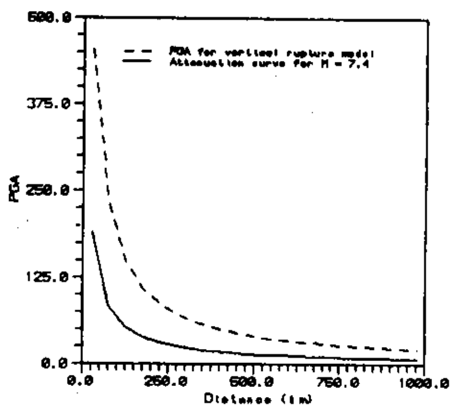

Fig 11 Attenuation curve for M = 7.4 earthquake having vertical rupture plane with bilateral rupture propagation and its comparison with that of attenuation relation of Abrahamson and Litehiser (1989).

Calculations were also made for dipping rupture model for of M 7.1 earthquake. Modelling parameter of this model is same as for M 7.1 earthquake having vertical rupture model except the dip which is assumed as 45° Fig 12 shows comparison of attenuation curves for stations along strike of modelled rupture plane and along its two perpendicular directions. It was seen that peak acceleration at stations far from the source is almost same while considerable difference is observed for near field stations. Moreover, maximum peak ground acceleration is observed along the direction of dip of the modelled rupture plane which is due to source directivity effect.

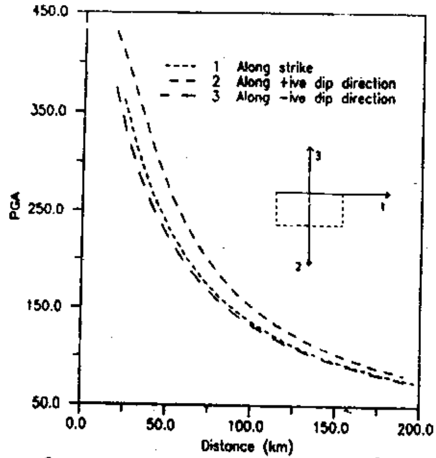

Fig 12 Attenuation curve for M = 7.1 earthquake having 45° dipping rupture plane with bilateral rupture propagation and its comparison with that of attenuation relation of Abrahamson and Litehiser (1989). The attenuation curve numbered as 1, 2 and 3 are for stations along strike, positive dip and negative dip directions, respectively.

Several trial simulations shows that peak ground acceleration obtained by present method are slightly effected by duration parameters while are heavily dependent on the attenuation relation used in the method. Peak acceleration obtained for M 7.1 earthquake for vertical rupture model was compared after incorporating empirical relation of duration of Midorikawa (1989) and Esteva and Rosenblueth (1964) in the methodology. The comparison shows that their is little change in the value of peak ground acceleration when the empirical relation of duration is changed (Fig 13). The same observation was also observed by Midorikawa (1993).

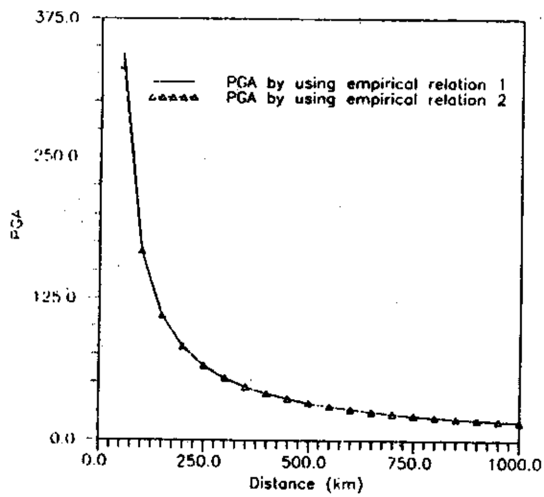

Fig 13 Peak ground acceleration for M 7.1 earthquake having vertical rupture model. The acceleration values at each station are obtained by incorporating the empirical relation of duration given by Midorikawa (1989) and Esteva and Rosenblueth (1964), respectively. The relations 1 and 2 referred in the figure are for empirical relations of Midorikawa (1989) and Esteva and Rosenblueth (1964), respectively.

CONCLUSIONS

Using the procedure presented in this work peak acceleration from the modeled rupture plane was calculated. The procedure of modelling was applied for calculating peak acceleration for Uttarkashi earthquake at thirteen stations which contain field strong motion data. The comparison of peak acceleration obtained after modelling with that from the field records shows acceptable consistency thereby confirming the efficacy of the approach. Several models and simulations were made at number of locations to study the dependency of presented methodology on various parameters. The study confirm the importance of this methodology for calculating peak ground acceleration over empirical attenuation relations and shows that the peak ground acceleration predicted by this methodology satisfy the property of directivity which is difficult to be met by attenuation relations.

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