Paper No. 176, Bulletin, I. S. E. T. Vol. 14, No. 3, pp. 83–100 September 1977

SITE DEPENDENT SPECTRA FOR ASEISMIC DESIGN

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INTRODUCTION

For aseismic design of structures, the ground motion data is assumed either in the form of an accelerogram or indirectly in the form of response spectra. The usual measures of response are maximum relative displacement which is a measure of the strain in the spring element of the system, maximum relative velocity which is a measure of the energy absorption in the spring of the system and maximum acceleration which is a measure of the maximum force in the spring system. The response spectra approach is generally used for design of ordinary structures and also for preliminary analysis of important ones where a number of trials may be required to arrive at the final result.

Engineers associated with the problems of earthquake resistant design have been concerned about the vital problem of choosing suitable response spectra for a particular site. This is a difficult problem because of the difficult nature of parameters involved in it.

The various earthquake parameters which influence the ground motion characteristics (peak ground acceleration, frequency and duration) are magnitude of earthquake, depth of focus, epicentral distance and source mechanism. The ground motion characteristics are further influenced by the geologic and soil conditions at the site, viz. depth of various soil layers their inclination as well as properties, type of intervening soil, depth of water table etc. Prediction of a precise and exact response spectra at a site in a deterministic way is not possible due to uncertain nature of parameters involved. Therefore an average spectra depending upon local site condition should be used for aseismic design of structures. This would necessarily require a large number of recorded earthquakes of approximately same magnitude and epicentral distance as the expected, on ground conditions similar to those of the site. Such an average spectra could then be expected to reflect the average values of various parameters at the site. Response curves for various confidence level has also been drawn.

Housner(3) was the first to propose an average response spectra and also the normalising (multiplying) factors for four actural recorded strong motion earthquakes. Kuribayashi et al.(4) studied the effect of magnitude, maximum acceleration, epicentral distance and soil condition and proposed average response spectra for rock, diluvial layers, stiff and soft soil. Hayashi et al.(2) proposed the response spectra for (i) dense sands and gravels, (ii) the soil of intermediate characteristics and (iii) extremely loose soil. Newmark(5, 6) also proposed smoothened response spectrum curves which could be applied to alluvial sites. Seed, Ugas and Lysmer(8,9) in 1974 analysed 104 records and proposed response spectra for (i) rock (ii) stiff soil (iii) deep cohesionless soils and (iv) soil deposits consisting of soft to medium clay, Chandrasekaran and Paul(1) have proposed the average response spectra for alluvial sites based on 50 earthquake records.

Earlier it was felt that peak ground acceleration was the only parameter which could describe the intensity of earthquake motion at a site and therefore was used for normalising the response spectra. However in order to estimate the peak acceleration,

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one has to resort to an empirical relationship correlating it with Magnitude, focal depth and epicentral distance. There are a number of empirical relationships now available for computing the peak ground acceleration but it is difficult to choose a suitable empirical relationship for use at a particular site. Similarly other criteria like peak ground velocity, ad/v^2 (where a, v, d are the peak ground acceleration, velocity and displacement) and spectral intensity could also be used as normalising factors alongwith peak ground acceleration. In the present study five methods of normalising the response spectra viz (i) peak ground acceleration, (ii) peak ground velocity, (iii) ad/v^2, (iv) spectral intensity for zero percent damping and (v) spectral intensity for five percent damping, have been examined and it is shown that peak ground acceleration is the most suitable parameter for normalising the response spectra. Based on this, average response spectra for rock and alluvial sites have been proposed.

It has been shown that a response spectra for a particular confidence level can be derived from statistical studies based on actual recorded earthquakes. The response spectra for horizontal and vertical vibration for different confidence levels are also given.

DATA ANALYSED

The earthquake records used for spectral analysis have been recorded at free field stations or in the basement of tall buildings. The free field motion is modified due to the presence of structure. In this analysis it is assumed that the influence of structure on the free field motion is small and therefore this effect has been ignored.

Thirty three records of accelerograms that were reported to be on rock site, taken from five earthquakes were considered for spectral analysis for rock site. As large number of records are from San Fernando earthquake, the sample is influenced by this earthquake. The magnitudes of records considered, ranges from 5.25 to 7.6 and epicentral distance ranges from 7 to 62 km. For horizontal response spectra, selection of accelerogram records were limited to those in which the peak ground acceleration is greater than 0.05 g. The associated sixteen earthquake records were considered for evaluation of vertical response spectra.

Forty earthquake records that were reported to be on alluvial site, taken from five earthquakes were considered for spectral analysis. This sample of records is also influenced by San Fernando earthquake. The magnitude of records considered ranges from 5.6 to 7.7 and epicentral distance ranges from 18 to 124 km. For horizontal response spectra selection of accelerogram records was limited to those in which the peak ground acceleration is greater than 0.03 g. The associated twenty earthquake records were considered for vertical response spectra. Tables 1 and 2 give the data for rock site used for analysis of horizontal and vertical response spectra respectively. Table 3 and 4 give same for alluvial site. The above data were taken from the references (7, 10, 11).

ANALYSIS OF DATA AND DISCUSSION

A simple average of the normalised spectra of all the 33 records on rock has been evaluated. It is found that the shape of average response curves for different cases of normalisation correspond very nearly to each other. It works out that for rock site 1.0g peak ground acceleration is approximately equal to peak ground velocity of 88 cm/s, ad/v^2 value of 25, undamped spectral intensity of 500 cm and 5 percent damped spectral intensity of 300 cm. Figure 1 shows the plot of average spectra corresponding to various normal-

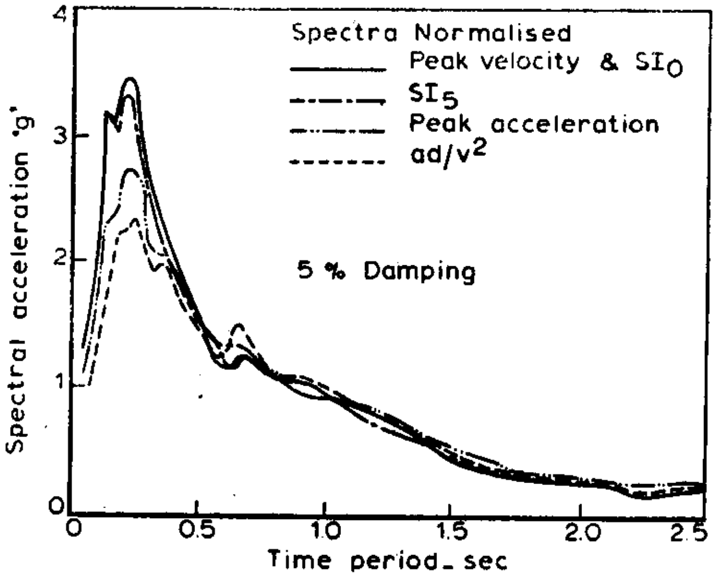

Fig. 1. Average response spectra

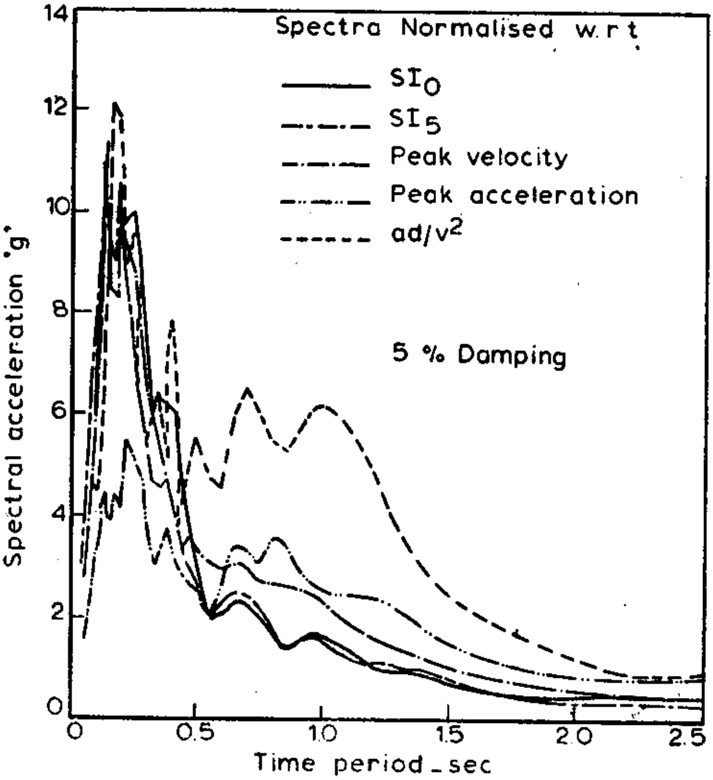

Fig. 2 Envelope of maximum response spectra

ising factors. For comparison all the curves are made to coincide with the average response spectra normalised w.r.t. acceleration in the longer period range, since in this part the shape of average curve is more or less flat. It is however seen that there is some deviation in the predominant period range. Maxima and minima envelopes of the spectra for 33 records on rocks have been obtained and shown in Figs. 2 and 3 respectively. It is seen from Fig. 2 that maxima envelope corresponding to peak ground acceleration gives minimum deviation from mean value around the predominant period range and maxima envelope corresponding to SI_0 and SI_5 give the minimum deviation in the longer period range. The normalisation corresponding to ad/v^2 gives maximum deviation from mean throughout the period range considered. Fig. 3 shows that the minima envelope corresponding to spectral intensity SI_0 shows minimum deviation from mean value in the longer period range while normalization corresponding to peak ground acceleration gives minimum deviation around predominant period. The normalisation corresponding to ad/v^2 again gives maximum deviation from mean throughout the period range considered. The envelopes corresponding to SI_0 and SI_5 are seen to be close to each other.

From the above study it is clear that near the predominant period normalisation corresponding to peak acceleration gives the minimum deviation from mean value whereas in the longer period range SI_0 and SI_5 normalisation gives the least deviation from mean. If peak ground acceleration is used for normalisation then spectra in shorter period range will give good result where as normalisation w.r.t. spectral intensity will give good result in the longer period range on the basis of least deviation from mean. Since an acceleration response spectra has many spikes at the shorter period range and almost smooth in the longer period range, therefore peak ground acceleration is used for normalisation in this study.

Figure 4 shows a comparison of minima, mean, maxima, mean plus one standard deviation, and mean plus three times the standard deviation curves. It is seen that average plus three times the standard deviation curve almost completely envelopes the maxima curve. Therefore this mean plus three times the standard deviation curve gives 100 percent confidence level.

Using peak ground acceleration as the criteria for normalization, the smoothened shape of response spectra normalised to 1.0g peak ground acceleration for 100 percent, 84 percent, 65 percent and 50 percent confidence level are shown in Fig. 5 for rock site.

The associated shape of vertical response spectra normalised to 1.0g peak ground acceleration corresponding to vertical component of earthquakes have also been derived for rock site. The shape of response curves for 100, 84, 65 and 50 percent confidence level for vertical components for different damping values are shown in Fig. 6.

Similarly Fig. 7 shows smoothened shape of response spectra normalised to 1.0g peak ground acceleration for 100, 84, and 50 percent confidence levels for alluvial site. The associated shape of vertical response spectra corresponding to vertical components of alluvial site have been shown in Fig. 8.

COMPARISON OF SHAPE OF RESPONSE SPECTRA PROPOSED BY VARIOUS INVESTIGATORS FOR DIFFERENT SITE CONDITIONS

It is very difficult to compare results of various investigators because of the vagueness in definition of soil types used by them. Various terms like hard ground, firm ground, stiff soil and rock have been used for describing the soil type. Similarly loose soil, deep cohesionless soil and alluvial soil have been used to describe relatively softer soil. Absence of quantitative description of soil type has been a serious handicap in these studies.

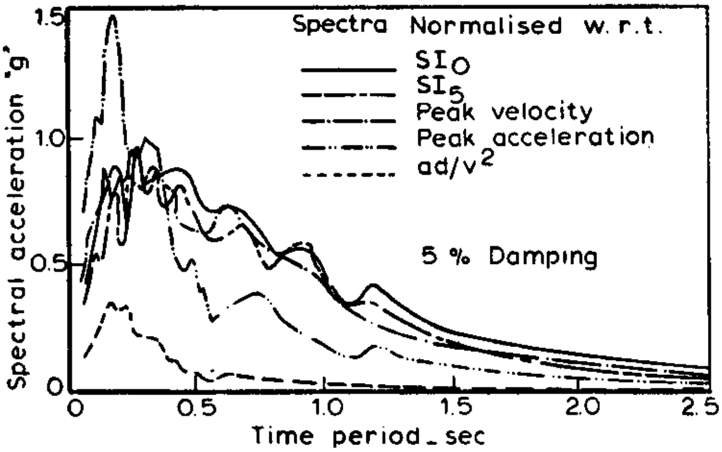

Fig. 3 Envelope of minimum response spectra

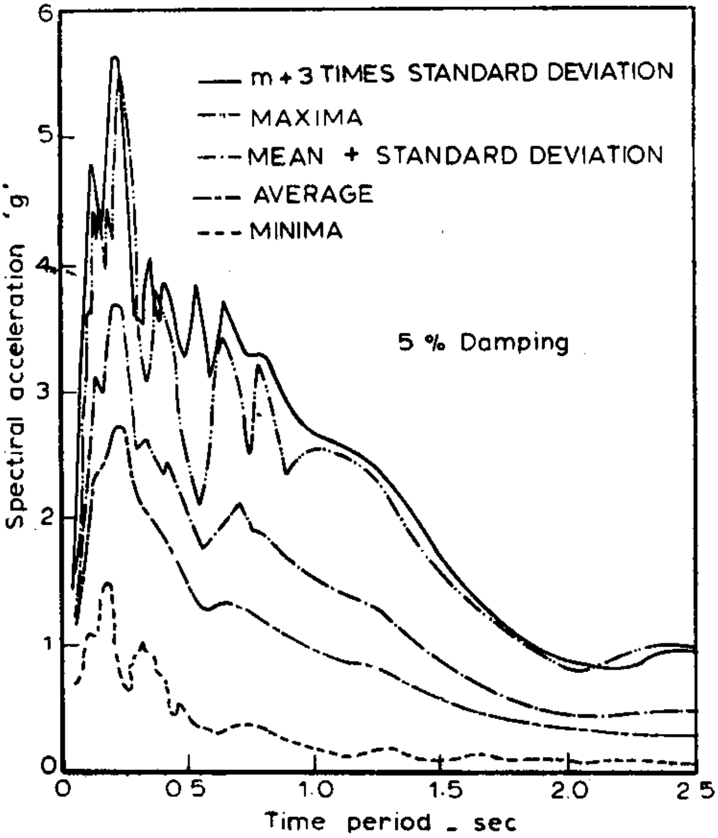

Fig. 4 Comparison of maxima, minima, average, mean plus standard deviation and mean plus 3 times s. d. Response curves

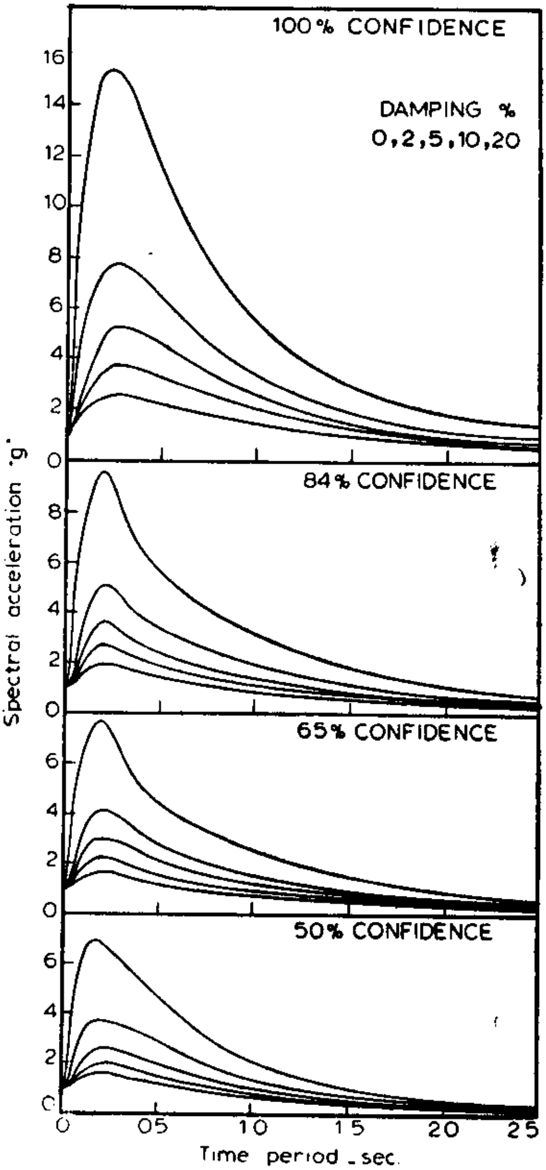

Fig. 5 Shape of horizontal response spectra for rock sites

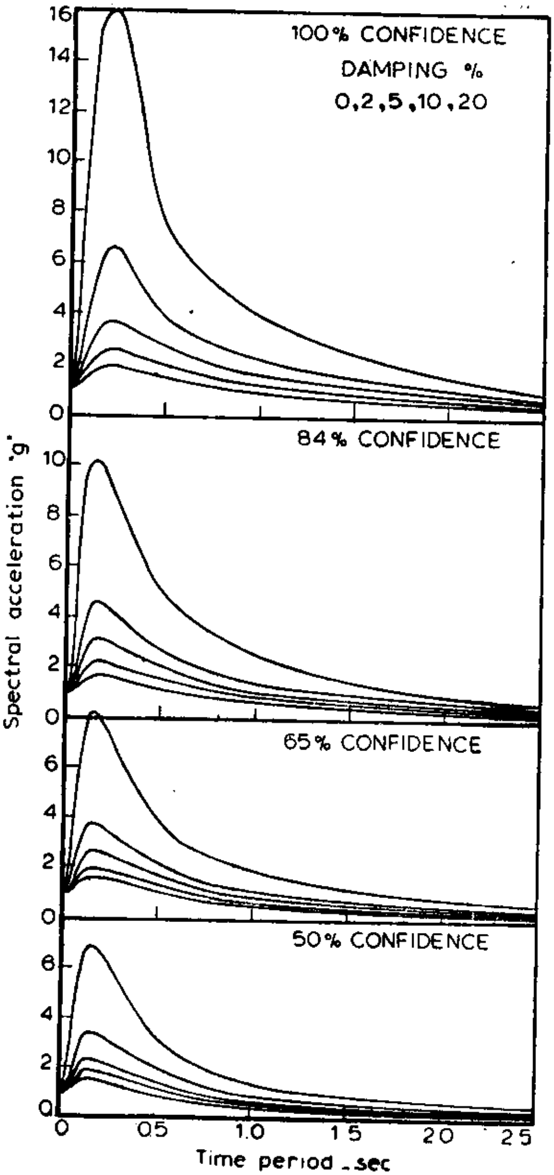

Fig. 6 Shape of vertical response spectra for rock sites

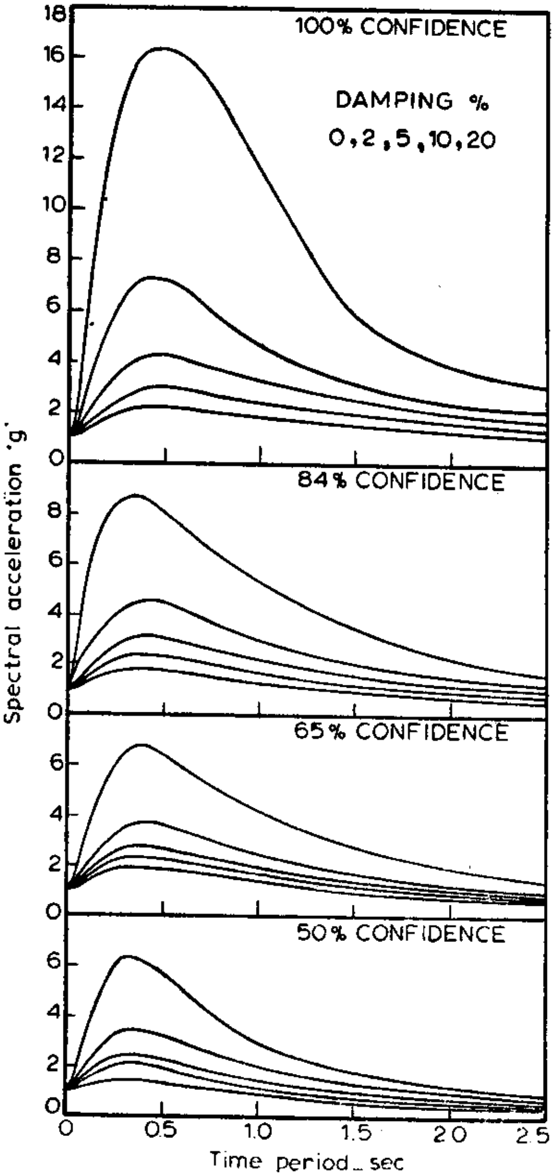

Fig. 7 Shape of horizontal response spectra for alluvial sites

However, a comparison of shape of response spectra proposed by various investigators has been attempted.

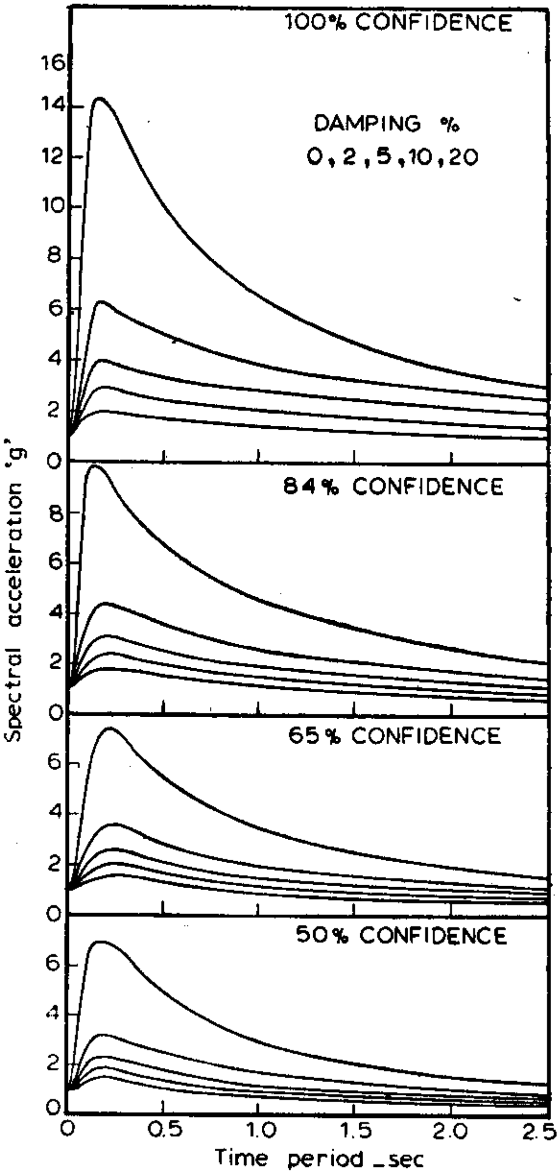

Fig. 8 Shape of vertical response spectra for alluvial sites

COMPARISON OF SHAPE OF RESPONSE SPECTRA FOR A ROCK SITE

The shape of average response spectra for 5% damping for rock sites as obtained by Seed et al, Newmark, Kuribayashi et al. and Hayashi et al. developed from different earthquake ensemble are compared with the shape of average response spectra proposed in this study in Fig. 9. It is seen that for periods beyond about one second, the spectra match resonably well with each other. However in the short period range the deviation is more, particularly in the case of curves proposed by Newmark. The predominant period for rock to stiff soil range from 0.2 to 0.3 sec.

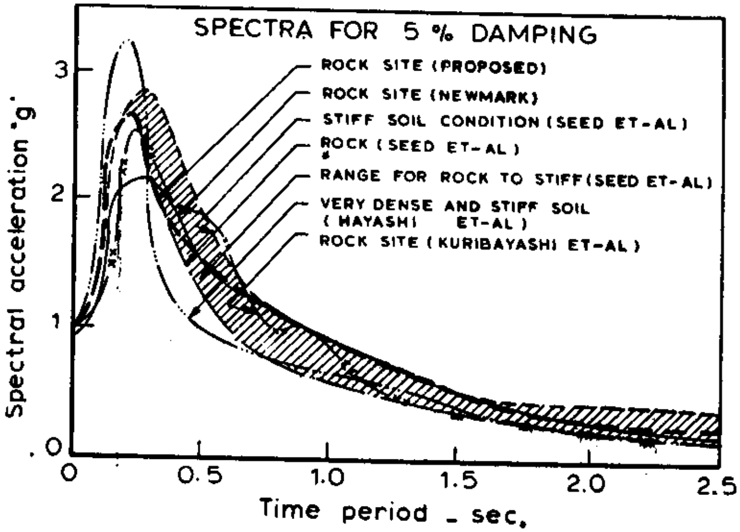

Fig. 9 Comparison of average acceleration response spectra for rock to stiff soil conditions by different studies

COMPARISON OF SHAPE OF RESPONSE SPECTRA FOR AN ALLUVIAL SITE

The shape of average response spectrum for alluvial and deep cohesionless soil proposed by various investigators considering a different set of earthquake records have been compared for 5% damping in Fig. 10. In the short period range upto 0.5 sec. all

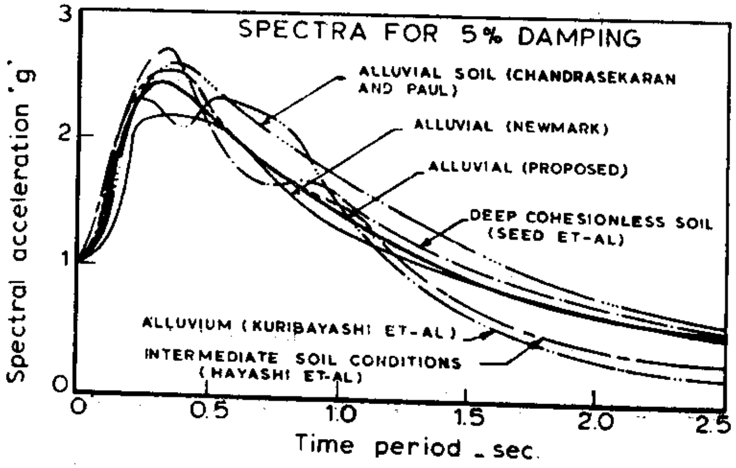

Fig 10 Comparison of average acceleration response spectra for alluvial intermediate and deep soil condition

the curves match resonably well. Beyond 0.5 sec there is significant variation. The shape of average response spectra proposed by Kurubayashi et al. and Hayashi et al. resemble very well in longer period range. The shape of response spectra as proposed in this study and those due to Chandrasekaran et al., Seed et al., and Newmark resemble well. It may be pointed out that the curves based on Japanese and U.S. earthquake data separately show deviation in the longer period range. The predominant period for an alluvial site is about 0.4 sec.

CONCLUSIONS

Following conclusions are drawn from the analytical study of large number of earthquake records.

(1) For normalising the response spectra for rock site, peak ground acceleration is found to be most suitable around the short period range and spectral intensity in the longer period range.

(2) Response spectra for various confidence level, normalised with respect to 1.0g peak ground acceleration are therefore recommended for rock and alluvial sites for use in aseismic design. Depending upon importance of various structures different confidence level spectra may be used.

(3) The average predominant period for rock site is about 0.25 sec. and for alluvial site is about 0.4 sec.

(4) For rock site 1.0g peak ground acceleration is approximately equal to peak ground velocity of 88 cm/s, ad/v^2 value of 25, undamped spectral intensity of 500 cm and 5 percent damped spectral intensity of 300 cm.

(5) It is recommended that for design of important structures, the average response spectra for the site should be obtained from the average of a large number of earthquake records having epicentral distance, soil condition and other parameters close to expected parameters.

ACKNOWLEDGEMENT

The authors express their gratefulness to Dr. A.R. Chandrasekaran Professor of Structural Dynamics in the School of Research and Training in Earthquake Engineering for allowing them to make free use of his personal library for the ground motion data used in the present study.

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TABLE I

DATA FOR ROCK SITE

Sl. No.	Station	Date	Magnitude	Focal depth (km)	Epic. dist. (km)	Direction	Peak accn, cm/s^2	Peak vel. cm/s	ad/v^2	SI_0 cm	SI_5 cm
1	2	3	4	5	6	7	8	9	10	11	12
1	Taft	7.21.52	7.6	16	55	N21E	152.7	15.7	4.151	141.491	64.576
2	Taft	7.21.52	7.6	16	55	S69E	175.9	17.7	5.166	161.214	75.013
3	Golden Gate	3.22.57	5.25	9	11	N10E	81.8	4.9	7.836	15.547	12.159
4	Golden Gate	3.22.57	5.25	9	11	S80E	102.8	4.6	3.894	19.635	16.426
5	Temblor	6.27.66	5.6	—	7	N65W	264.3	14.5	5.908	83.426	54.452
6	Temblor	6.27.66	5.6	—	7	S25W	340.8	22.5	3.704	88.038	71.803
7	Castaic	2.09.71	6.6	13	29	N21E	309.4	16.5	4.773	108.988	65.449
8	Castaic	2.09.71	6.6	13	29	N69W	265.4	27.2	3.336	172.640	91.345
9	Santafelica dam	2.09.71	6.6	13	33	S08E	213.0	9.9	15.213	75.510	34.953
10	Los Angeles water and power	2.09.71	6.6	13	41	N50E	126.6	23.2	5.809	99.230	57.406
11	—do—	2.09.71	6.6	13	41	S40W	169.2	16.1	4.134	94.180	57.987
12	Los Angeles Z011 zonal	2.09.71	6.6	13	42	S28W	71.1	11.5	3.766	69.625	40.106
13	—do—	2.09.71	6.6	13	42	S62E	64.2	13.8	3.671	71.196	40.984
14	Lakehuges St. No. 1	2.09.71	6.6	13	31	N21W	145.5	18.0	1.527	126.922	85.850
15	—do—	2.09.71	6.6	13	31	N69W	108.9	14.4	1.523	92.398	54.449

Table 1 Contd.

1	2	3	4	5	6	7	8	9	10	11	12
16	Lakehuges St. No. 4	2.09.71	6.6	13	29	N21E	143.5	8.6	3.298	51.917	37.851
17	Lakehuges 12	2.09.71	6.6	13	25	N21E	346.2	14.7	2.884	75.897	45.897
18	3838 Lankershim Los Angeles	2.09.71	6.6	13	30	N00E	164.2	12.3	5.847	79.405	41.518
19	—do—	2.09.71	6.6	13	40	S90W	147.6	15.0	3.542	88.888	52.110
20	Grift Park Obs.	2.09.71	6.6	13	33	S90W	167.4	14.6	4.241	103.515	62.763
21	—do—	2.09.71	6.6	13	33	S00W	176.9	20.2	3.169	121.386	64.462
22	Fairmont Reser.	2.09.71	6.6	13	36	N34W	97.1	8.3	11.431	28.477	19.518
23	—do—	2.09.71	6.6	13	36	N56E	64.7	3.8	5.337	40.247	28.440
24	Santa Anita Reservoir	2.09.71	6.6	13	42	N03E	137.7	5.0	17.075	28.293	15.548
25	—do—	2.09.71	6.6	13	42	N87W	165.8	6.6	22.457	30.604	19.896
26	Pudding Stone Dam	2.09.71	6.6	13	62	N55E	69.7	4.6	8.917	31.502	16.757
27	—do—	2.09.71	6.6	13	62	N35W	53.3	4.2	5.439	27.153	15.065
28	Pasadena Seis. Lab.	2.09.71	6.6	13	34	S00W	87.5	5.8	4.162	36.864	21.512
29	—do—	2.09.71	6.6	13	34	S90W	188.6	11.6	7.008	75.128	53.720
30	Los Angeles 800W first	2.09.71	6.6	13	41	N53W	138.0	19.6	3.592	106.890	61.000
31	—do—	2.09.71	6.6	13	41	N37E	86.8	17.9	2.492	103.775	59.695
32	Sanbarnandino	9.12.70	5.4	—	19	NS	113.8	4.5	10.115	23.724	18.935
33	—do—	9.12.70	5.4	—	19	EW	57.5	3.1	10.172	20.365	10.765

TABLE 2

DATA FOR ROCK SITE (VERTICAL COMPONENT)

Sl. No.	Station	Date	Magnitude	Focal depth (km)	Epicentral Dist (km)	Peak Accn. cm/sec^2
1.	Taft	7.21.52	7.6	16	65	102.9
2.	Golden Gate	3.22.57	5.25	9	11	37.2
3.	Tembler	6.27.66	5.6	—	7	129.8
4.	Castaic	2.09.71	6.6	13	29	153.3
5.	Santa Felica Dam	2.09.71	6.6	13	33	63.7
6.	Los Angeles Water and Power	2.09.71	6.6	13	41	67.2
7.	Los Angeles Z011 Zonal	2.09.71	6.6	13	42	48.7
8.	Lake huges st No. ≠4	2.09.71	6.6	13	25	150.8
9.	3838 Lankershim Los Angeles	2.09.71	6.6	13	30	69.7
10.	Grift park obs.	2.09.71	6.6	13	33	120.3
11.	Fairmont Reser.	2.09.71	6.6	13	36	32.9
12.	Santa Anita Reser.	2.09.71	6.6	13	42	47.6
13.	Pudding Stone Dam	2.09.71	6.6	13	62	37·8
14.	Pasadena Seism. Lab.	2.09.71	6.6	13	34	83.5
15.	Los Angeles 800W first	2.09.71	6.6	13	41	60.9
16.	Sanbarnandino	9.12.70	5.4	—	19	52.5

TABLE 3

DATA FOR ALLUVIAL SITE (40 RECORDS)

Sl. No.	Name of Station	Date	Component	Magnitude	Focal Dist (km)	Epicentral Dist (km)	Peak ground Acceleration cm/s^2
1	2	3	4	5	6	7	8
1.	El Centro	5.18.40		6.3	24	48	341.7
2.	El Centro	5.18.40	W	6.3	24	48	210.1
3.	Pasadena	7.21.52	S	7.7	16	124	46.5
4.	Pasadena	7.21.52	W	7.7	16	124	52.1
5.	Santa Barbara	7.21.52	N42E	7.7	16	89	87.8
6.	Santa Barbara	7.21.52	S48E	7.7	16	89	128.6
7.	Eureca	12.21.54	N11W	6.6	10	24	164.5
8.	Eureca	12.21.54	N79E	6.6	10	24	252.7
9.	Ferndale	12.21.54	N44E	6.6	10	40	155.7
10.	Ferndale	12.21.54	N46E	6.6	10	40	197.3
11.	El Centro	2.09.56	S00W	6.6	10	18	32.4
12.	El Centro	2.09.56	S90W	6.6	10	18	50.1
13.	Hollister	4.08.61	S01W	5.6	11	21	63.4
14.	Hollister	4.08.61	N89W	5.6	11	21	175.7
15.	El Centro	4.08.61	S	6.5	11	64	127.8
16.	El Centro	4.08.61	W	6.5	11	64	56.3
17.	Los Angeles 8244 Origin	2.09.71	N00W	6.6	13	20	250.0
18.	—do—	2.09.71	S90W	6.6	13	20	131.7
19.	Los Angeles Hollywood (Storage)	2.09.71	N90E	6.6	13	35	148.2

Contd...

Table 3 contd....

1	2	3	4	5	6	7	8
20.	—do—	2.09.71	S00W	6.6	13	35	107.8
21.	Los Angeles 7080 Hollywood	2.09.71	N90E	6.6	13	34	98.0
22.	—do—	2.09.71	N00E	6.6	13	34	81.2
23.	Los Angeles 120 Robertson	2.09.71	S02W	6.6	13	36	98.2
24.	—do—	2.09.71	N90E	6.6	13	36	96.2
25.	Pasadena CIT athenacum	2.09.71	N00E	6.6	13	37	107.3
26.	—do—	2.09.71	N00E	6.6	13	37	93.5
27.	4680 Whillshrie Los Angeles	2.09.71	N15E	6.6	13	38	115.0
28.	—do—	2.09.71	N75E	6.6	13	38	82.0
29.	Los Angeles 646 Olive	2·09.71	S37W	6.6	13	42	192.0
30.	—do—	2.09.71	S53W	6.6	13	42	236.4
31.	Glendal	2.09.71	S70E	6.6	13	32	265.7
32.	Glendal	2.09.71	S20W	6.6	13	32	209.1
33.	Los Angeles 616 Normahdie	2.09.71	N00E	6.6	13	39	107.6
34.	—do—	2.09.71	S90W	6.6	13	39	112.0
35.	O.S.O. Pump Plant	2.09.71	N	6.6	13	52	85.2
36.	—do—	2.09.71	W	6.6	13	52	103.7
37.	Los Angeles 611W Sixth Street	2.09.71	N52W	6.6	13	41	101.9
38.	—do—	2.09.71	N38E	6.6	13	41	78·5
39.	Los Angeles 3710 Whillshrie Building basement	2.09.71	W	6.6	13	39	115.7
40.	—do—	2.09.71	S	6.6	13	39	146.7

TABLE 4

DATA FOR ALLUVIAL SITE (VERTICAL COMPONENT)

Sl. No.	Name of Station	Data	Magnitude	Focal Depth (km)	Epicentral Dist (km)	Peak Accn. cm/s^2
1.	El Centro	5.18.40	6.3	—	48	206.3
2.	Pasadena	7.21.52	7.7	16	124	29.3
3.	Santa Barbara	7.21.52	7.7	16	89	43.6
4.	Eureca	12.21.54	6.6	10	24	81.3
5.	Ferndale	12.21.54	6.6	10	40	41.9
6.	El Centro	2.09.56	6.6	10	80	32.4
7.	Hollister	4.48.61	5.6	11	21	49.1
8.	El Centro	4.08.61	6.5	11	64	29.7
9.	Los Angeles 8244 Origin	2.09.71	6.6	13	20	167.5
10.	Los Angeles Hollywood (storage)	2.09.71	6.6	13	35	49.8
11.	Los Angeles 7080 Hollywood	2.09.71	6.6	13	34	57.2
12.	Los Angeles 120 Robertson	2.09.71	6.6	13	36	26.5
13.	Pasadena CIT athenacum	2.09.71	6.6	13	37	92.9
14.	4680 Whillshrie Los Angeles	2.09.71	6·6	13	33	64.8
15.	Los Angeles 646 Olive	2.09.71	6.6	13	42	69.2
16.	Glendal	2.09.71	6.6	13	32	131.5
17.	Los Angeles 616 Normahdie	2.09.71	6.6	13	39	51.6
18.	O.S.O. Pump Plant	2 09.71	6.6	13	52	35.5
19.	Los Angeles 611W Sixth Street	2.09.71	6.6	13	41	53.2
20.	Los Angeles 3710 Whillshrie building basement	2.09.71	6.6	13	39	73.1