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ANALYSIS OF STRONG MOTION ACCELEROGRAMS OF UTTARKASHI EARTHQUAKE OF OCTOBER 20, 1991

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ABSTRACT

In the very early hours of October 20, 1991 a moderately strong earthquake of magnitude about Mb 6.5 occurred in Uttarkashi region of U.P. Himalayas. Thirteen strong motion accelerographs have been triggered by this event. Peak values of acceleration, velocity and displacement as well as response and Fourier spectra were evaluated. Maximum acceleration recorded in a horizontal component was 3040 mm/s*s and in vertical direction was 2888 mm/s*s. Attenuation of observed acceleration is reasonably predicted by McGuire's relationship (McGuire, 1978). The normalized shape of spectra indicates higher values in the short period range as compared to USNRC spectra (WASH-1254, 1973). The mean value of characteristic frequency is 5.26 Hz in horizontal direction and 6.84 Hz in vertical direction.

INTRODUCTION

The Uttarkashi region in the State of Uttar Pradesh, India is in an active seismic zone and has been identified to be on the border of Zones IV and V (the most severe being Zone V) by the Bureau of Indian Standards (IS:1893-1984, 1986). Under a high priority research area of the Department of Science and Technology, Government of India, the research scheme entitled "Strong Motion Array" is under installation in the region by the Department of Earthquake Engineering, University of Roorkee, Roorkee. As of October 1991, 28 out of a planned 40 station array had been installed. Each station consists of a three component strong motion analog accelerograph, SMA-1 manufactured by M/S Kinemetrics, U.S.A. The location of these stations (only first four letters of the name of places are used) is shown in Figure 1.

At 02:53 hrs. (IST) on October 20, 1991 a moderately strong earthquake of body wave magnitude of about 6.5 (PDE, 1991) occurred in Uttarkashi region of U.P. Himalayas. The parameters as reported by United States Geological Survey (PDE, 1991) are as follows:

Origin Time: 21 hr 23 min 15.5 sec (GMT)
Latitude: 30.738 N Longitude : 78.792 E
Focal Depth : 19 km
Mb=6.5 and Msz=7.1

This earthquake caused a lot of damage to poorly constructed buildings in the epicentral region. About 2000 people lost their lives.

All the 28 stations were inspected after the event and 13 stations were found to have recorded the event. These 13 stations are Almora, Barkot, Bhatwari, Ghansiali, Karnprayag, Kosani, Koteshwar, Koti, Purola, Rudraprayag, Srinagar, Tehri and Uttarkashi (figure 1). Table 1 gives duration and peak value of accelerations recorded at the stations. At 13 other stations, the instruments were found to be functional but they did not trigger due to acceleration level of ground motion being lower than triggering threshold level of the instrument at those sites, say, less than one percent of gravity. At two stations, the power supply had malfunctioned.

The records have been duly processed using standard procedures (Lee and Trifunac, 1979; Chandrasekar and Das, 1990a).

This paper gives the peak value of ground acceleration, velocity and .displacement for the three component of motion at each station (Table 2). The peak values of resultant of the two horizontal components were evaluated and it is seen that the two orthogonal components generally have a low correlation (Table 4). The attenuation of peak values of acceleration for horizontal and vertical component with respect to distance from the epicenter has been plotted (figures 4 and 5). The root mean square acceleration and predominant frequency (Kennedy and Short, 1985) has been worked out for each component of acceleration record.

Response Spectra and Fourier Spectra have been worked out for each record. Mean and standard deviation for normalized shape of spectra have been obtained (Table 5). The records were normalized with respect to a peak ground acceleration of unit gravity. The shape (figures 8a,b and 9a,b) clearly indicates a concentration of energy in short period range which is also reflected in the type of damage to heavy unreinforced structures. There is a rapid attenuation at long periods which indicate that high rockfill dams would be relatively safer in such earthquake.

The process of digitizing analog accelerograms would clip some high frequency peaks. In one case, closest to the epicenter, one of the peaks of the vertical component of corrected acceleration record was arbitrarily raised from peak value of 2888 mm/s*s to a value of 3600 mm/s*s and the resultant spectra compared with that of original record. The spectra shows very little difference. For engineering purposes, therefore, it may be concluded that a stray large peak in a record is of no consequence.

The analysis of the records indicate a rapid attenuation of (i) acceleration with respect to distance and (ii) response spectra with respect to period in the long period range.

The information obtained would be very valuable for design of engineering structures in this segment of Himalayan region.

ANALYSIS OF PEAK VALUES

The filter settings of the ORMSBY filter used in this study are 0.17-0.20 Hz and 25.0-27.0 Hz (Chandrasekaran and Das, 1989,1990a). There are several procedures of strong motion data processing and all of them would give nearly the same corrected acceleration values. The derived velocity could be somewhat different marginally but the derived displacement could vary considerably.

Table 2 gives a listing of peak values of acceleration, velocity and displacement at the thirteen stations. The largest motion in a horizontal component was at Uttarkashi and in a vertical component at Bhatwari. The acceleration and velocity values at various stations are plotted in figure 2.

Figures 3a to 3d show the corrected accelerograms at Bhatwari, Uttarkashi, Ghansiali and Barkot. At these stations, the horizontal motion had exceeded 10% gravity.

Table 3 gives the peak values of acceleration in the two horizontal components of earthquake motion and the resultant values of peak acceleration obtained by vector addition. It is seen that the resultant peak is not very much higher than that of the larger of the two horizontal components indicating generally a low correlation. This is also confirmed by the perusal of the correlation coefficient (Bendat and Piersol, 1971) obtained for the two horizontal components at all the stations as given in Table 4.

Figures 4 and 5 show the attenuation of peak acceleration (in case of horizontal component- the larger of the two) with respect to distance of the stations from epicenter (Epicenter postulated by USGS). For comparison, McGuire's attenuation relationship (McGuire, 1978), (which is one of the popularly used empirical formula) has also been plotted. It is seen that McGuire's relationship is a reasonable fit in most of the range. Incidentally, the April 26, 1986 event in the Kangra region (Chandrasekaran, 1986) also showed a similar attenuation relationship with respect to distance (Das and Chandrasekaran, 1990)

ROOT MEAN SQUARE ACCELERATION (RMS)

It is now well realized that stray peak of acceleration is not an index of the damaging potential of an accelerogram. More often, in design, effective peak acceleration is used in conjunction with a normalized shape of spectra. RMS acceleration has been proposed as a measure of effective peak acceleration (Kennedy and Short, 1985) and is defined as follows:

Let E(t) denote the cumulative energy per unit mass at time t of the record where $E(t) = \int^{t} a^2(t).dt$. TV denotes effective duration and is equal to time taken between E>»«» and E>»>» and maximum value E_m is measured at 0.95 of total duration of record.

Then

$$a_{rms} = \sqrt{\frac{E(T_D)}{T_D}}$$

The RMS values for the accelerograms, recorded during this earthquake, are shown in Figures 6a and b in the form of a ratio to the peak value of accelerations.

The mean value of the ratio of RMS to maximum peak acceleration is 0.331 for horizontal component and 0.325 for vertical component.

CHARACTERISTIC MEAN FREQUENCY

Sometimes, number of zero crossings in an arbitrarily selected time window of acceleration record has been used as a measure of characteristic frequency. A better definition has been proposed in (Kennedy and Short, 1985) and it is as follows.

The mean frequency is square root of ratio of second and zero moment, $\Omega = \sqrt{\lambda_2 / \lambda_0}$. where λ_i is defined in terms of Power Spectral Density function G(f)

$$\lambda_i = \int_0^{\infty} f^i . G(f) . df$$

The value of characteristic frequency is shown in Figures 7a and b.

The mean value of this characteristic frequency is 5.26 Hz for horizontal components and 6.84 Hz for vertical component.

RESPONSE SPECTRA

Response spectra derived from these accelerograms is of utmost engineering interest. Response Spectrum values for various periods and damping have been evaluated for all the 39 accelerograms.

This data has been statistically analyzed to obtain mean and mean+sigma shape of spectra by normalizing the values corresponding to zero period acceleration of unit gravity.

Figures 8a and b show plot of mean and mean+sigma normalized shape of spectra for horizontal and vertical components. In order to eliminate any bias of records where the peak accelerations are small, the shape of spectra has also been obtained by eliminating horizontal components having peak acceleration below 0.04g and vertical components below 0.02g (Figures 9a and b). Table 5 gives mean and mean+sigma values of spectra. In the present set of records, the shape has not been affected by this bias, as only five out of 26 in horizontal and three out of 13 in vertical direction had low values of acceleration. From the shape of spectra it could be seen that energy is concentrated in the low period range and the shape attenuates rapidly with increase in period. Further, comparing with the standard shape of spectra proposed by USNRC (WASH-1254, 1973), it is seen that the values are higher in the short period range and considerably lower in the long period range. Further, USNRC spectra is not that conservative in short period range for this tectonic setup.

FOURIER SPECTRA

Fourier Spectra gives an idea of the energy associated in various frequencies that are contained in the waveform of ground motion. The Fourier velocity components have also been normalized with respect to peak ground acceleration of unit gravity and mean and mean+sigma values obtained for all the records and are shown in Figure 10.

Shinozuka et al., 1984 had proposed Power Spectral Density (PSD) function compatible with USNRC Spectra. The PSD is given by

$$S_0(w) = S_0 \frac{1+4\ \beta_g^2\ (w/w_g)^2}{\left[1-(w/w_g)^2\right]^2 + 4\ \beta_g^2\ (w/w_g)^2}$$

with $S_0 = 7096.76\ cm^2/sec^3$ $w_g = 10.66$ rad/sec and $\beta_g = 0.9793$

PSD function can be converted into Fourier amplitudes by assuming an effective time duration of ground motion of 20 seconds. This Fourier spectra (Shinozuka) is also plotted in Figure 10. It could be noted that the Shinozuka spectra lies between mean and mean+sigma Fourier spectra in low frequency range upto 2.5 Hz and beyond 13 Hz it is above mean+sigma spectra. Since, the Fourier amplitudes are anyway smaller beyond 13 Hz it could be seen that the proposed PSD function of Shinozuka is not that conservative when compared with the data for this event.

EFFECT OF STRAY HIGH PEAK IN AN ACCELEROGRAM

Motion near epicenter, particularly the vertical component has energy concentrated in high frequency range. The current practice of digital signal processing of an analog signal uses data samples at equal interval of time. In such process, there is a possibility of a peak occurring between the sampled data. This is so in the case of vertical component of the acceleration record at Bhatwari. The peak of the corrected acceleration data (by the data processing technique adopted) was 2888 mm/s*s. A visual inspection of the record with approximate scaling may indicate a peak of 3600 mm/s*s.

In order to check whether a stray large peak has any influence on the response spectra, the peak acceleration value was arbitrarily raised from 2888 cm/s*s to 3600 cm/s*s. Figure 11 shows a comparison of response spectra corresponding to 5% damping. It is seen that the two spectra are nearly identical. Thus, stray large peak has no engineering significance.

CONCLUSIONS

Strong motion data has been obtained for the first time from U.P. Himalayas. The vertical component recorded was strongest so far from any region in Himalayas. The pattern of attenuation of ground motion and normalized shape of response spectra is quite similar to that observed in Kangra region. However, these characteristics are quite different from that of Northeast India (Chandrasekaran and Das, 1989, 1990a, 1990b).

This data would be very useful for design of engineering structures in this region.

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TABLE 1

DURATION AND PEAK VALUE OF HORIZONTAL COMPONENT OF ACCELERATION AT STATIONS

STATIONS	DURATION OF RECORDS IN SEC	EFFECTIVE DURATION T_D IN SEC	MAX.PEAK ACC IN g	TIME OF OCCURRENCE OF PEAK FROM START IN SEC.
ALMORA	21.5	11.64	0.021	1.62
BARKOT	32.0	8.08	0.093	6.06
BHATWARI	42.0	8.34	0.289	4.76
GHANSIALI	42.5	10.82	0.115	6.40
KARNPRAYAG	22.4	4.78	0.077	3.06
KOSANI	13.5	10.40	0.032	11.80
KOTESHWAR	34.0	4.32	0.099	7.80
KOTI	16.0	2.24	0.041	0.22
PUROLA	36.0	9.06	0.092	5.67
RUDRAPRAYAG	39.8	8.86	0.052	10.20
SRINAGAR	41.3	10.90	0.065	9.70
TEHRI	32.2	6.22	0.071	8.28
UTTARKASHI	42.0	9.60	0.304	5.90

TABLE 2

SUMMARY OF STRONG MOTION DATA

UTTARKASHI EARTHQUAKE OCTOBER 20, 1991 UTTAR PRADESH, INDIA

S. NO.	LOCATION	COMPONENT	DERIVED MAXIMUM PEAK GROUND ACCELE-RATION IN CM/ SEC/SEC	DERIVED MAXIMUM PEAK GROUND VELOCITY (MM/SEC)	DERIVED MAXIMUM PEAK GROUND DISP-LACEMENT (MM)
1	2	3	4	5	6
1.	ALMORA	L-N 53 W	17.41	13.32	3.42
		V-VERT	18.44	15.48	3.98
		T-N 37 E	21.02	12.62	4.50
2.	BARKOT	L-N 10 E	93.18	57.87	10.93
		V-VERT	43.65	27.53	5.62
		T-N 80 W	80.47	44.84	6.98
3.	BHATWARI	L-N 85 E	248.37	178.73	37.54
		V-VERT	288.78	133.65	23.53
		T-N 05 W	241.89	297.78	53.23
4.	GHANSIALI	L-N 00 E	115.59	80.44	13.57
		V-VERT	99.23	95.94	25.90
		T-N 90 E	114.89	78.21	13.37
5.	KARNPRAYAG	L- -----	60.99	36.90	5.90
		V-VERT	25.96	14.98	2.17
		T- -----	77.35	37.30	4.02
6.	KOSANI	L-N 25 W	28.34	18.82	3.77
		V-VERT	11.04	9.17	2.41
		T-N 65 E	31.50	15.55	2.86
7.	KOTESHWAR	L-N 30 W	98.85	51.55	11.14
		V-VERT	74.34	85.25	20.47
		T-N 60 E	65.23	39.27	6.78

Table 2 contd...

1	2	3	4	5	6
8.	KOTI	L-N 10 E	20.64	23.43	4.27
		V-VERT	14.26	17.65	5.05
		T-N 80 W	40.95	28.60	3.40
9.	PUROLA	L-N 65 W	73.95	48.13	8.44
		V-VERT	51.74	25.57	4.49
		T-N 25 E	91.68	45.91	9.22
10.	RUDRAPRAYAG	L- -----	52.29	20.70	7.85
		V-VERT	44.13	17.92	3.83
		T- -----	50.76	27.06	4.01
11.	SRINAGAR	L- -----	65.44	19.45	5.86
		V-VERT	33.09	35.25	7.62
		T- -----	49.45	20.20	5.07
12.	TEHRI	L-N 63 W	71.41	42.15	8.17
		V-VERT	57.82	88.41	23.68
		T-N 27 E	61.13	92.30	19.84
13.	UTTARKASHI	L-N 15 W	237.27	169.56	21.15
		V-VERT	192.62	141.56	22.98
		T-N 75 E	303.99	194.68	19.85

TABLE 3

RESULTANT PEAK GROUND ACCELERATION OF TWO HORIZONTAL COMPONENTS RECORDED AT STATIONS

STATIONS	COMPONENT LONGITUDE (cm/s*s)	COMPONENT TRANSVERSE (cm/s*s)	RESULTANT (cm/s*s)
ALMORA	17.40	21.01	22.27
BARKOT	93.18	80.47	103.88
BHATWARI	248.40	241.80	271.63
GHANSIALI	115.60	114.90	141.98
KARNPRAYAG	60.98	77.34	84.74
KOSANI	28.33	31.49	31.58
KOTESHWAR	98.84	65.23	99.08
KOTI	20.64	40.94	41.09
PUROLA	73.94	91.68	96.13
RUDRAPRAYAG	52.29	50.76	65.27
SRINAGAR	65.44	49.44	65.77
TEHRI	71.41	61.12	73.63
UTTARKASHI	237.20	304.00	313.09

TABLE 4

CORRELATION COEFFICIENT BETWEEN THE TWO HORIZONTAL COMPONENTS

STATION	CORRELATION COEFFICIENT	STATION	CORRELATION COEFFICIENT
ALMORA	0.132002	KOTI	0.045154
BARKOT	0.154385	PUROLA	0.389840
BHATWARI	0.360287	RUDRAPRAYAG	0.232426
GHANSIALI	0.036798	SRINAGAR	0.164316
KARNPRAYAG	0.340744	TEHRI	0.125726
KOSANI	0.024766	UTTARKASHI	0.060516
KOTESHWAR	0.119300		

TABLE-5

MEAN AND MEAN+SIGMA VALUES OF NORMALIZED SPECTRA USING 13 STATIONS DATA

Period	Mean(H)	Mean+ Sigma(H)	Mean(V)	Mean+ Sigma(V)	Mean(H)	Mean+ Sigma(H)	Mean(V)	Mean+ Sigma(V)
	All Records		All Records		cut off g=0.04		cut off g=.02g	
1	2	3	4	5	6	7	8	9
0.040	1.069	1.155	1.151	1.314	1.079	1.172	1.143	1.305
0.042	1.069	1.156	1.139	1.294	1.080	1.174	1.129	1.271
0.044	1.075	1.163	1:149	1.308	1.086	1.180	1.142	1.268
0.046	1.081	1.166	1.191	1.362	1.089	1.181	1.193	1.350
0.048	1.091	1.176	1.239	1.456	1.098	1.190	1.258	1.475
0.050	1.114	1.233	1.256	1.483	1.126	1.255	1.284	1.521
0.055	1.173	1.320	1.347	1.715	1.190	1.356	1.427	1.811
0.060	1.220	1.397	1.402	1.869	1.244	1.433	1.570	1.959
0.065	1.283	1.536	1.723	2.232	1.310	1.585	1.865	2.347
0.070	1.390	1.766	1.861	2.536	1.418	1.830	2.042	2.711
0.075	1.470	1.993	2.027	2.780	1.510	2.000	2.233	2.974
0.080	1.602	2.380	2.253	3.190	1.669	2.523	2.511	3.433
0.085	1.733	2.660	2.254	3.167	.1.839	2.841	2.501	3.405
0.090	1.859	2.793	2.293	3.152	1.991	2.905	2.527	3.360
0.095	1.912	2.715	2.391	3.299	2.036	2.802	2.626	3.526
0.100	1.958	2.733	2.443	3.387	2.079	2.896	2.669	3.615
0.110	2.213	3.313	2.533	3.424	2.363	3.535	2.690	3.621
0.120	2.335	3.531	2.532	3.407	2.469	3.761	2.693	3.617
0.130	2.403	3.400	2.413	3.173	2.470	3.642	2.607	3.360
0.140	2.513	3.373	2.255	2.803	2.550	3.472	2.390	3.017
0.150	2.679	3.500	2.215	2.873	2.601	3.600	2.336	3.007
0.160	2.631	3.459	2.246	2.890	2.505	3.373	2.344	3.039
0.170	2.736	3.681	2.187	2.799	2.600	3.583	2.264	2.939
0.180	2.606	3.714	2.218	2.901	2.643	3.679	2.256	3.019
0.190	2.630	3.603	2.333	3.243	2.507	3.602	2.373	3.416
0.200	2.651	3.595	2.306	3.094	2.599	3.507	2.322	3.229
0.220	2.625	3.424	2.191	2.790	2.560	3.442	2.166	2.041
0.240	2.743	3.602	2.182	2.918	2.735	3.609	2.071	2.050
0.260	2.690	3.500	1.934	2.605	2.743	3.664	1.801	2.714
0.280	2.676	3.575	1.737	2.340	2.690	3.671	1.600	2.224
0.300	2.510	3.452	1.696	2.201	2.523	3.545	1.540	2.120
0.320	2.400	3.510	1.792	2.433	2.326	3.506	1.529	1.936
0.340	2.421	3.719	1.763	2.470	2.337	3.759	1.443	1.851
0.360	2.242	3.467	1.602	2.344	2.204	3.561	1.397	1.705
0.380	2.040	3.000	1.490	2.057	2.033	3.175	1.266	1.613
0.400	1.911	2.755	1.305	1.842	1.807	2.762	1.209	1.513

Table 5 contd...

1	2	3	4	5	6	7	8	9
0.420	1.812	2.469	1.323	1.713	1.815	2.408	1.196	1.511
0.440	1.706	2.266	1.289	1.664	1.735	2.311	1.217	1.609
0.460	1.604	2.073	1.230	1.575	1.632	2.099	1.164	1.500
0.480	1.494	1.892	1.194	1.484	1.526	1.906	1.120	1.390
0.500	1.429	1.797	1.171	1.423	1.469	1.833	1.114	1.367
0.550	1.310	1.770	1.147	1.454	1.339	1.822	1.110	1.443
0.600	1.301	1.972	1.093	1.477	1.331	2.052	1.046	1.435
0.650	1.183	1.906	1.063	1.434	1.187	1.972	1.025	1.411
0.700	1.016	1.585	1.043	1.441	1.007	1.618	0.997	1.391
0.750	0.975	1.486	1.044	1.403	0.937	1.423	0.990	1.309
0.800	0.929	1.412	1.004	1.640	0.895	1.328	1.016	1.308
0.850	0.900	1.446	1.110	1.809	0.874	1.371	0.996	1.396
0.900	0.873	1.497	1.057	1.728	0.854	1.436	0.947	1.429
0.950	0.830	1.441	0.989	1.589	0.816	1.397	0.914	1.470
1.000	0.763	1.310	0.964	1.579	0.762	1.303	0.904	1.537
1.100	0.666	1.150	0.979	1.681	0.667	1.177	0.909	1.579
1.200	0.619	1.091	0.887	1.510	0.629	1.126	0.847	1.400
1.300	0.552	0.970	0.823	1.377	0.565	1.015	0.813	1.410
1.400	0.473	0.817	0.756	1.290	0.484	0.840	0.749	1.345
1.500	0.409	0.700	0.669	1.180	0.410	0.730	0.693	1.261
1.600	0.355	0.605	0.592	1.050	0.358	0.620	0.631	1.140
1.700	0.315	0.540	0.535	0.925	0.321	0.560	0.550	0.999
1.800	0.291	0.502	0.490	0.820	0.290	0.531	0.497	0.867
1.900	0.263	0.446	0.453	0.739	0.269	0.472	0.445	0.756
2.000	0.230	0.393	0.412	0.656	0.239	0.409	0.395	0.650
2.200	0.204	0.315	0.336	0.499	0.197	0.312	0.315	0.479
2.400	0.170	0.250	0.285	0.415	0.157	0.239	0.269	0.395
2.600	0.153	0.239	0.244	0.356	0.134	0.199	0.228	0.343

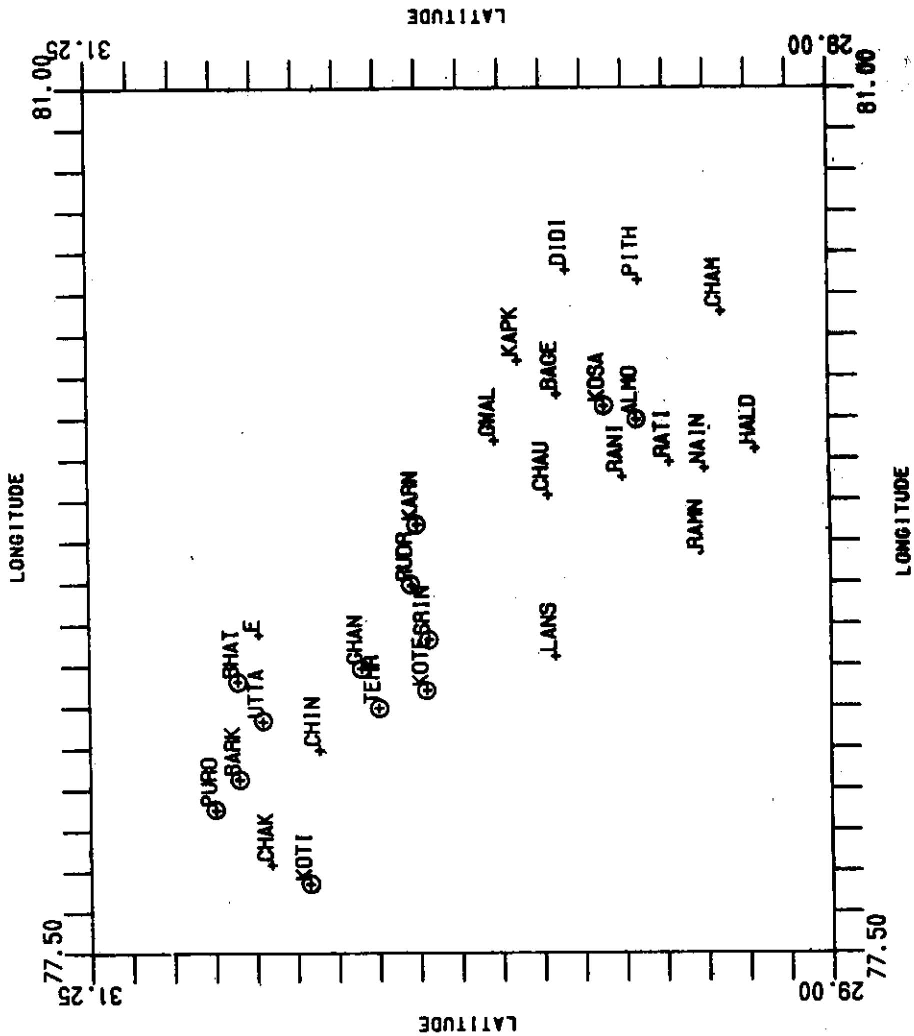

Fig. 1 Location of strong motion array stations in U.P. hills. ⊕ - Stations recorded earthquake of October 20,1991. E - Epicentre.Only first four letters of name of the places are used

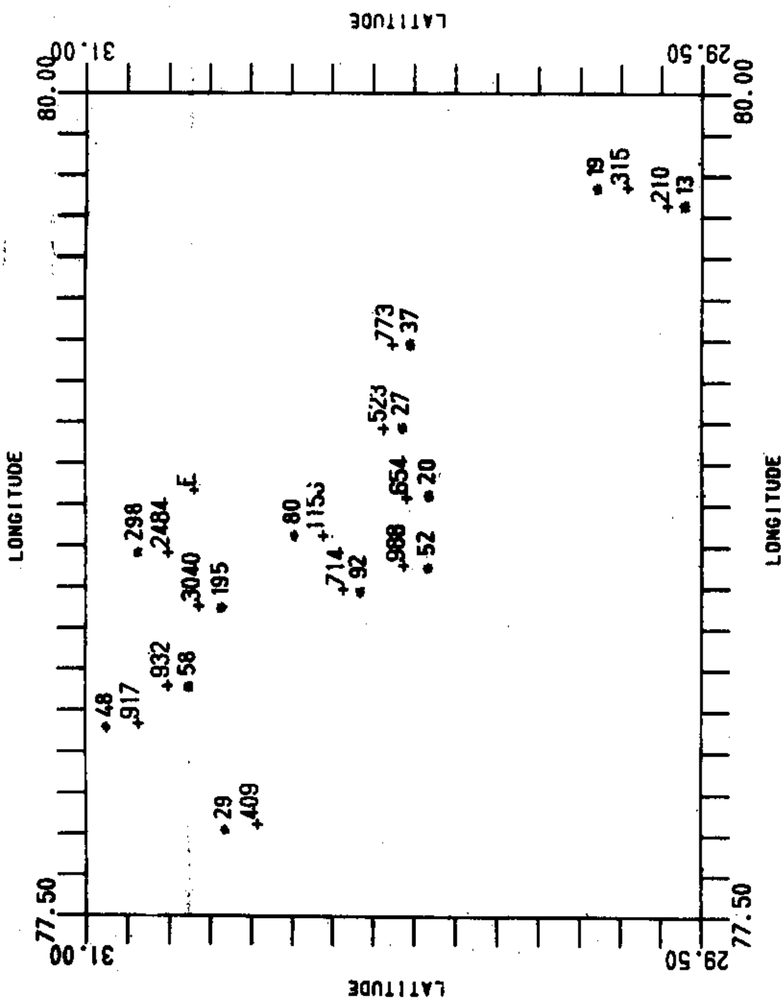

Fig. 2 Maximum peak horizontal acceleration (mm/s*s), velocity (mm/s) and epicentre (E) for October 20,1991 event. + - Acceleration, also mark station locations, * - velocity

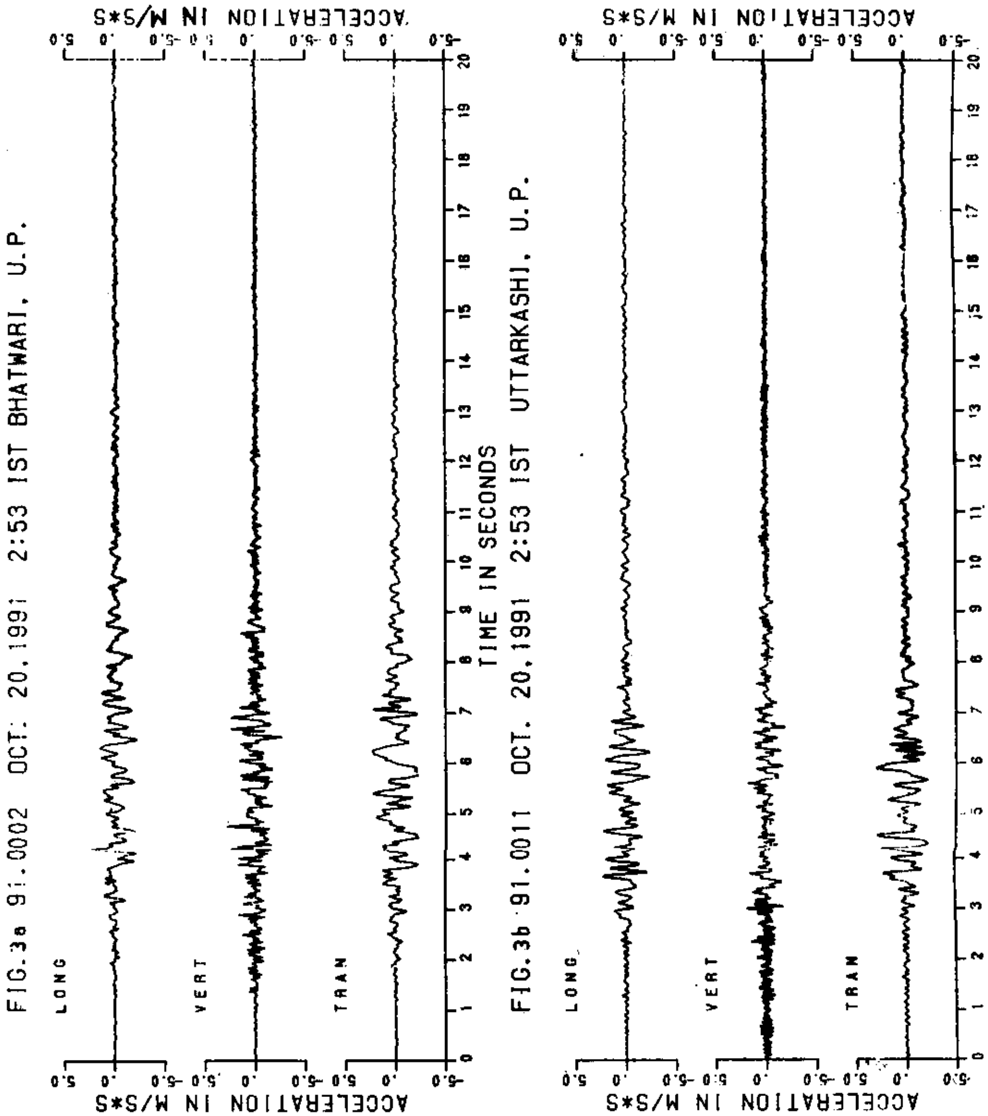

FIG.3a 91.0002 OCT. 20,1991 2:53 IST BHATWARI, U.P.

FIG.3b 91.0011 OCT. 20,1991 2:53 IST UTTARKASHI, U.P.

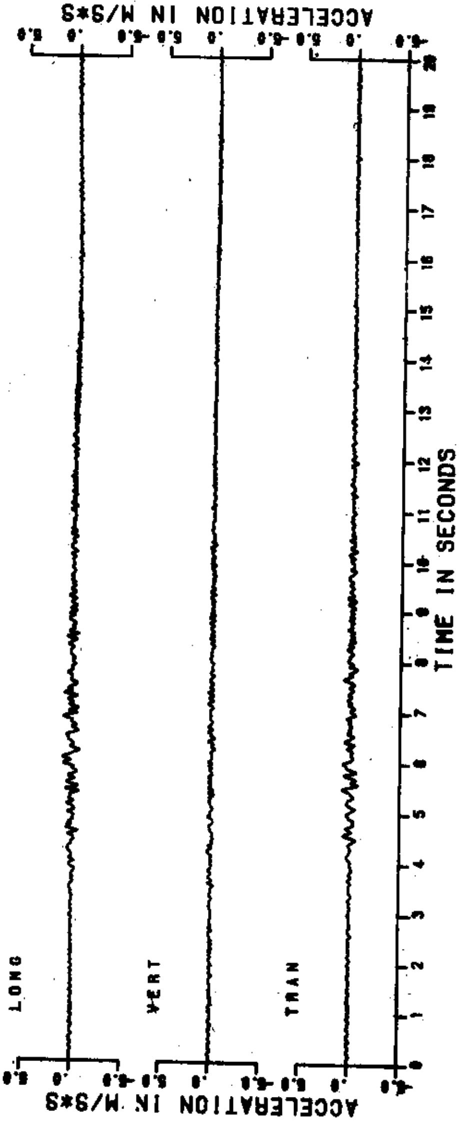

FIG.3c 91.0001 OCT. 20,1991 2:53 IST BARKOT. U.P.

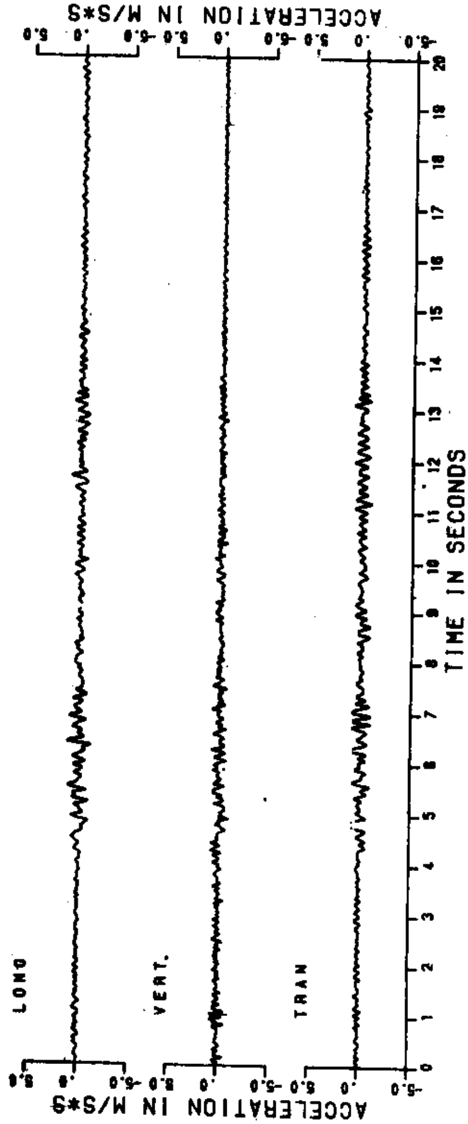

FIG.3 d 91.0003 OCT. 20,1991 2:53 IST GHANSIALI, U.P.

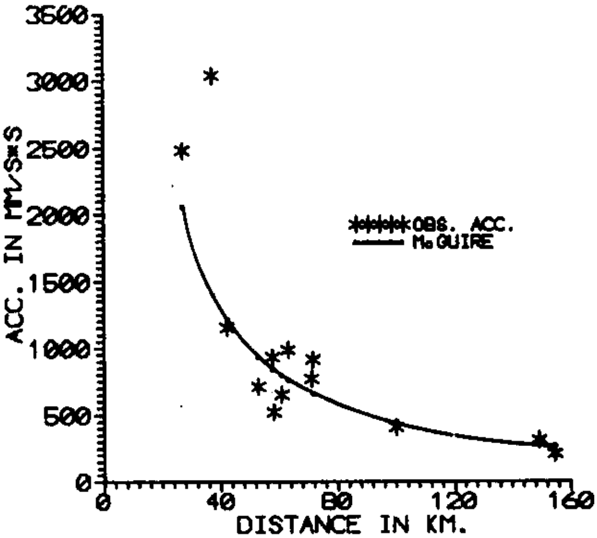

FIG.4 ATTENUATION W.R.T. USGS EPICENTER USING McGUIRE EMPIRICAL FORMULA (HORIZ).

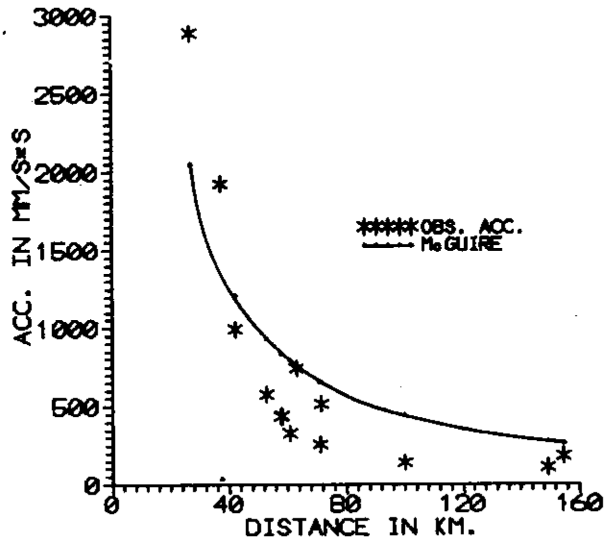

FIG.5 ATTENUATION W.R.T. USGS EPICENTER USING McGUIRE EMPIRICAL FORMULA (VERT).

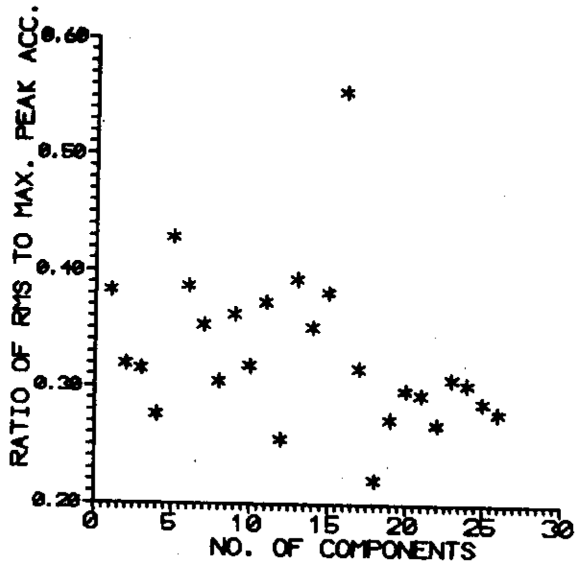

FIG.6a DISCRETE PLOT BETWEEN RATION OF RMS TO MAX. PEAK ACC. AND NO. OF RECORDS (HORIZ. COMP.)

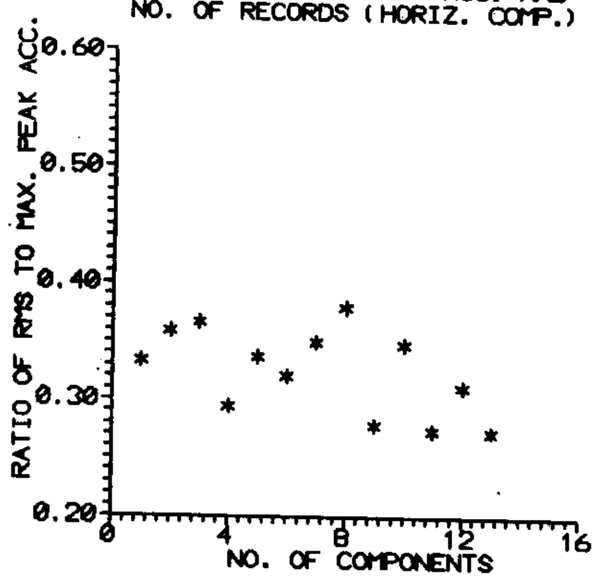

FIG.6b DISCRETE PLOT BETWEEN RATIO OF RMS TO MAX. PEAK ACC. AND NO. OF RECORDS (VERT. COMP.)

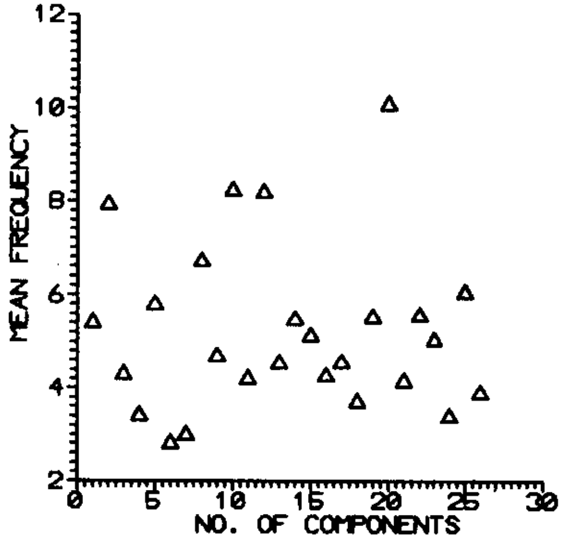

FIG.7a DISCRETE PLOT BETWEEN MEAN FREQUENCY AND NO. OF RECORDS. (HORIZ. COMP.)

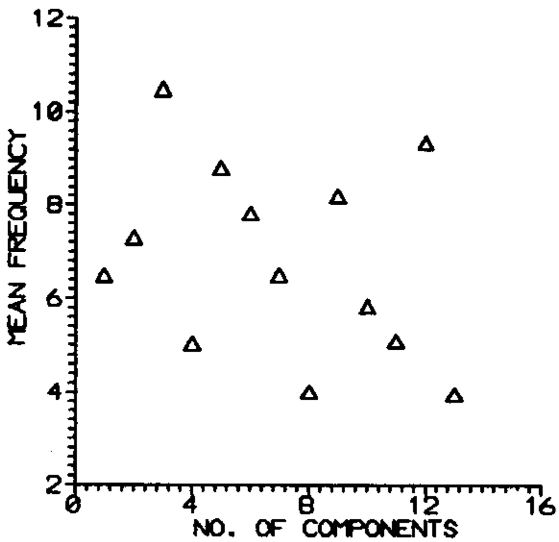

FIG.7b DISCRETE PLOT BETWEEN MEAN FREQUENCY AND NO. OF RECORDS. (VERT. COMP.)

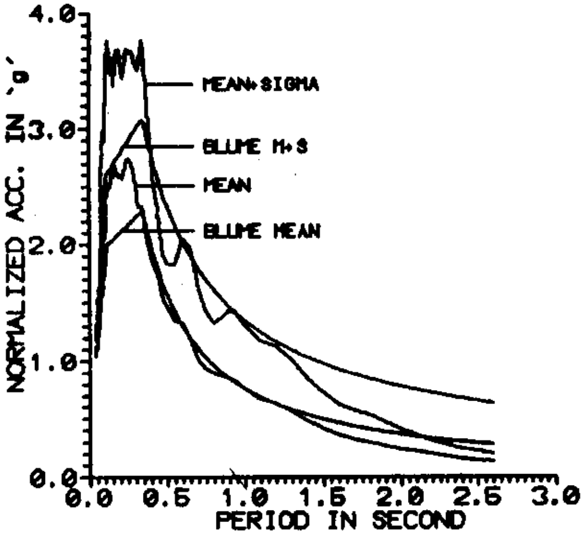

FIG.8a MEAN AND MEAN+SIGMA SHAPE OF RESPONSE SPECTRA (5% D)-HORIZ.

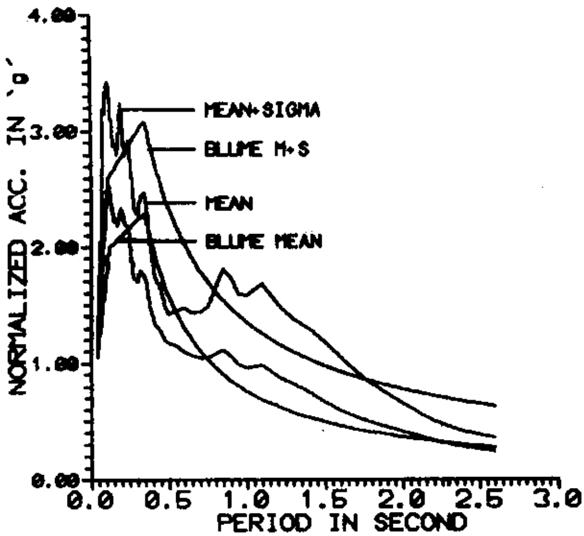

FIG.8b MEAN AND MEAN+SIGMA SHAPE OF RESPONSE SPECTRA (5% D)-VERT.

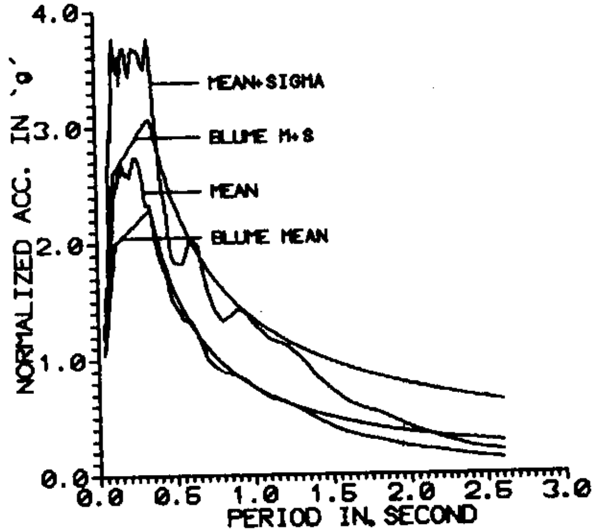

FIG.9a MEAN AND MEAN+SIGMA SHAPE OF RESPONSE SPECTRA (5% D)-HORIZ. (Selected Records H=0.04g)

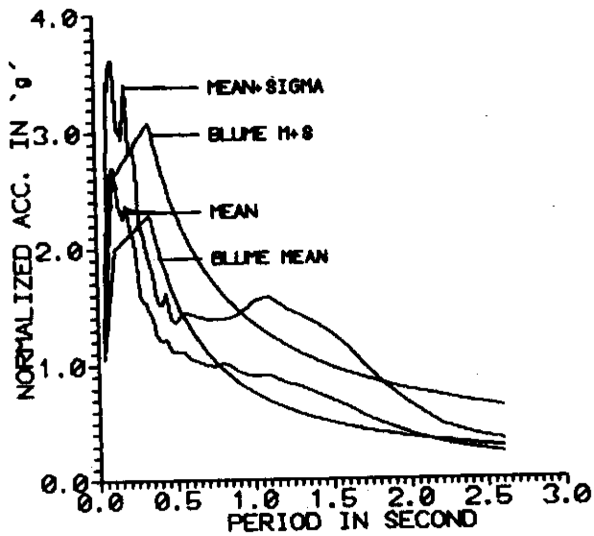

FIG.9b MEAN AND MEAN+SIGMA SHAPE OF RESPONSE SPECTRA (5% D)-VERT. (Selected Records V=0.02g)

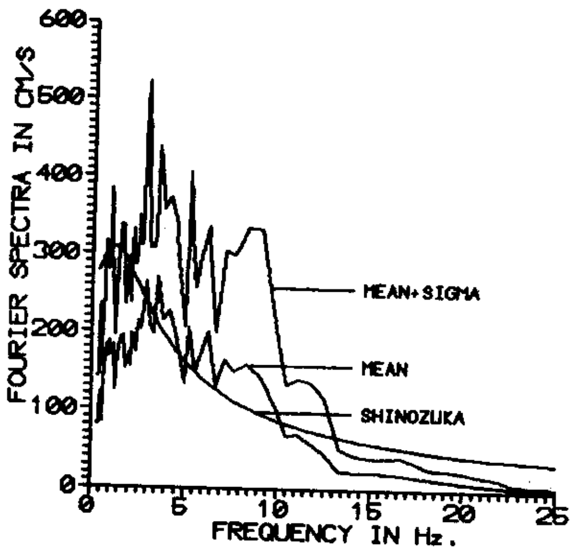

FIG.10 NORMALIZED FOURIER SPECTRA FOR HORIZONTAL COMPONENTS

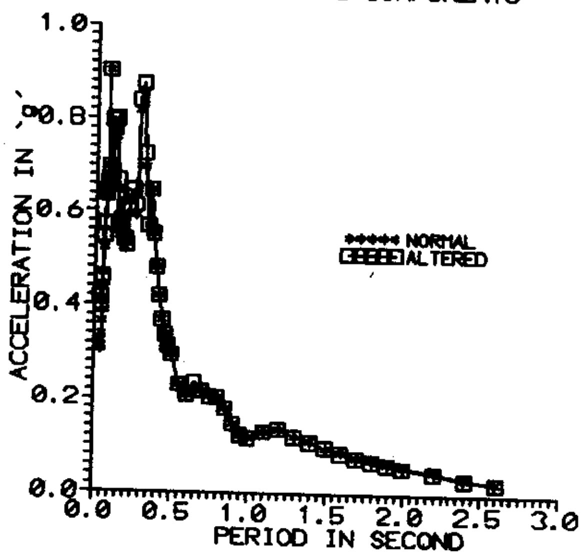

FIG.11 COMPARISON OF RESPONSE SPECTRA FOR A MODIFICATION OF TIME HISTORY.