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Post-Earthquake Assessment of Structures using Free-Field Motions

Application Note #72

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SUMMARY

This document outlines several approaches for post-earthquake assessment of structures based on parameters that are obtained from near free-field motions. The approach is initially based on procedures required for nuclear power plants by the Nuclear Regulatory Commission (NRC). Several studies have been performed to select and standardize post-earthquake assessment parameters for the NRC. However, due to the highly regulatory nature of the NRC and the fact that power plants are very conservatively designed as compared to most structures (e.g., they are to remain linear), procedures described herein do deviate from regulatory guides.

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OUTLINE

INTRODUCTION

In 1988, the Electric Power Research Institute (EPRI NP-5930) conducted a study that set out to determine what constitutes damaging earthquake motion and to develop criteria for determining exceedance of what is called the Operating Basis Earthquake (OBE). In this study, several ground motion characteristics were investigated and trends were established based on observed structural damage for over 250 earthquake histories. The conclusion reached by the study was that a combination of two parameters; peak spectral response pseudo-acceleration (PSA) and cumulative absolute velocity (CAV), is best suited for assessing the potential damage of a given ground motion history. In 1991 the CAV check was standardized for better performance and stability over a broader range of seismic record lengths (EPRI TR-100082). In this document threshold values were also updated. In 1997 the NRC published a regulatory guide (NRC-1.166 1997) that provided details on implementation of post-earthquake actions for nuclear power plants. This document includes PSA and CAV as well as a new exceedance check using velocity response spectra. Because no references are specified, it is unclear where threshold values come from and if the intent was to use pseudo-velocity response spectra. This document provides technical background on a proposed approach which is initially based on the procedures outlined in the above referenced guides and reports. It is aimed to be an introductory guide to be used in proposals for which post-earthquake assessment using free-field motions is desired.

RESPONSE SPECTRUM ANALYSIS

The Response Spectrum Analysis (RSA) compares calculated response spectra to the site-specific Design Response Spectrum (DRS) for a specific range of periods. The goal is to detect if local ground motion is likely to impart design level forces to nearby structures. Because of the various factors-of-safety imbedded in structural design, this is a very conservative approach. Additionally, there is no guarantee that the nearby structures were designed using the DRS. In fact, contemporary structures are typically designed to resist forces associated with 'scaled down' DRS. Response spectra give maximum responses of single-degree-of-freedom (SDOF) systems for a range of periods and specified damping to a given component of ground motion. In general, it is a plot of some peak response (e.g., relative displacement or deformation) against period for a fixed damping ratio.

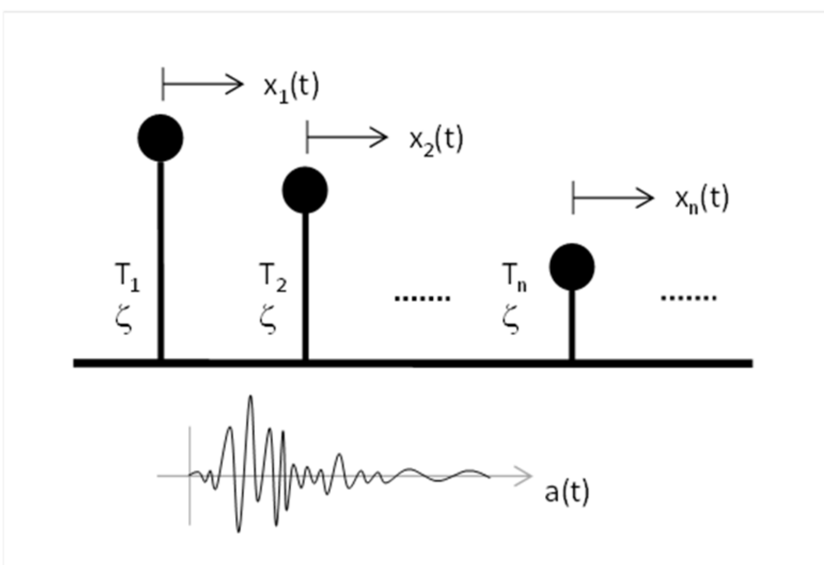

Figure 1. SDOF models where $x_n(t)$ = relative displacement of n^{th} SDOF with respect to ground and $a(t)$ = absolute ground acceleration

The governing equation of motion of a linear SDOF system subjected to ground acceleration *a(t)* is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -ma(t)$$

where m, c, and k are the SDOF system mass, viscous damping, and stiffness respectively. Alternatively, the equation of motion can be written as

$$\ddot{x}(t) + 2\omega_n\zeta\dot{x}(t) + \omega_n^2 x(t) = -a(t)$$

where $\omega_n = \sqrt{k/m}$ and $\zeta = c/2m\omega_n$ are the SDOF system natural circular frequency and fraction critical damping.

The 2nd order partial differential equation can be numerically solved in several different ways. The Nigam-Jennings algorithm has been shown to be very computationally efficient (Nigam and Jennings 1968). Once the displacement response history for a given SODF system is known, the peak pseudo-acceleration (PSA) and peak pseudo-velocity (PSV) are defined as

$$PSA = \omega_n^2 |x(t)|_{max} \quad \text{and} \quad PSV = \omega_n |x(t)|_{max}$$

Note that relative displacement or deformation is of the greatest importance to structural engineers as it relates to the internal forces. For example, the equivalent static earthquake force or base shear, is related to PSA not maximum acceleration. Similarly, strain energy imparted to a system by an earthquake is related to PSV not maximum velocity. For these reasons, we calculate pseudo-acceleration and pseudo-velocity response spectra. However, it should be noted that in the frequency range of interest here, the difference between actual and pseudo quantities are small (Chopra, 2007).

Design Response Spectrum (IBC-2006 & ASCE 7-05)

This section describes how the site-specific design response spectrum (DRS) is created based on procedures outlined in IBC-2006 and ASCE 7-05.

The site-specific information required to calculate a DRS, usually provided by the customer, include two mapped acceleration parameters and the soil site class.

S_s = mapped, 5% damped, spectral response acceleration at short period (0.2 s) available in ASCE 7-05 Figure 22-1 or IBC 2006 Figure 1613.5(1) for continental united states

S_1 = mapped, 5% damped, spectral response acceleration at 1 s available in ASCE 7-05 Figure 22-2 or IBC 2006 Figure 1613.5(2) for continental united states

Soil Site Class (viz. A, B, C, D, E or F) which generally depends on the shear wave velocity, see ASCE 7-05 Table 20.3-1 or IBC 2006 Table 1613.5.2

Mapped 5% damped spectral accelerations are also available from the USGS website; http://earthquake.usgs.gov/research/hazmaps/design/

Based on the provided site class and spectral response acceleration parameters, the site coefficients (F_a and F_v) are found from appropriate Tables; ASCE 7-05 Table 11.4-1 & 2 or IBC-2006 Table 1613.5(1) & (2), and repeated below.

Site Class	Site Coefficient , Fa					Site Coefficient , Fv				
	S_S < 0.25	S_S = 0.5	S_S = 0.75	S_S = 1.0	S_S >1.5	S_1 < 0.1	S_1 = 0.2	S_1 = 0.3	S_1 = 0.4	S_1 > 0.5
A	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0	1.7	1.6	1.5	1.4	1.3
D	1.6	1.4	1.2	1.1	1.0	2.4	2.0	1.8	1.6	1.5
E	2.5	1.7	1.2	0.9	0.9	3.5	3.2	2.8	2.4	2.4

Linear interpolation is allowed for intermediate values of S_S and S_1.

The spectral response acceleration for short period and at 1 s adjusted for site class effects are then defined as

$S_{MS} = F_a S_S$ and $S_{M1} = F_v S_1$

Finally, the design spectral accelerations for short period and at 1 s are defined as

$S_{DS} = \frac{2}{3} S_{MS}$ and $S_{D1} = \frac{2}{3} S_{M1}$

The design response spectral acceleration (Sa) curve is defined as

$$Sa = S_{DS}\,(0.4 + 0.6\,T/T_0) \quad \text{for} \quad T < T_0$$
$$Sa = S_{DS} \quad \text{for} \quad T_0 < T < T_S$$
$$Sa = S_{D1}/T \quad \text{for} \quad T > T_S$$

where $T_0 = 0.2\,S_{D1}/S_{DS}$ and $T_S = S_{D1}/S_{DS}$. The design response spectral velocities (Sv) are computed by dividing the spectral accelerations (Sa) by the associated natural circular frequency; $\omega_n = 2\pi/T$

$$Sv = Sa/\omega_n = Sa\,T/2\pi$$

Determination of Exceedance

A DRS exceedance is said to occur if either

1) the pseudo-acceleration response spectra (PSA) generated using translational free-field ground motions are larger than the corresponding DRS accelerations (Sa) for periods between 0.1 to 0.5s (2 to 10 Hz)[1,2]

or

2) the pseudo-velocity response spectra (PSV) generated using translational free-field ground motions are larger than the corresponding DRS velocities (Sv) for periods between 0.5 and 2s (0.5 to 2 Hz)[1].

Note that in order to check vertical spectra, the vertical design response spectra must be provided. The IBC provisions detailed above are for translational motions only. However, structures tend to be much stronger and stiffer (e.g. T < 0.05s) in the vertical directions.

Response spectra shall be calculated and checked for exceedance at period intervals of 0.02s; this translates to 95 period steps. It is important to use many steps (or periods) because response spectra are naturally very jagged and may clip the exceedance curves at multiple instances but over a very fine bandwidth.

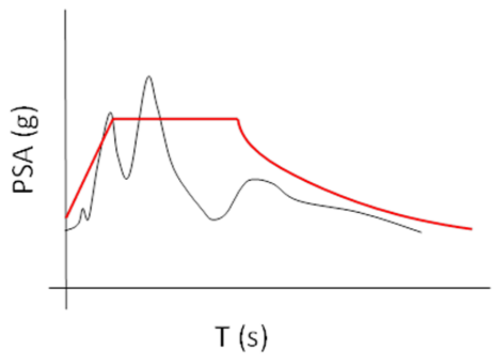

Figure 2. Comparison of calculated and design spectral accelerations

An additional exceedance check may include checking response spectra against maximum constant values. This approach is a good alternative for cases in which DRS may not be available. Maximum response spectral acceleration of 0.2g[3] and velocity of 15.2 cm/s are recommended in NRC RG-1.166.

CUMULATIVE ABSOLUTE VELOCITY

The Cumulative Absolute Velocity (*CAV*) parameter can be conceptualized as the area under the absolute acceleration time history and has been shown to be fairly sensitive to potentially damaging low-frequency motions. It was first introduced in EPRI NP-5390 and later updated in EPRI TR-100082. In the latter report, the *CAV* is defined as

$$CAV = \sum_{i}^{N} CAV_i \quad where \quad CAV_i = \int_{t_i}^{t_i+1} |a(t)|dt$$

where *a(t)* is the acceleration values in a 1-second interval (from t_i to t_i+1) where at least one value exceeds 0.025g and *N* is the record length in seconds.

Any numerical integration method may be used to calculate the CAV value. One of the more robust approaches is the trapezoidal rule which is expressed as

$$\int_a^b f(x)dx \approx (b-a)\frac{f(a)+f(b)}{2}$$

The simplest implementation would be to approximate the integral at each time step (Δt) and then sum over the 1-s interval;

$$CAV_i \approx \sum_{n=1}^{1/\Delta t} \frac{\Delta t}{2}\{|a(t_i + n\Delta t)| + |a(t_i + n\Delta t - \Delta t)|\}$$

The CAV check is exceeded for an event if the CAV calculation is greater than 0.16 g-s[4].

NOTES

Response spectra are often idealized as divided into period ranges, or regions in which structural responses are best related to a particular ground motion parameter. For example, structural responses within the acceleration-sensitive region (less than 0.5s) are most directly related to ground acceleration. Meaning, the pseudo-acceleration response of SDOF structures is ideally constant and equal to the ground acceleration amplified by a factor depending on the system damping. Similarly, within the velocity-sensitive region (from 0.5 to 3s), the pseudo-velocity response of SDOF structures is ideally constant and equal to the ground velocity amplified by a factor depending on the system damping. Finally, the displacement-sensitive region is designated for periods greater than 3s.

An upper limit of 10Hz was found to be a reasonable limit because high-frequency motions do not cause damage to engineered components. This was showed by comparing parameter values for filtered (low pass below 10Hz) and unfiltered records and the number of records above threshold values. It was also supported by blast data results, equipment vibration data, fragility test data for equipment, and design code requirements for high frequency loads.

The threshold value of 0.2g for PSA comes from the threshold value for average spectral acceleration from 2 to 10 HZ as defined in EPRI-5930. It is used for PSA and is said to be conservative.

In EPRI-5930, for a given damage parameter (e.g., PSA or CAV), threshold values are defined as the lowest parameter value for all site intensities equal to or larger than MMI VII. MMI VII was selected as a conservative measure of damage to buildings of good design and construction. The analysis in EPRI-5930 included counting earthquake records where parameter values exceeded threshold values for MMI less than VII. This would indicate a false-positive exceedance.

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