SCALING OF RESPONSE SPECTRA AND ENERGY DISSIPATION IN SDOF SYSTEMS

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SUMMARY

This paper contains summaries of two studies recently completed at the University of Illinois, one on response spectra and one on energy absorption. Design spectra are commonly normalized by peak ground motions. In the current study alternative scaling factors were evaluated. It was found that a three parameter system of spectrum intensities may afford a better means for scaling spectra. The study on energy absorption focused on the total amount of energy imparted to a simple structure, and the dissipative mechanisms including the number of yield excursions and reversals. Also an effective motion criterion was identified.

SCALING METHODS FOR EARTHQUAKE RESPONSE SPECTRA

Introduction

Early recommendations for earthquake design spectra were published by Housner, and by Newmark and Hall. In 1973 the results of companion statistical studies by Newmark and Blume were reported, which together form the basis for much of the current design practice (Ref. 1). In current practice, the earthquake hazard at a site is characterized by estimates of the expected peak values of ground acceleration, velocity, and displacement. The corresponding design spectra are constructed by amplifying these ground motion maxima by appropriate factors determined from the previously reported statistical studies. In the roughly ten years since the development of these design procedures, two important observations have been made. First, from the statistical studies themselves, it has been noted that the dispersion or scatter in the data is large. For example, coefficients of variation exceeding 50 percent have resulted when spectra are normalized or scaled by peak ground motion values. Secondly, from observations following actual earthquakes, it has been noted that levels of damage are inconsistent with large ground motion maxima. That is, greater levels of damage might have been expected had the peak instrumental ground motions been known beforehand. Of course, these peak parameters convey little or no information regarding the earthquake duration and frequency content, two important elements

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affecting damage. The conclusion is that ground motion maxima, alone, are poor indicators of earthquake damage potential or earthquake strength.

The objective of this study (Ref. 2) is to evaluate the current practice of scaling earthquake response spectra by the three peak ground motions. Other investigators such as Mahin and Bertero have suggested such studies, and, Cornell, Banon, and Shakal have reported results in which response spectra were scaled by mean Fourier amplitudes of acceleration. In this study, alternative scaling techniques are investigated in greater detail than heretofore considered. The approach, simply stated, is to statistically evaluate normalizing factors which have been proposed over the years, with the goal of reducing (ideally, minimizing) the dispersion or scatter encountered in current scaling methods.

Statistical Evaluation

The normalizing factors considered in this study are categorized into two groups, one based on ground motion data and the other on response-related quantities. The parameters within the group based on recorded ground motions are the integrals of the squared ground motions, and the root-square, mean-square, and root-mean-square motions. Those in the response-related category include the spectrum intensity and the amplitudes of the Fourier spectrum of ground acceleration. A three-parameter system of spectrum intensities, computed from the 2 percent damped elastic pseudovelocity spectrum, is developed. The spectrum intensities are determined within low, intermediate, and high ranges of frequency, appropriately selected to provide the least average dispersion in the corresponding frequency regions of the elastic spectra. A similar set of three mean Fourier amplitudes is derived.

In the statistical analysis, spectra for elastic and inelastic systems, computed from an ensemble of 12 earthquake accelerograms, are considered. The group of ground motions was selected to encompass a wide variety of conditions such as geographical location, earthquake magnitude, epicentral distance, and amplitude and duration of strong shaking. The response spectra, computed for displacement ductilities of 1 (elastic), 1.5, 2, 3, 5, and 10 included those for elastoplastic systems with 2, 5, and 10 percent damping. Bilinear systems with 5 percent damping and 2, 5, and 10 percent strain-hardening were also considered.

Results

The results of the study of alternative scaling procedures for earthquake response spectra may be summarized as follows.

1. For elastic spectra, the root-square displacement offers moderate reductions in scatter compared with that which results from normalization by the peak ground displacement. In the low frequency region, between 0.07 and 0.2 HZ the root-square displacement provides, on the average, about a 30 percent decrease in the coefficient of variation for the normalized spectra.

Unlike the displacement region, in the velocity and acceleration regions none of the alternative ground motion parameters provide less dispersion than that which results from normalization by the corresponding peak ground motion.

2. For all inelastic spectra, none of the normalizing factors based on ground motion data provide noteworthy reductions in scatter compared with those obtained from normalization by the peak ground motions.

3. As shown in Table 1, the spectrum intensities and mean Fourier amplitudes provide, on the average, less dispersion in normalized elastic spectra than that which results from normalization by the peak ground motions. For elastic spectra with 2 percent damping, as illustrated in Fig. 1, the spectrum intensities provide about 40 percent less scatter in the displacement and acceleration regions. In the intermediate frequency or velocity region, normalizing by the corresponding spectrum intensity reduces the dispersion by 20 percent. These reductions in average dispersion decrease with damping, particularly in the displacement and acceleration regions. For 10 percent damped spectra, the reductions are about 20 percent in each spectral region.

   The mean Fourier amplitudes decrease the average dispersion in elastic spectra with small damping. For elastic spectra with 2 percent damping, the mean Fourier amplitudes provide 15 to 20 percent less scatter in the normalized spectra. The improvement afforded by the mean Fourier amplitudes diminishes rapidly with damping, especially in the high frequency or acceleration region of the spectra. For 5 and 10 percent damped spectra, normalization by the associated mean Fourier amplitude actually increases the dispersion compared with that obtained from the peak acceleration.

4. The spectrum intensities outperform the mean Fourier amplitudes as normalizing factors for the inelastic spectra. The reductions in average scatter produced by the spectrum intensities decrease with damping, strain-hardening, and level of inelastic response. However, in the displacement region, reductions in average dispersion are apparent for all damping and strain-hardening for ductilities up to about 3. Although the reductions are smaller in the velocity region, the corresponding spectrum intensity decreases the scatter for systems with ductilities less than about 4. The improvement afforded by the spectrum intensity in the acceleration region decays rapidly with damping and ductility. For damping less than 5 percent of critical and for ductilities less than about 1.7, the spectrum intensity reduces the scatter in the normalized spectral ordinates.

ENERGY ABSORPTION IN SDOF STRUCTURES

Introduction

Well designed and well constructed buildings should be able to absorb and dissipate the imparted energy during earthquake excitation with minimal damage. The structural response parameter most widely employed up to the present time to evaluate the performance of structures is the displacement ductility which may be defined simply as the ratio of the maximum to yield displacement. The displacement ductility, however, does not account for the cumulative damage that may occur as a result of cyclic deformations. A parameter widely employed to characterize the severity of ground shaking at a given site is the peak ground acceleration. Although it is a relatively easy quantity to estimate, peak ground acceleration is a poor measure of the amount of energy imparted to structures and the damage potential of earthquake ground motion.

The purposes of the current study are to investigate the nonlinear response of simple structures and the damage potential of an earthquake ground motion as measured in terms of the amount of energy imparted to a structure, the amount of energy dissipated by inelastic deformation and damping, and the displacement ductility of the structure and the number of yield excursions and reversals experienced during the excitation. Based on the amount of energy imparted to structures a possible effective motion criterion is defined.

Time-History Response

Valuable information may be obtained by studying the time-history response of structural systems when they are subjected to various ground motions. Two quantities of particular interest are the number of yield excursions and the number of yield reversals that a structure experiences during the entire motion. A design based only on displacement ductility disregards the number of yield excursions and reversals which may be valuable in understanding the amount of damage sustained by structures after an earthquake excitation.

Another quantity of interest is the duration of ground motion (or portion of the record) during which most or all inelastic deformations take place in the structure. This quantity may be obtained from the energy time-history response of the structure and may be used as one technique for classification of ground motion records.

The energy time-history curve reflects the type of ground motion to which structures are subjected. The energy input curve for a low-frequency structure subjected to long duration strong motion, such as the El-Centro ground motion, has a large number of peaks and troughs as compared to two or three major peaks when the structure is subjected to a motion with a single high acceleration spike such as the Parkfield ground motion. Those peaks result from the fact that for low-frequency (long-period) structures a large proportion of the energy imparted to the structure is stored in the form of strain and kinetic energy, and each peak corresponds to a strong cycle of earthquake input excitation which may or may not have a significant influence on the response.

For high-frequency structures the stored energy represents a small proportion of the energy imparted to the structure. The latter is dissipated almost immediately (by damping and yielding), and the maximum displacement coincides in general with the strong motion part of the excitation. For a structure subjected to ground motion with a high-frequency acceleration spike, the energy input curve shows a sudden jump at about the same time the peak ground acceleration occurs, and most inelastic deformations in the structure take place around that time.

The times by which 5, 75, and 90 percent of the energy absorbed in a structure is dissipated are given in Table 2. They will be referred to as $t_{e0.05}$, $t_{e0.75}$, and $t_{e0.90}$, respectively. Before $t_{e0.05}$ and after $t_{e0.90}$ most or all energy imparted to a structure is dissipated by damping and is associated with little or no damage in the structure.

The times given in Table 2 are for structures with a frequency equal to 2.0 HZ, a damping of 5 percent of critical and a displacement ductility of 3 under the various ground motions. The difference between $t_{e0.75}$ and $t_{e0.05}$ corresponds to the portion of the ground motion during which most or all inelastic deformation occur in the structure. It is denoted herein as effective duration, T_e, and may be used as one technique for classification of ground motion records. The records employed in this study may be classified in three groups as follows: (1) records with $T_e <$ 3.5 sec will be referred to as short duration records; (2) records with $3.5 < T_e < 7.5$ sec will be referred to as moderate duration records; and (3) records with $T_e > 7.5$ sec will be referred to as long duration records.

The input ground motion has a great effect on the number of yield excursions. Over the whole frequency range, structures with a given damping and displacement ductility undergo in general a larger number of yield excursions when they are subjected to long duration motion, such as the El Centro records, than when they are subjected to a short duration motion, such as the Parkfield record (Ref. 3).

Equivalent Number of Yield Cycles

A useful comparative index of the severity of ground shaking is the equivalent number of yield cycles, N. This index is numerically equal to the ratio of the total energy dissipated by yielding, E_H, in a structure when subjected to ground motion to the area under the force-deformation curve for the structure when it is loaded monotonically until it reaches the same maximum displacement it experienced during the excitation, namely

$$N = \frac{E_H}{\omega^2 U_Y^2 (\mu - 1)}$$

where ω is the circular frequency, U_Y is the yield displacement and μ is the displacement ductility of the structure. The smallest value N can have is 1. In this case, the structure yields only in one direction and reaches its maximum displacement.

For structures with the same displacement ductility, the value of N is, in general, higher for a long duration ground motion than it is for a short duration ground motion, as shown in Fig. 2. The differences in the values of N are accentuated by an increase in the displacement ductility. This implies that as the displacement ductility increases, it becomes less appropriate to be used as a measure of damage especially for structures subjected to long duration ground motions (Ref. 3). As a result, the value of N in addition to the displacement ductility provides a good measure of the cyclic deformations of structures from which the damage sustained by these structures may be inferred.

Effective Motion

As a result of this study, effective motion might be defined in terms of the damage potential as characterized by the amount of energy imparted to structures when they are subjected to that ground motion. In order to obtain the effective motion corresponding to a free-field ground motion, a reference ground motion, characterized as a ground motion whose effective acceleration as defined by Newmark and Hall (Ref. 4) may be assumed equal to its peak acceleration, is chosen. In this study, the North-South component of the El Centro record, 1940 Imperial Valley earthquake is employed as a reference motion.

The maximum accelerations for the free-field ground motion records and their corresponding effective motions are summarized in Table 2. As noted elsewhere (Ref. 4), and from this table, it is apparent that the maximum acceleration of an effective motion is equal to that of its corresponding free-field ground motion for long duration motion which normally occurs at some distance from the epicenter. It is smaller than the maximum acceleration of the free-field ground motion for moderate and short duration motions. It should also be remembered that the response and energy spectra corresponding to moderate and short duration records peak over a narrow frequency range. As a result, the damage potential of these ground motions on structures with frequencies outside that range is in general less than might be inferred from the maximum acceleration of either the free-field ground motion or its corresponding effective motion.

REFERENCES

1. Newmark, N. M., Blume, J. A., and Kapur, K. K., Seismic Design Spectra for Nuclear Power Plants, Journal of the Power Division, ASCE, Vol. 99, No. PO2, Nov. 1973, pp. 287-303. (See also USNRC Regulatory Guide 1.60, Rev. 1, Dec. 1973.)

2. Nau, J. M. and Hall, W. J., An Evaluation of Scaling Methods for Earthquake Response Spectra, Civil Engineering Studies, Structural Research Series No. 499, University of Illinois, Urbana, Illinois, May 1982, 327 p.

3. Zahrah, T. F. and Hall, W. J., Seismic Energy Absorption in Simple Structures, Civil Engineering Studies, Structural Research Series No. 501, University of Illinois, Urbana, Illinois, July 1982, 225 p.

4. Newmark, N. M. and Hall, W. J., Earthquake Spectra and Design, Earthquake Engineering Research Institute Monograph Series, Vol. 3, 1982, 103 p.

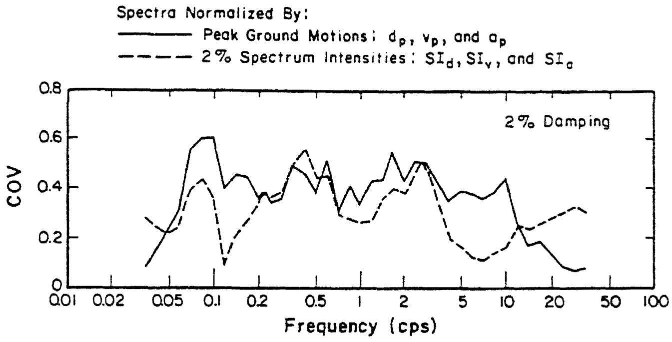

FIGURE 1. COEFFICIENTS OF VARIATION FOR ELASTIC SPECTRA NORMALIZED BY PEAK GROUND MOTIONS AND 2% SPECTRUM INTENSITIES

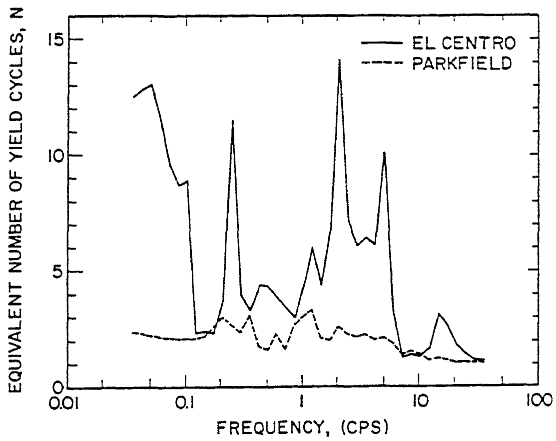

FIGURE 2. EQUIVALENT NUMBER OF YIELD CYCLES FOR ELASTO-PLASTIC SYSTEMS WITH $\beta = 2\%$ and $\mu = 5$ WHEN SUBJECTED TO EL-CENTRO AND PARKFIELD GROUND MOTIONS

TABLE 1. COMPARISON OF AVERAGE COEFFICIENTS OF VARIATION FOR ELASTIC SPECTRA

Damping, Percent	Displacement Region, 0.071 - 0.20 cps Average COV for Spectra Normalized by:		
	Peak Displ.	2% SI (0.08-0.24)	FS(0.035-0.31)
2	0.48	0.28	0.38
5	0.41	0.25	0.35
10	0.34	0.25	0.35

Damping, Percent	Velocity Region, 0.20 - 2.0 cps Average COV for Spectra Normalized by:		
	Peak Vel.	2% SI (0.50-3.5)	FS(0.28-1.3)
2	0.45	0.36	0.39
5	0.40	0.33	0.37
10	0.36	0.30	0.34

Damping, Percent	Acceleration Region, 2.0 - 8.5 cps Average COV for Spectra Normalized by:		
	Peak Accel.	2% SI (5.4-35)	FS(1.4-19)
2	0.41	0.24	0.35
5	0.37	0.24	0.39
10	0.31	0.24	0.42

TABLE 2. COMPARISON OF EFFECTIVE DURATION, AND MAXIMUM AND EFFECTIVE ACCELERATIONS

Ground Motion Record	$t_{e_{0.05}}$ (sec)	$t_{e_{0.75}}$ (sec)	$t_{e_{0.90}}$ (sec)	Effective Duration* (sec)	Maximum Acceleration (g)	
					Free Field Motion	Effective Motion
COYOTE LAKE	4.5	5.1	6.5	0.6	0.42	0.27
PARKFIELD	5.8	6.7	7.0	0.9	0.49	0.35
GAVILAN COLLEGE	4.0	5.0	5.7	1.0	0.14	0.05
MELENDY RANCH	2.9	4.6	9.0†	1.7	0.52	0.35
BONDS CORNER	5.3	10.3	12.3	5.0	0.79	0.70
PACOIMA DAM	5.2	10.3	10.6	5.1	1.17	0.80
TAFT	6.0	17.7	27.2	11.7	0.18	0.18
EL-CENTRO	3.8	21.5	28.3	17.7	0.35	0.35

* Effective duration is equal to $t_{e_{0.75}} - t_{e_{0.05}}$

† Last yield excursion occured at $t = 5.52$ sec.