REPRESENTING EARTHQUAKE GROUND MOTIONS FOR DESIGN

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SUMMARY

A procedure is presented and illustrated for developing site-dependent smooth response spectra that are in agreement with, and are derived from, a set of recorded ground motions. The motions are selected so as to be "compatible" with a site seismic condition defined in terms of magnitude and distance. The paper also outlines the steps required to obtain risk-consistent smooth "design" response spectra in case two or more different types of earthquakes may cause design level shaking at the site.

INTRODUCTION

A most important step in sèismic safety evaluation of civil engineering facilities is the specification of the seismic input. Depending on the type of structure, its importance, and the type of analysis contemplated, different characterizations of the input earthquake motion are appropriate. In present earthquake engineering practice, the seismic input will likely be expressed either in terms of a set of smooth response spectra or by a selection of one or more representative "time histories" of earthquake motion. The designer often makes use of standard response spectra shapes, derived on the basis of statistical analysis of many strong motion records representing a wide range of source and site conditions and epicentral distances (1,2). The standard response spectra shapes may correspond to the mean of the amplification factors or to the mean plus one standard deviation. Which of these is used depends largely on whether or not it is desirable to add conservatism at this particular step in the seismic design process.

In a recent study (2), the writer sought to evaluate the consequences of the widespread practice of <u>scaling</u> accelerograms and smooth response spectra on maximum acceleration. The study consisted of a series of statistical analyses of elastic and inelastic response spectra as well as a measure of cumulative damage for a set of 140 horizontal components of strong motion accelerograms. The purpose was to assess the degree of conservatism inherent in design procedures based on the use of scaled response spectra or scaled earthquake records. The study found evidence of significant bias which can be avoided if the earthquake engineer uses smooth response spectra or selects accelerograms that are as much as possible compatible with the site seismic condition. In pursuit of this idea, the paper develops and illustrates a procedure, applicable in practice, to obtain site-dependent smooth response spectra compatible with a set of selected accelerograms. It is assumed that the time histories as well as the response spectra must at some point be scaled with respect to a prescribed peak ground acceleration.

There is clearly no unique "best way" to construct smooth response spectra that represent a set of time histories. It is as much an art as it is a

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science. Obvious factors to be considered are: (i) the size and quality of the (recorded ground motion) data base, (ii) desired simplicity and uniformity of the response spectra shapes, and (iii) accuracy in representing expected ground motion spectral content. Statistical uncertainty decreases in function of the number of time histories that are used to estimate the mean and the standard deviation of the response spectra ordinates. But systematic errors or biases are introduced when the set of time histories contains records with source or site characteristics that deviate significantly from the seismic condition the response spectra are supposed to represent.

Much the same argument can be made when one analyzes the decision about how to subdivide the frequency range for the purpose of computing means and standard deviations of spectral amplification factors. Actually, the number of choices can be limited considerably by making use of a strong body of "prior information" that indicates that response spectra are approximately proportional to ground acceleration, ground velocity and ground displacement in different, adjacent frequency ranges (4,5). Therefore, it may be assumed at the outset that the smooth response spectra will be piecewise linear, and alternately parallel to the constant acceleration, velocity and displacement lines in the usual tripartite logarithmic representation of response spectra. It will then suffice to calculate (for each damping) the mean and the standard deviation of a single amplification factor that can be applied throughout the appropriate frequency range.

METHODOLOGY AND CASE STUDY

The proposed methodology is introduced through an example involving two hypothetical seismic conditions. Each site/source condition is specified in terms of a magnitude, epicentral distance, and local site condition (soil vs. rock). Also, based on information about motion attenuation with distance and dependence on magnitude, a "design" maximum ground acceleration is specified for each case. The criteria for the (hypothetical) seismic conditions are summarized in Table I. In the first case, a moderate magnitude - short distance event is specified, while the second case involves a large magnitude - long distance event. Depending on the seismic region, the "design" ground motion amplitudes may be obtained from an attenuation relationship in function of a specified magnitude and distnace, from correlations with a specified Intensity, or directly from a regional seismic risk map which corresponds to an appropriate mean return period (see for example, Ref. 6). The particular attenuation relations used in Table I are based on western United States data. It must be emphasized that they serve only an illustrative purpose here. Detailed discussion about methodology to obtain ground motion amplitudes given a seismic condition, or to obtain design amplitudes, is beyond the scope of the paper.

It is assumed that the pool of available earthquake records consists of 140 horizontal components of 70 western United States strong-motion records corresponding to different event/site pairs. It is the same data set selected by McGuire and Barnard (7) to avoid bias due to unusually large numbers of records from a signle event, i.e., the 1971 San Fernando earthquake. Eleven sites (22 records) were classified by McGuire as "rock" sites, and 59 sites (118 records) as "soil" sites.

The records selected to represent the site ground motion are given in Tables II and III. Obviously, the selection process requires compromise and judgement, but the following objective criteria were used: (a) agreement of site geology (rock vs. soil), (b) close matching of the specified magnitude and distance, and (c) minimizing the amount of accelerogram scaling required. In general, other constraints may have to be added, e.g., the type of faulting, focal depth, regional geology. Of course, the more constrained the search, the harder it will be to find the desired number of motions without deviating too much from the specified site condition. In the cases at hand, 8 accelerograms (2 x 4 horizontal components) were selected to represent the moderate magnitude - short distance event (Case I). For the large magnitude - large distance event (Case II) only 4 accelerograms (2 x 2 horizontal components) were found that came reasonably close to the prescribed site/source condition. Tables II and III list, for each accelerogram selected, the peak acceleration and velocity (a_p and v_p), event magnitude, source-to-site distance, the site condition, and the scale factor required to match the "design" maximum acceleration.

The next step is to assess the implications of the selection of ground motions on the response spectra shapes. The 2% damped response spectra are evaluated for 12 natural periods ranging between 0.05 sec and 2 sec. The statistics (mean, standard deviation and coefficient of variation) of the spectral amplification factors S_A/a_p and S_V/v_p are listed in Table IV and V. The velocity amplification factor S_V/v_p is directly related to the acceleration amplification factor S_A/a_p as follows: $S_V/v_p = (T_n/2\pi)(a_p/v_p)(S_A/a_p)$. It will now be shown how the data presented in these tables can be used to construct smooth response spectra. Consider as a specific example the data in Table IV which pertain to the 2% damped response spectra for Case I.

In Table IV, consider <u>first</u> the values of the coefficient of variation (c.o.v.) of the ratios S_A/a_p and S_V/v_p as a function of natural period. The c.o.v. values of the <u>velocity</u> amplification factor are significantly lower within a range of moderate periods (from about 0.5 to 1.0 sec) than on either side of this period range. The c.o.v. values of the <u>acceleration</u> amplification factor do not vary much between 0.1 and 0.4 sec but make an upward jump (at T_n = 0.5 sec) just when the variability of the velocity amplification factor begins to decrease dramatically. Based on these patterns (of dependence of c.o.v. on natural period), the "corner period" which will separate the period ranges of amplified acceleration and amplified velocity can be roughly estimated (the corner period is about 0.5 sec in this case).

The <u>second</u> step is to evaluate the mean and the standard deviation of the amplification factors S_A/a_p and S_V/v_p. Note the patterns of variation of the mean amplification factors with period. The mean values of S_A/a_p initially increase with period, then, reach a plateau in the range $0.2 \text{ sec} \le T_n \le 0.5$ sec, and finally decrease rapidly as T_n increases beyond 0.5 sec. In the range $0.2 \text{ sec} \le T_n \le 0.5$ sec, the mean of the acceleration amplification factor is 2.9 and its standard deviation is about 0.8. Similarly, in the amplified velocity range, $0.5 \text{ sec} \le T_n \le 2$ sec, the mean of the velocity amplification factor is 2.05 and its standard deviation is about 0.8.

In the short period range of the response spectrum, a gradual transition must be made betweeen the zero-period value $S_A/a_p = 1$ and the level prevailing in the period range where the acceleration amplification is constant. A solid guide is the array of computed mean acceleration amplification factors in this transition range (see Table IV). The corresponding standard deviations are also available to aid in constructing scaled spectra corresponding to the mean plus one standard deviation.

The following procedure is suggested for estimating the spectra in the amplified velocity range of the response spectrum: (i) estimate the ratio v_p/a_p either by averaging the values of this ratio for each of the records selected, or by using the attenuation relationships (predictions of a_p and v_p in function of M and R), and (ii) multiply this ratio by the mean (or mean + σ) velocity amplification factor S_V/v_p. A parallel procedure may be followed in the amplified displacement range of the response spectrum.

It is proposed that the uncertainty in the ratio v_p/a_p not be reflected in the standard deviation of the scaled response spectra in the amplified velocity range. The standard deviation need only reflect uncertainty in the amplification factor S_V/v_p. This stems from the fact that the maximum ground velocity can be estimated independently, just as well as the maximum ground acceleration. In the velocity range of the response spectrum, when it comes to assessing variability, one may view the ground velocity, not the ground acceleration, as the "anchor". The result is that the coefficient of variation of the scaled response spectra will not necessarily be larger for moderate and large periods than for relatively short periods. The smooth response spectra for 2% damping (for natural periods below 2 seconds) corresponding to the two seismic conditions are shown in Fig. 1. The figure shows the response spectra corresponding to the mean and to the mean plus one standard deviation.

DESIGN RESPONSE SPECTRA

Up to this point, the paper has made reference to compatible ground motion representations for a given site seismic condition. For purposes of illustration, two different seismic conditions (Cases I and II) were considered. The terminology "design seismic condition" or "design response spectra" was deliberately avoided. The smooth response spectra corresponding to a given seismic condition may indeed be interpreted as design response spectra if that particular condition greatly dominates the seismic risk at the site. If two or more different seismic conditions significantly contribute to the seismic risk at the site, then it becomes necessary to combine the information about the (conditional) responses given each seismic condition with information (provided by seismic risk assessment) about the relative likelihood of occurrence of each seismic condition. A procedure to do this is illustrated below.

Take as an example a "soil site" where the 0.1 g design earthquake may originate either from a moderate earthquake at moderate distance (Type I) or from a large, distant earthquake (Type II). The probabilities, p_I and $p_{II} = 1 - p_I$, that the design earthquake will be of a particular type, can be obtained from a combination of seismological and geological information, supported by judgement and (preferably) by formal seismic risk analysis. It may be appropriate to use a different set of relative risks (p_I and p_{II})

for the acceleration and velocity ranges of the response spectra. Ground motions and smooth site response spectra representing the two seismic conditions have been obtained before. Specifically, means and standard deviations of the amplification factors governing the shape of the response spectra in the various period ranges have been determined. From this information, one can evaluate the probability that the amplification factor S_A/a_p is less than a specified value, say r, given the type of earthquake. These conditional probabilities will be denoted by $p(r|I)$ and $p(r|II)$.

The probability that the design response spectra amplification factor will be less than a given value, r, is:

$$p(r) = p(r|I)p_I + p(r|II)p_{II}$$

This probability of no exceedance must be evaluated for a range of values of the factor r. From the relationship between p(r) and r, the engineer can then obtain the design amplification factor corresponding to a prescribed exceedance probability. To carry out the computations, a choice has to be made concerning the probability distribution of the amplification factors for each type of earthquake. This choice is not critical if probabilities of no exceedance between 0.5 and 0.9 are involved. (The normal distribution was assumed in the illustrative calculation.) Of course, the procedure needs to be repeated for a limited number of periods for each damping ratio for which response spectra are sought. As an illustration, the median design response spectra were calculated for a situation where, in the amplified acceleration range, the large, distant earthquake (Type II) was judged to carry 30%, and the closer, moderate earthquake (Type I) 70%, of the seismic risk at the 0.1 g design level; it follows that $p_I = 0.7$ and $p_{II} = 0.3$. In the amplified velocity range, we assume $p_I = p_{II} = 0.5$. The resulting median design response spectra for 2% damping are shown in Fig. 2, together with the median response spectra for the two "constituent" seismic conditions.

CONCLUSIONS

A procedure has been presented for developing site-specific smooth response spectra that are in agreement with (and are derived from) a set of accelerograms selected on the basis of their compatibility with a prescribed site seismic condition. The proposed approach to response spectra smoothing, while obviously not unique, has the following desirable features: (i) it relies on "prior" information about response spectra shapes in the acceleration, velocity (and displacement) ranges of the spectrum, (ii) it permits the calculation of relatively stable estimates of the means and standard deviations based on only a small number of records, and (iii) it makes full use of information about maximum ground velocity (or displacement) and about the amplification factors in the velocity (or displacement) range of the response spectra. Finally, the paper outlines the steps required to obtain smooth design response spectra if two or more different types of earthquakes can cause design level shaking at the site. A more detailed account of the methodology and more specific information about the effect of scaling accelerograms w.r.t. maximum acceleration on elastic and inelastic response measures may be found in Ref. 3.

REFERENCES

1. Newmark, N.M., Blume, J.A., and Kapur, K., "Design Response Spectra for Nuclear Power Plants", Journal, Power Division, American Society of Civil Engineers, Vol. 99, No. PO2, 1973, pp. 287-303.

2. Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, "Design Response Spectra for Nuclear Power Plants", Regulatory Guide No. 1.60, Washington, D.C.

3. Vanmarcke, E.H., "Representation of Earthquake Ground Motion: Scaled Accelerograms and Equivalent Response Spectra", Miscell. Paper S-73-1, Report 14 in Series on State-of-the-Art for Assessing Earthquake Hazards in the United States, U.S. Army Engineer Waterways Experiment Station, August 1979.

4. Newmark, N.M. and Hall, W.J., "A Rational Approach to Seismic Design Standards for Structures", Proc. 5th WCEE, Rome, 1973.

5. Newmark, N.M. and Rosenblueth, E., Fundamentals of Earthquake Engineering, Prentice-Hall, Englewood Cliffs, New Jersey, 1971.

6. Cornell, C.A., "Engineering Seismic Risk Analysis", Bulletin of the Seismological Society of America, Vol. 58, No. 5, pp. 1583-1606, October 1968.

7. McGuire, R.K. and Barnhard, J.A., "Magnitude Distance and Intensity Data for C.I.T. Strong Motion Records", U.S. Geological Survey Journal of Research, Vol. 5, No. 3, 1977.

8. Donovan, N.C., "Site Response Procedures for Major Buildings", paper presented at ASCE National Structural Engineering Meeting, San Francisco, April 1973.

9. Orphal and Lahoud, "Prediction of Peak Ground Motion from Earthquakes", Bulletin of the Seismological Society of America, Vol. 64, No. 5, pp. 1563-1574, October 1974.

FIG. 1 RESPONSE SPECTRA (β=0.02) FOR CASES I AND II

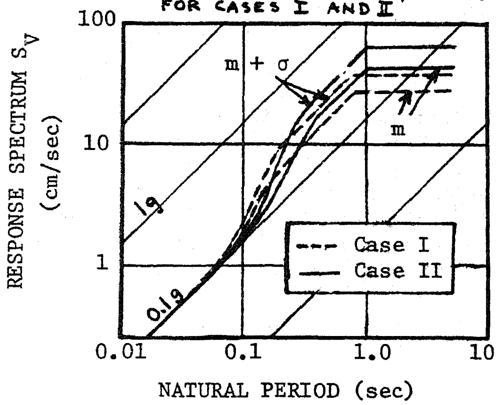
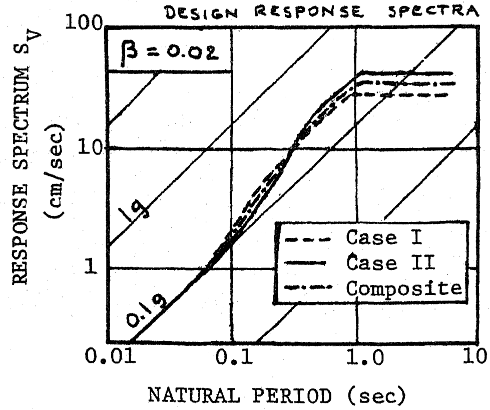


FIG. 2 CONSTRUCTION OF MEDIAN DESIGN RESPONSE SPECTRA



SITE/SOURCE CONDITIONS		Case I	Case II
Magnitude		6.5	8.0
Focal Distance (km)		50	150
Local Site Geology		Soil	Soil
Maximum Acceleration* Predicted (cm/sec^2)	(1)	99.5	69.9
	(2)	118	102
For Design		0.1 g	0.1 g

*Maximum accelerations are predicted from attenuation relationships proposed by Donovan (9) and Orphal and Lahoud (10). These relationships all have the form:

$$a_p = b_1 e^{b_2 M} R_o^{-b_3}$$

where a_p = maximum acceleration in cm/sec^2, M = Richter Magnitude, R_o = R + c, R = focal distance (km), b_1, b_2, b_3 and c a re constants. The respective values of the constants (b_1, b_2, b_3 and c) are: (1) Donovan: 1080, 0.51, 1.32 and 25; and (2) Orphal and Lahoud: 69, 0.92, 1.39 and 0.

TABLE I

Case I M = 6.5 R = 50 km Soil Site a_{design} = 0.1 g

Selected Earthquake Records

	M	R (km)	Local Site Geology	a_p (g)	Scale Factor	v_p (cm/sec)	v_p/a_p (cm/sec x g)
U300	6.4	50	Soil	0.121 0.116	0.83 0.86	6.92 5.74	57.19 49.48
T286	6.5	48	Soil	0.060 0.047	1.67 2.13	6.22 6.05	103.67 128.72
F086	6.6	46	Soil	0.107 0.082	0.93 1.22	17.4 15.1	162.12 184.15
A009	6.6	40	Soil	0.159 0.201	0.63 0.50	35.6 26.0	223.89 129.35

Mean: 0.11 g

Mean: 129.8
St. Dev.: 60.11
C.o.v.: 0.463

TABLE II Ground Motions Selected to Represent "Case I" Site Seismic Condition

Case II M = 8.0 R = 150 km Soil Site a_{design} = 0.1 g

Selected Earthquake Records

	M	R (km)	Local Site Geology	a_p (g)	Scale Factor	v_p (cm/sec)	v_p/a_p (cm/sec x g)
A003	7.7	127	Soil	0.047 0.053	2.13 1.89	6.2 9.1	131.9 171.7
A006	7.7	119	Soil	0.055 0.044	1.82 2.27	6.1 9.4	110.9 213.6

Mean: 0.05 g

Mean: 157.0
St. Dev.: 45.36
C.o.v.: 0.29

TABLE III Ground Motions Selected to Represent "Case II" Site Seismic Condition

RATIOS S_A/a_p						NATURAL PERIODS						CASE I
EARTHQUAKE	0.05	0.08	0.10	0.15	0.20	0.30	0.40	0.50	0.75	1.00	1.50	2.00
U300-1	1.05	0.96	1.41	1.68	2.28	2.56	2.79	1.70	1.28	1.01	0.32	0.13
U300-2	1.04	1.19	1.19	3.34	3.33	3.66	3.59	1.34	0.97	0.72	0.18	0.15
T286-1	1.25	1.60	2.05	2.85	3.73	3.30	3.03	3.73	1.78	1.07	1.72	1.09
T286-2	1.15	1.49	2.17	2.79	3.09	2.53	3.62	4.83	2.15	1.85	2.15	1.10
F086-1	1.02	1.04	1.28	1.79	2.99	3.62	2.22	2.53	1.63	2.65	1.32	0.77
F086-2	1.05	1.10	1.38	2.63	3.44	3.60	3.95	2.42	1.93	1.93	1.02	0.71
A009-1	1.01	1.15	1.54	1.77	1.96	2.87	4.44	2.73	3.24	1.73	3.21	1.96
A009-2	1.06	1.18	1.14	2.27	2.20	1.44	1.72	2.14	2.24	2.07	2.27	0.73
MEAN	1.08	1.21	1.52	2.39	2.88	2.95	3.17	2.68	1.90	1.63	1.52	0.93
ST. DEV.	0.08	0.22	0.39	0.61	0.65	0.77	0.91	1.13	0.69	0.64	1.03	0.59
C.O.V.	0.07	0.18	0.25	0.26	0.23	0.26	0.29	0.42	0.36	0.40	0.68	0.71
RATIOS S_V/v_p												
MEAN	0.08	0.14	0.23	0.56	0.90	1.38	1.93	1.83	1.88	2.09	2.57	1.84
ST. DEV.	0.05	0.08	0.12	0.44	0.58	0.98	1.27	0.81	0.50	0.55	1.37	0.94
C.O.V.	0.57	0.56	0.53	0.77	0.65	0.71	0.66	0.44	0.27	0.26	0.53	0.51

TABLE IV Response Spectra Amplification Factors and Their Statistics for 2% damping for Earthquake Selected for the "Case I" Site Seismic Condition.

RATIOS S_A/a_p						NATURAL PERIODS						CASE II
EARTHQUAKE	0.05	0.08	0.10	0.15	0.20	0.30	0.40	0.50	0.75	1.00	1.50	2.00
A003-1	1.04	1.08	1.31	1.35	1.67	2.62	3.09	3.85	3.17	2.45	1.35	1.86
A003-2	1.03	1.06	1.14	1.49	2.00	2.98	2.55	3.04	4.23	3.96	1.42	1.45
A006-1	1.01	1.14	1.07	1.89	2.31	3.76	4.09	5.07	2.55	3.18	1.70	1.02
A006-2	1.03	1.15	1.30	1.43	2.25	4.07	3.34	3.59	3.32	3.48	3.50	1.16
MEAN	1.03	1.11	1.21	1.54	2.06	3.36	3.27	3.89	3.32	3.27	1.99	1.37
ST. DEV.	0.01	0.04	0.12	0.24	0.29	0.67	0.64	0.86	0.69	0.63	1.02	0.37
C.O.V.	0.01	0.04	0.10	0.16	0.14	0.20	0.20	0.22	0.21	0.19	0.51	0.27
RATIOS S_V/v_p												
MEAN	0.05	0.09	0.13	0.25	0.43	1.06	1.42	2.13	2.55	3.38	2.94	2.90
ST. DEV.	0.02	0.03	0.03	0.11	0.15	0.36	0.64	1.05	0.49	0.86	0.92	1.12
C.O.V.	0.28	0.29	0.24	0.42	0.34	0.34	0.45	0.49	0.19	0.25	0.31	0.39

TABLE V Response Spectra Amplification Factors and Their Statistics for 2% Damping for Earthquakes Selected for the "Case II" Site Seismic Condition