ATTENUATION RELATIONSHIP FOR ESTIMATION OF PEAK GROUND VERTICAL ACCELERATION USING DATA FROM STRONG MOTION ARRAYS IN INDIA

Mukat L SHARMA[1]

SUMMARY

An attenuation relationship for peak vertical ground accelerations for the Himalayan region in India has been developed. The database consisting of 66 peak ground vertical accelerations from five earthquakes recorded by Strong Motion Arrays in India have been used to develop the relationship. The present analysis includes two step stratified regression model. The attenuation relationship proposed is

$$\log(A) = -2.87 + 0.634M - 1.16\log(X + e^{0.62M})$$

where A is the peak ground vertical acceleration (g), M is the magnitude and X is the hypocentral distance from the source. The residual sum of squares is 0.142. The vertical to horizontal acceleration ratio with respect to the hypocentral distance using the relationship

$$\log(A) = -1.072 + 0.3903M - 1.21\log(X + e^{0.5873M})$$

developed on the same data set for horizontal peak ground accelerations have been studied. The attenuation relationship needs upgradation as and when more and more data becomes available in future. The vertical to horizontal ratio of peak ground accelerations suggests investigations using larger data set.

INTRODUCTION

Site specific seismic hazard evaluation studies require estimation of strong ground motion from probable earthquakes. The estimation of peak ground acceleration in terms of magnitude, source-to-site distance, tectonic environment and source type using attenuation relationships has been a major research topic in seismic hazard estimation studies. Such relationships are developed in past for various regions and comprehensive reviews have been published for such relationships (Boore and Joyner (1982), Campbell (1985), Joyner and Boore (1988), Abrahamson and Letihiser (1989), Fukushima and Tanaka (1990), etc.). Most of the relationships are developed using worldwide acceleration data acquired through the strong motion arrays. The general form of regression models have been described by Campbell (1985). For the regions where strong motion data is not available for such analysis, the attenuation relationships developed for other regions are used based on the resemblance of the characteristics of the both regions. In some of the cases, where lesser data is available the empirical relations are developed by pooling some of the data from other regions also (Fukushima and Tanaka, 1990).

The vertical accelerations are generally smaller than horizontal accelerations for strong motion data from earthquakes recorded at shorter distances. In fact, when averaging over all strong motion records, the two third ratio is conservative. Sometimes for larger earthquakes this ratio seems to increase. The magnitude 6.2 Long Beach earthquake of 1933 was recorded at several sites, one at a source distance of just over 6 km. The vertical

[1] *Department of Earthquake Engineering, University of Roorkee, Roorkee, INDIA*

to Horizontal (V/H) ratio for this record was just over 1.0. It is precisely the large earthquakes at near distances that often contribute most significantly to earthquake design load estimates. This suggests that separate attenuation relationships may be required for peak ground vertical and peak ground horizontal ground acceleration. An attenuation relationship for peak ground vertical acceleration is developed in the present study. This relationship is then compared with the attenuation relationship developed on the same data set for peak ground horizontal ground acceleration and the ratios of vertical to horizontal peak ground acceleration are then compared with the actual ratios recorded by the stations.

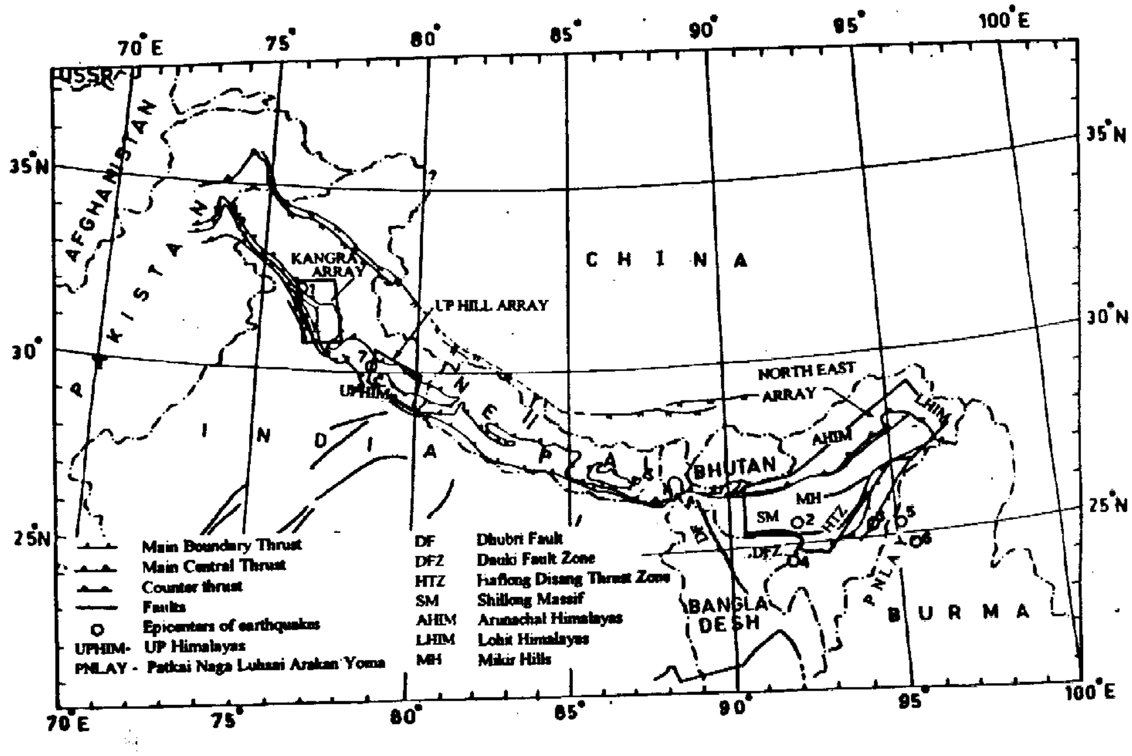

Fig. 1. Strong motion arrays in India deployed by Department of Earthquake Engineering, University of Roorkee. The location of the contributing earthquakes are also shown (o).

ACCELERATION DATA

The data base used for the study has been made available by Department of Earthquake Engineering which has deployed three strong motion arrays in the Indian region, namely, Kangra Array in the Himachal Pradesh (N-W India), Uttar Pradseh (UP) array (N-C India) and Shillong array in Meghalaya and Assam (N-E India). Figure 1 shows the locations of the arrays. The Kangra array has 50 analog strong motion accelerographs (SMA-1), the Shillong array 45, and the Uttar Pradesh Array 40 analog SMA-1 accelerographs.

All the arrays are deployed in one of the world's most seismically active region of the Himalayas. The Kangra array is located in the Lesser Himalayas with elevations ranging from 470 m to 2,700 m. There are numerous faults and thrusts, but among these, two are of prominence and can be traced all along the length of the Himalayas (Fig. 1). The tectonic feature separating Tertiaries from Mesozoic is the main boundary Thrust (MBT) and Mesozoic from central crystellines is the Main Central Thrust (MCT). The Uttar Pradesh array is also deployed around MBT and MCT in the UP Himalayas. The array trends northwest to southeast covering a length of about 280 km and follows the regional strike of the tectonic features and merges with the Kangra Array in the NW. The Shillong Array is deployed in the Shillong massif in the states of Meghalaya and Assam. It mainly encompasses the most active features of the region, namely, Dauki Fault Zone, Dhubri fault and the Haflong Disang Thrust Zone. Regionally, the northeast India can be classified into four major geotectonic units and these are Arunachal Himalayas, Lohit Himalayas, the Patkai-Naga-Luhasi-Arakan-Yoma (Indo-Burma) hill ranges and Shillong plateau-Assam basin. Shillong massif and Mikir Hills exposes the basement rocks and are surrounded by the Tertiary formation. The wedge shaped Shillong plateau is a horst which has been block uplifted since Jurassic time.

Table 1

List of contributing earthquakes

Earthquake	Date	Time GMT	Lat. N	Long. E	Depth Km	Mag.
1	4/26/86	1305	32.17	76.28	7.0	5.5
2	9/10/86	1320	25.42	92.08	28.0	5.5
3	5/18/87	0153	25.27	94.20	50.0	5.7
4	2/06/88	1450	24.64	91.51	15.0	5.8
5	8/06/88	0036	25.14	95.12	91.0	6.8
6	9/01/90	1851	24.75	95.24	119.0	6.1
7	10/19/91	2123	30.73	78.79	19.0	6.6

There are seven earthquakes contributing data for this study, one of which has been recorded by the Kangra array (M=5.7), five by Shillong array (M=5.5 to 6.8) and one by Uttar Pradesh array (M=6.6) (Chandrasekaran and Das, 1993 ; Chandrasekaran and Das, 1994). The earthquakes with their locations and origin times are tabulated in Table 1. The earthquake locations are also shown in Fig. 1. The peak ground accelerations recorded by these earthquakes at various stations after the preliminary processing are taken from Chandrasekaran and Das, 1992. The site types are considered to be rock sites if deployed on granite/quartzite/sandstone and soil if deployed on exposed soil covers on the basement. The data from the earthquakes recorded by these arrays have been used to compute the attenuation relationship.

ATTENUATION RELATIONSHIP

Systematic reviews by various authors are put forward for the development of attenuation relations for the peak ground acceleration in the past 20 years (Boore and Joyner, 1982; Campbell, 1985; Tanaka and Fukushima, 1987; Joyner and Boore, 1988; Abrahamson and Letihiser, 1989; Fukushima and Tanaka, 1990, etc.). The general form of the attenuation relation may be considered as

$$\log(a) = f_1(M) + f_2(r,E) + f_3(r,M,E) + f_4(F) + \varepsilon \quad (1)$$

where a is the peak ground acceleration (horizontal or vertical); $f_1(M)$ is a function of earthquake magnitude; $f_2(r,E)$ is a function of earthquake-to-recording site distance and the tectonic environment; $f_3(r,M,E)$ is a non separable function of magnitude, distance and tectonic environment; $f_4(F)$ is a function of fault type and ε is a random variable representing uncertainty in log(a). The models considered in past are either $f_1(M)$, $f_2(r,E)$ and $f_4(F)$ (Joyner and Boore used this model) or $f_1(M)$, $f_3(r,M,E)$ and $f_4(F)$ (Campbell used this model). The first model assumes that the distance and magnitude have separable influence on peak ground acceleration and the second model considered it to be non separable. Abrahamson and Letihiser(1989) used hybrid model of Campbell and Joyner and Boore. The forms of the functions $f_1(M)$, $f_2(r,E)$, $f_3(r,M,E)$, and $f_4(F)$ are discussed by Campbell (1985). The same type of forms have been taken here also while doing the regression analysis.

To work out the attenuation relation, as a first step a linear regression analysis was carried out considering a simple relation as

$$\log(A) = -b\log(X) + c \quad (2)$$

where *A* is the acceleration, X is the hypocentral distance and b and c are the regression coefficients. The average value of the decay parameter computed separately for each earthquake is 1.18. Figure 2 shows the magnitude-distance distribution of peak ground vertical accelerations.

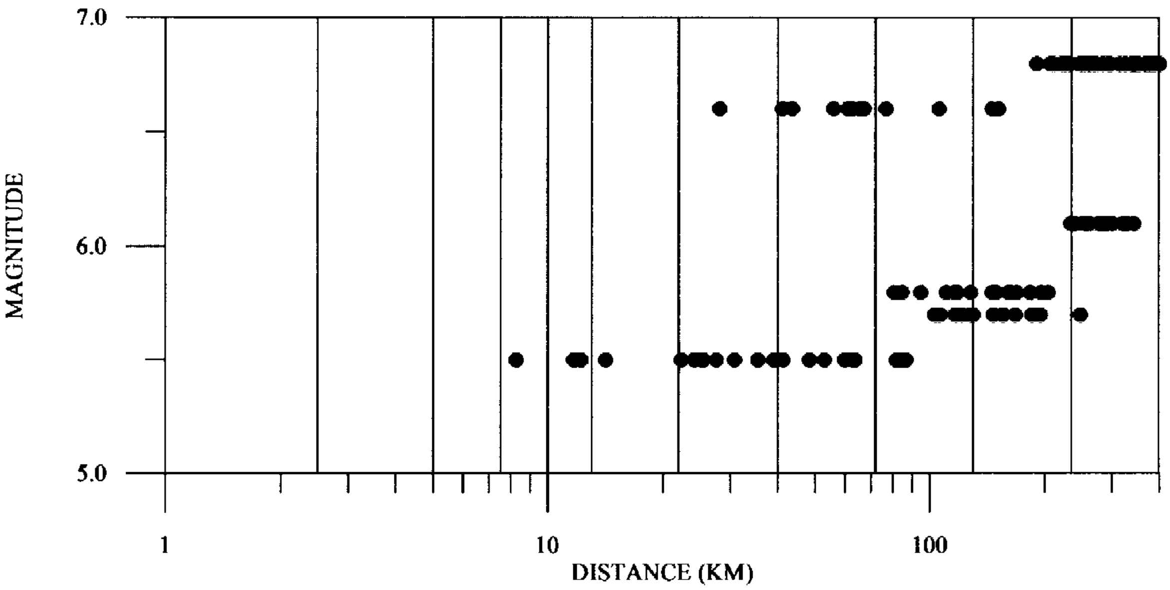

FIG. 2 Magnitude-distance distribution of peak ground vertical acceleration data. The vertical lines drawn are the distance bins used for the weighted non-linear analysis.

Next, a general multiple regression analysis was performed for the whole data set by assuming the basic regression model as

$$\log(A) = aM - b\log(X) + c \tag{3}$$

where M is the magnitude and a, b and c are the regression coefficients. The value of decay parameter while considering the whole data set came out to be 0.405(0.086) which is much less than the average value for each earthquake, i.e., 1.18. The figure in the bracket is the standard error. This phenomenon has been well illustrated by Fukushima and Tanaka (1990) by considering the actual recordings as well as the synthetic data using numerical experiments. To overcome this Fukushima and Tanaka (1990) used the two step stratified regression analysis as used by Joyner and Boore (1988) to avoid the interaction of b value estimates. The same strategy is used here by considering the regression model to be

$$\log(A) = -b\log(X) + \sum d_i l_i \tag{4}$$

where d_i is a coefficient for i^{th} earthquake and l_i is a dummy variable (equals to 1 for i^{th} earthquake, 0 otherwise). Using this, the value of b was computed to be 1.16(0.02) which is much closer to the average value of 1.18 as compared to 0.406.

The regression model is selected based on the equation (1) which is the general form of the attenuation relationship. The term $f_4(F)$ is not considered since the focal mechanisms for these earthquakes as reported are not well defined and considering this term may include more errors in the regression model. Abrahamson and Letihiser (1989) derived attenuation relation for vertical and horizontal peak ground acceleration in US by segregating the data into interplate and intraplate and found very small difference for the two source regions (only a factor of 0.0011Er where E = 1 or 0 for interplate and intraplate and r is the shortest distance to the zone of energy release). Since the data set is small in the present study and the tectonic term gave small difference as computed by Abrahamson and Letihiser, the tectonic environment term is neglected while choosing the regression model. The magnitude versus the epicentral distance gave the correlation coefficient as 0.63 so that the Campbell type of regression model is preferred for the analysis which includes $f_1(M)$, $f_3(r, M, E)$ and $f_4(F)$, but not the tectonic term. To avoid the interaction of magnitude and distance in determination of b value, we fix the decay constant to be 1.16 as Joyner and Boore did. The regression model thus selected for the attenuation relation as from equation (1) is considered as follows

$$\log(A) = c_1 + c_2 M - b\log(X + e^{c_3 M}) \tag{5}$$

where c_1, c_2 and c_3 are the regression coefficients where b is fixed to be 1.16.

In an ideal data set, there would be a uniform sampling of peak ground acceleration over all magnitudes and distances, however, due to limited data a weighting regression analysis has been performed. The weights are determined by dividing the data into a number of subsets based on distance. The distance bins are taken to be 2.5 km each upto 10 km and then distance bins as shown in Fig. 2 are taken to be equal on logarithmic distance. In each distance interval, each earthquake is given equal weight by assigning a relative weight of $1/n_{jl}$ to the record where n_{jl} is the total number of recordings for the jth earthquake within the lth distance bin. The weights are then normalised so that they sum to the total number of recordings (Sharma, 1998).

The nonlinear regression analysis was carried out considering the whole data in the first instance. Due to the large focal depths for the earthquake of August 6, 1988 and Jan. 10, 1990, the regression parameters gave large errors. Finally, these earthquakes were rejected and analysis was carried out only for the five earthquakes. The results of the regression analysis gave the values of c_1, c_2 and c_3 as -2.87(0.50), 0.634(0.08) and 0.620(0.06). The attenuation relationship thus computed is as follows :

$$\log(A) = -2.87 + 0.634M - 1.16\log(X + e^{0.62M}) \qquad (6)$$

The attenuation relationship developed as in equation (6) alongwith the data set of the peak ground vertical accelerations with the same magnitudes is plotted in Fig. 3. The residual sum of squares for equation (6) is 0.142 which is sum of the squares of the difference of the observed and predicted peak vertical accelerations.

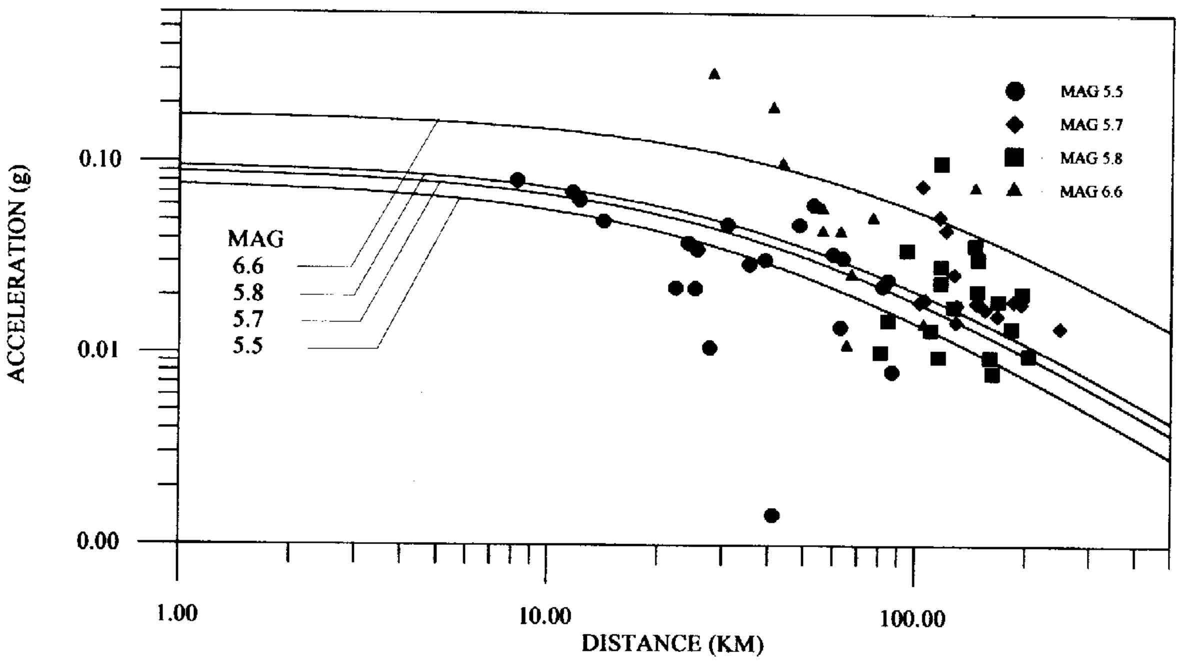

FIG. 3 Proposed new attenuation relationship plotted along with the data set used for the study.

Table 2

Regression coefficients and Residual sum of squares obtained by deleting one coefficient.

Parameter deleted	Computed coefficients	Residual sum of squares
None (present relationship)	c_1=-2.87(0.50), c_2= 0.634(0.08) c_3=0.62(0.06)	0.142
$e^{c_3 M}$	c_1=-3.54(0.801), c_2=0.690(0.690)	0.377
$c_2 M$	c_1=.762(0.113), c_3=0.579(0.085)	0.257
c_1	c_2=0.147(0.019), c_3=0.639(0.074)	0.229

To check the capability of the data to compute the regression coefficients, the constants c_1, c_2 and c_3 in equation (5) were first deleted one by one to compute the rest of the regression coefficients. The resulting equation has increased residual sum as given in Table 2. The increase in the residual sum of squares may be either due to dropping of certain parameter which means the parameter is needed or because of the model with smaller number of parameters which generally gives higher residuals. Therefore, further investigations with larger data set are needed in such case where the increase is small.

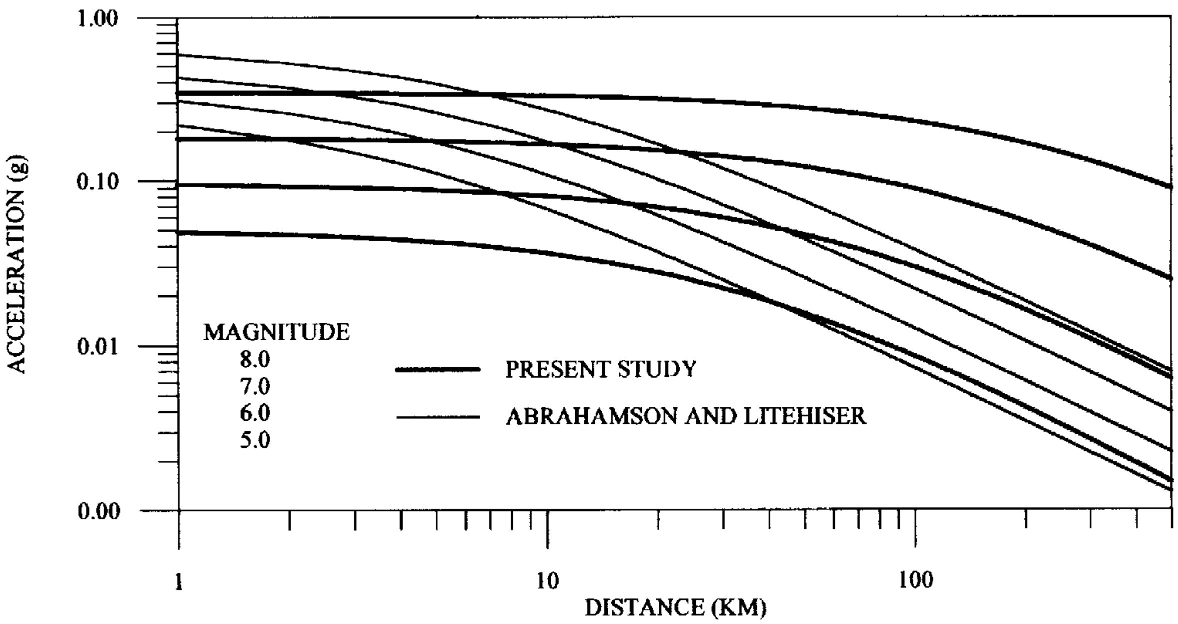

FIG. 4. Comparison of the newly developed attenuation relationship with the realtionship given by Abrahason and Litehiser (1989)

Since there are few strong motion recordings available, it is very difficult to have the reliable empirical relationship for the peak ground accelerations. But in absence of such data, one may verify the results with such relationships for other tectonically and geologically similar regions and compare them statistically. Only five earthquakes have been used in the final analysis which is a small data set for such type of analysis. The comparison is done with the relationship proposed by Abrahamson and Letihiser (1989)

$$\log(a) = -1.15 + 0.245\,M - 1.096\,\log(r + e^{0.256\,M}) + 0.096\,F - 0.0011\,Er \qquad (7)$$

where a is peak vertical acceleration, r is the distance in km to the closest approach of the zone of energy release, M is the magnitude, F is dummy variable that is 1 for reverse or reverse oblique fault otherwise 0, and E is a dummy variable that is 1 for interplate and 0 for intraplate events, have been considered. These relationships alongwith the proposed are plotted in fig. 4 for magnitudes 5.0, 6.0, 7.0 and 8.0. Close inspection of the figure suggests that proposed relationship gives lesser acceleration values at short distances and at larger distances it gives somewhat higher values of accelerations. It is, generally, observed that most of such empirical relationships give unrealistically high values of ground motion for large magnitudes at very close source-to-site distance (Sharma and Agrawal, 1994). The source-to-site distance in the empirical relations is defined from a fixed point on the fault under the assumption that the entire seismic energy originates from that point. The various definitions of source to site distance does not matter as long as the site is far away from the source (Gupta et al., 1994). The present relationship giving lesser values at shorter distance needs further investigations when more data is available in future.

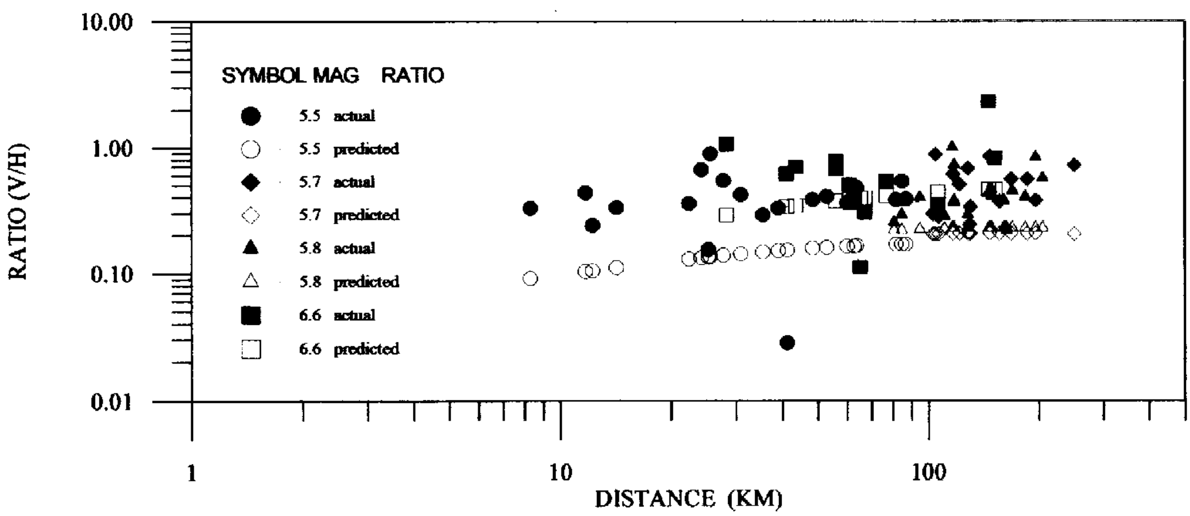

FIG. 5 Comparison of predicted and actual V/H ratio for different magnitudes.

The vertical to horizontal ratios of peak ground acceleration are estimated with reference to distance using the attenuation relationship developed for vertical peak ground acceleration in the present study and horizontal peak ground attenuation relationship developed on the same data earlier by Sharma (1998). The comparison of the actual (observed) to predicted V/H ratio is shown in fig. 5 for magnitudes 5.5, 5.7, 5.8 and 6.6. The comparison shows too much of scatter due to lack of data for magnitudes and distances (see fig. 2). The term $e^{c_3 M}$ in equation (5) is the most important parameter for the decay of the values with distance. c_3 is varied between 0.567 (parameter value for horizontal) to 0.20 and the regression analysis is carried out again to compute other parameters of the vertical peak ground acceleration attenuation relationship The sum of squares of residuals shows minor changes (c_3 = .567, 0.55, 0.5, 0.45, 0.40, 0.30, 0.20 and sum of squares of residuals is 0.1438, 0.1437, 0.1435, 0.1460, 0.1270, 0.475, 0.1490 respectively) which in turn shows that either the parameter is not important or the data set is very small. Table 3 shows that this term is important and that is why a larger set of data is required for upgradation of this attenuation relationship and the estimation of V/H ratio.

CONCLUSIONS

The peak ground vertical acceleration values recorded at 66 stations from five earthquakes have been used for the regression analysis to develop empirical relationship. The attenuation relationship as given in eq (6) has been proposed for the Himalayan region in India. This attenuation relationship needs upgradation as and when more and more data on strong ground motion is recorded in this region. The comparison of vertical to horizontal peak ground acceleration suggest further investigations using a larger data set.

ACKNOWLEDGMENT

The strong motion data for the study has been provided by the research scheme 'Strong Motion Arrays in India' sponsored by Department of Sciences and Technology, Govt. of India.

REFRENCES

Abrahamson, N. A. and J. J. Letihiser (1989), Attenuation of vertical peak accelerations, *Bull. Seis. Soc. Am.,* 79, 549-580.

Boore, D. M. and W. B. Joyner (1982) The empirical prediction of ground motion, *Bull. Seis. Soc. Am.,* Vol. 72, S43-S60.

Campbell, K. W. (1981) Near source attenuation of peak horizontal acceleration, *Bull. Seis. Soc. Am.,* 71, 2039-2070.

Campbell, K. W. (1985) Strong motion attenuation relations : A ten year perspective, *Earthquake Spectra*, Vol. 1, No. 4, 759-803.

Chandrasekaran, A. R. and Das, J. D.(1994) Analysis of Strong Motion Accelerograms of N.E. India Earthquake of January 10, 1990, *Report EQ.94-01, Department of Earthquake Engg., University of Roorkee, Roorkee, India.*

Chandrasekaran, A. R. and Das, J. D. (1993) Strong earthquake ground motion data in EQINFOS for India: Part 1B. Edited by M. D. Trifunac, M. I. Todorovski and V. W. Lee, *Report No. CE 93-04,* Roorkee, India and Los Angeles, California, March, 1993, pp 1-90.

Chandrasekaran, A. R. and Das, J. D.(1992) Strong motion arrays in India and analysis of data from Shillong array, Current Science, Vol. 62, No. 1&2, 233-250.

Fukushima, Y. and T. Tanaka (1990) A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan, *Bull. Seis. Soc. Am.,* Vol. 80, 757-783.

Gupta, I. D., T. V. S. Rama Krishna and V. C. Deshpande (1994) Predicting near source strong ground motion due to large magnitude earthquakes, *Proc. Xth Symp. on Eartheq. Engg.*, Roorkee, India, 73-82.

Joyner, W. B. and D. M. Boore (1981) Peak horizontal acceleration and velocity from strong motion records from 1979 Imperial Valley, California, earthquake, *Bull. Seis. Soc. Am.,* 71, 2011-2038.

Joyner, W. B. and D. M. Boore (1988) Measurement, characterisation, and prediction of strong ground motion, *Proc. Eartheq. Engg. and Soil Dyn. II GT Div/ASCE*, Utah, 43-102.

Sharma, M. L. (1998) Attenuation relationship for estimation of peak ground vertical acceleration using data from strong motion arrays in India, *Bull. Seis. Soc. Am.*, *88*, 1063-1069.

Sharma M. L., and P. N. Agrawal (1994) A comparative study of few attenuation relationships, *Proc. Xth Symp. on Eartheq. Engg.*, Roorkee, India, 169-176.

Tanaka, T. and Y. Fukushima (1987) Attenuation relations for peak amplitudes of earthquake ground motions, *Proc. Vth Eartheq. Ground Motion Symp.*, Arch. Inst., Japan, 7-16 (in Japanese).