0015

SEISMIC GROUND MOTION SIGNALS FROM DESIGN SPECTRUM FOR SOFT SOIL IN MEXICO CITY

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SUMMARY

A methodology to obtain ground time histories, which match seismic response spectra, is presented. Spectral Density Functions (SDF) for ground acceleration are obtained from seismic design spectra in seismic zones of Mexico City. Deterministic Amplitude Method (DAM) is applied to produce acceleration time series for soft soil conditions, which are finally used as input to carry out response analysis of single degree of freedom systems. The maximum displacements are compared against those calculated by using real earthquake recorded in 1985.

INTRODUCTION

When analysing building and other structures under earthquake actions, two approaches are accepted by international standards, one is based on spectral analysis and the other on time domain analysis. For the second case input time series have to be selected. The common practice is to use records from tremors near the place of interest. Unfortunately, high uncertainty in structural response is introduced due to the fact that such input does not cover all maximums in the whole band of interest. Another engineering practice is to generate synthetic series from Power Spectral Densities based on theoretical models, which sometimes have to be adjusted through seismic measurements. The main problem of both approaches is the fact that their acceleration intensities do not match those recommended by major design codes.

In this paper a methodology to produce earthquake ground motion time series from design spectra recommended by codes is presented. Two main steps in obtaining the design time series are shown: first, the representation of seismic response spectra by a SDF; second, time series simulation through DAM. Both approaches are based on Random Vibration Theory.

GROUND ACCELERATION SPECTRAL DENSITY FUNCTION

In this section a procedure to determine a ground acceleration SDF from a given response spectrum is shown (Vanmarcke, 1976). Is well known that a response spectrum is a graph that shows maximum responses of multiple single degree of freedom systems subjected to base movement (Fig. 1).

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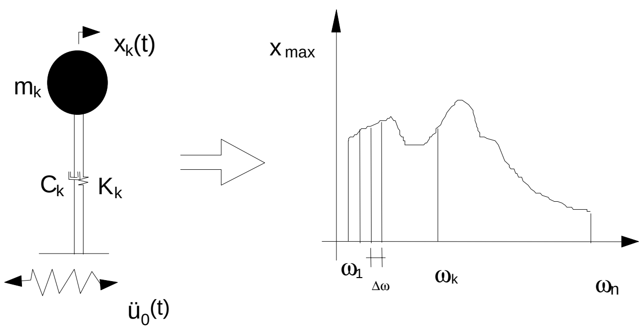

Figure 1. Schematic representation of the response spectrum definition.

If the seismic excitation is considered as a stationary zero-mean random process, the SDF of the acceleration response of each oscillator can be obtained as:

$$S_{aa}(\omega) = \omega_k^4 \left\| H_k(\omega) \right\|^2 S_{\ddot{U}_0 \ddot{U}_0}(\omega) \tag{1}$$

where ω_k is the natural vibration frequency of the k-th oscillator, and $H_k(\omega)$ its corresponding transfer function. By using the ground acceleration SDF for positive frequencies (one side SDF) $G_{\ddot{U}_0 \ddot{U}_0}(\omega) = \frac{1}{2} S_{\ddot{U}_0 \ddot{U}_0}(\omega)$, Eq. (1) yields:

$$S_{aa}(\omega) = 2\omega_k^4 \left\| H_k(\omega) \right\|^2 G_{\ddot{U}_0 \ddot{U}_0}(\omega), \quad for\ \omega \geq 0 \tag{2}$$

and the variance of the oscillator response is calculated as the area under the respective SDF curve:

$$\sigma_a^2 = \int_0^{\infty} \omega_k^4 \left\| H_k(\omega) \right\|^2 G_{\ddot{U}_0 \ddot{U}_0}(\omega) d\omega \tag{3}$$

It can be shown (Vanmarcke, 1976) that an approximation to Eq. (3) is given by:

$$\sigma_a^2 = G_{\ddot{U}_g \ddot{U}_g}(\omega_i) \cdot \omega_i \left[\frac{\pi}{4\xi_i} - 1.0 \right] + \int_0^{\omega_i} G_{\ddot{U}_g \ddot{U}_g}(\omega) d\omega \tag{4}$$

The expected k-th maximum response can be obtained by the following expression:

$$a_{max} = F_a \sigma_a \tag{5}$$

here F_a is the acceleration response peak factor.

Equation (5) is used to obtain a first estimate of the standard deviation of the maximum response for each oscillator. Information needed is the response spectrum and initial trial values for the peak factor. Using Eqs. (4) and (5), in an iterative manner the one side SDF of ground acceleration $G_{\ddot{U}_0 \ddot{U}_0}(\omega)$ is defined. A convergence criterion to compare the peak factor values obtained in two consecutive cycles is applied.

The aforementioned procedure was applied to the design response spectra specified for the three seismic areas of Mexico City (D.O.F., 1995); such spectra are shown in Figs. (2), and in Fig. (3) their corresponding one-sided SDF. For soft soil case a narrow-band process was obtained with characteristic periods at 3.9 sec (ϖ =1.61 rad/sec) and 0.6 sec (ω =10.47 rad/sec), while for firm soils a wide-band process was obtained with significant contributions in high frequencies. In the three cases the dominant periods match with the limiting horizontal section of the design seismic spectrum where soil vibration periods preclude the structure from the resonance phenomenon.

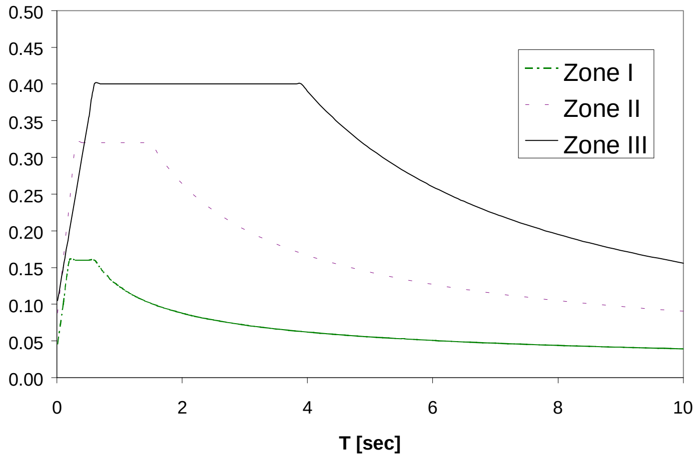

Figure 2. Design Spectra for Seismic Areas of Mexico City.

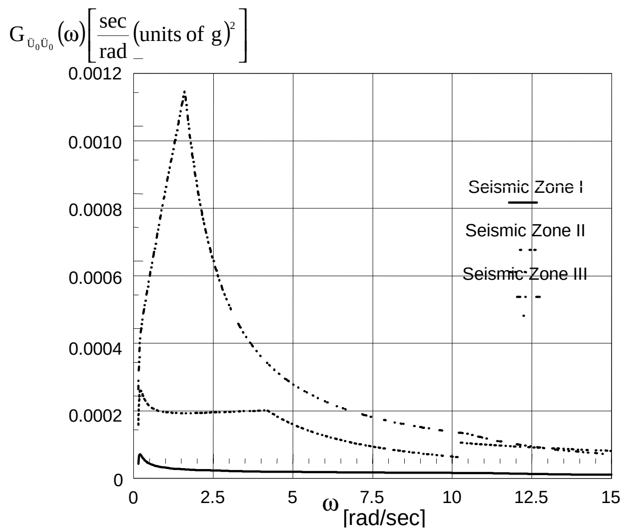

Figure 3. Ground Acceleration Spectral Density Functions for Seismic Areas in Mexico City.

SIMULATION OF GROUND ACCELERATION TIME HISTORIES

If the strongest ground seismic motion is considered as a stationary zero-mean random process with Gaussian distribution, and being expressed by a spectral density function $S_{\ddot{U}_0\ddot{U}_0}(\omega)$, ground acceleration time histories $\ddot{U}_0(t)$ can be obtained by using the Spectral Representation Method (Shinozuka and Deodatis, 1991). This method is based on the superposition of harmonic components having deterministic amplitudes and random phase angles:

$$\ddot{U}_0(t) = \sqrt{2}\sum_{n=1}^{N} A_n \cos(\omega_n t + \phi_n) \tag{6}$$

where $A_n = \sqrt{2S_{\ddot{U}_0\ddot{U}_0}(\omega_n)\Delta\omega}$ is the amplitude of the harmonic component with frequency $\omega_n = n\Delta\omega$, and ϕ_n is the phase angle evenly distributed between 0 and 2π.

To construct a time series, is necessary to divide $S_{\ddot{U}_0\ddot{U}_0}(\omega)$ into N spectral bands, whose width will be $\Delta\varpi$, and select a frequency (ω_n) to be representative for each spectral band. In the frequency domain, each of those bands is represented by a Dirac function, while in the time domain it corresponds to a sinusoidal component with random phase.

In Figure (4), three simulations for the strongest phase of the ground acceleration for the soft soil area in Mexico City lasting 20 seconds are sketched. Time series considered 256 points and a time step of 0.081 sec. Time histories show apparent periods between 1.5 and 3.0 sec, and maximum accelerations of 0.35*g*, (*g* is the gravity acceleration), 0.205*g* and 0.22*g*, for the 1st, 2nd and 3rd simulation, respectively. It can be also noticed in this figure the presence of motion components with short periods, which arise from the spectral density function that contains all periods range covered by horizontal section in the design spectrum.

Figure (5) shows the record of the extraordinary earthquake, East-West movement in soft soil of Mexico City occurred in 1985. In figure (6) the strongest ground motion is isolated, between 20 sec and 40 sec, it has a typical long period for far tremors (T=2 sec) and maximum accelerations of 0.18g.

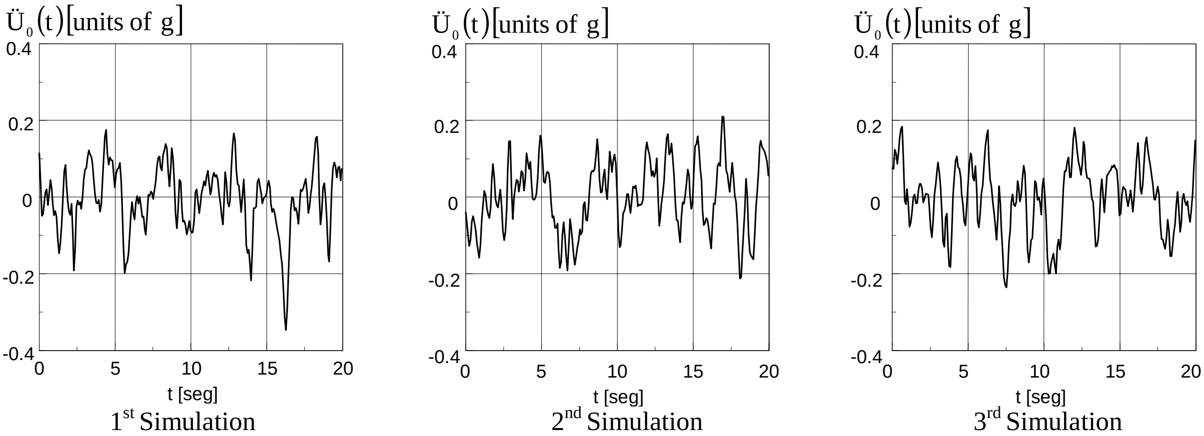

Figure 4. Simulations of ground acceleration for the soft soil area in Mexico City.

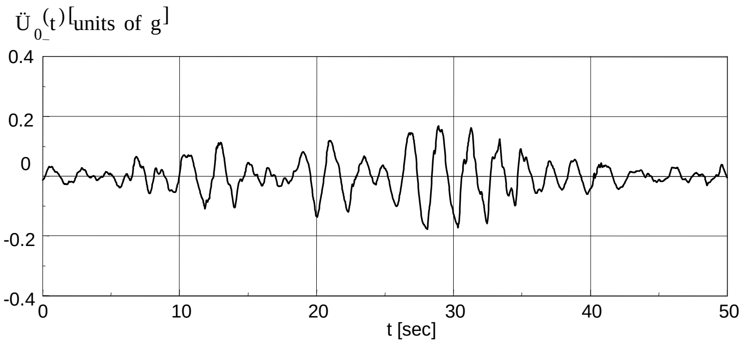

Figure 5. Acceleration time history registered in soft soil of Mexico City in 1985.

When comparing recorded earthquake time history in the interest site with those directly obtained by simulation from design spectrum, it can be seen that periods content in the secondly mentioned includes short periods but dominant long periods. Acceleration intensities for all time histories are similar in magnitude (○0.02*g*). It is also observed that the 1st simulation serial maximum intensity is about three times the corresponding for the real earthquake.

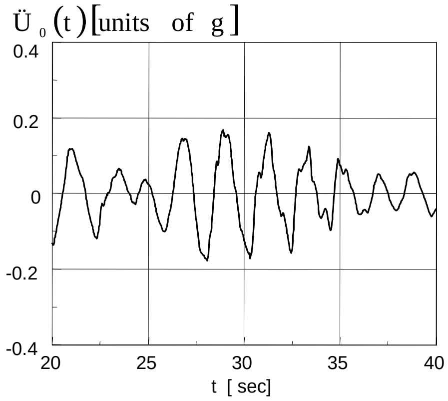

Figure 6. Strong phase of Mexico City earthquake registered in 1985

ESTIMATE OF SPECTRAL DENSITY FUNCTIONS

Ground acceleration SDF can be obtained from actual earthquake records or from numerical or experimental simulations. Spectral estimation methods are based on the Fourier Transform of the time series. By applying the Fast Fourier Transform (FFT) over ground acceleration register $\ddot{U}_0(t)$, an estimate of the SDF $\hat{S}_{\ddot{U}_0\ddot{U}_0}(f)$ can be calculated with Eq. (7):

$$\hat{S}_{\ddot{U}_0\ddot{U}_0}(f) = \frac{1}{T_0}\left\| \Delta t \sum_{k=0}^{N-1} \ddot{U}_0(k\Delta t) e^{-t2\pi fk\Delta t} \right\|^2 \tag{7}$$

where T_0 is the time series duration, and $\| \ \|$ is the norm of the argument. The FFT algorithm requires $N = 2^r$, r being a positive integer.

In Figure (7) estimates of SDF´s for three ground acceleration (strong phase) simulations are presented. In all cases, estimates perfectly match with the ground acceleration SDF determined for the soft soil area in Mexico City (Fig. 3). This assures that each time series will contain all components of spectral frequencies.

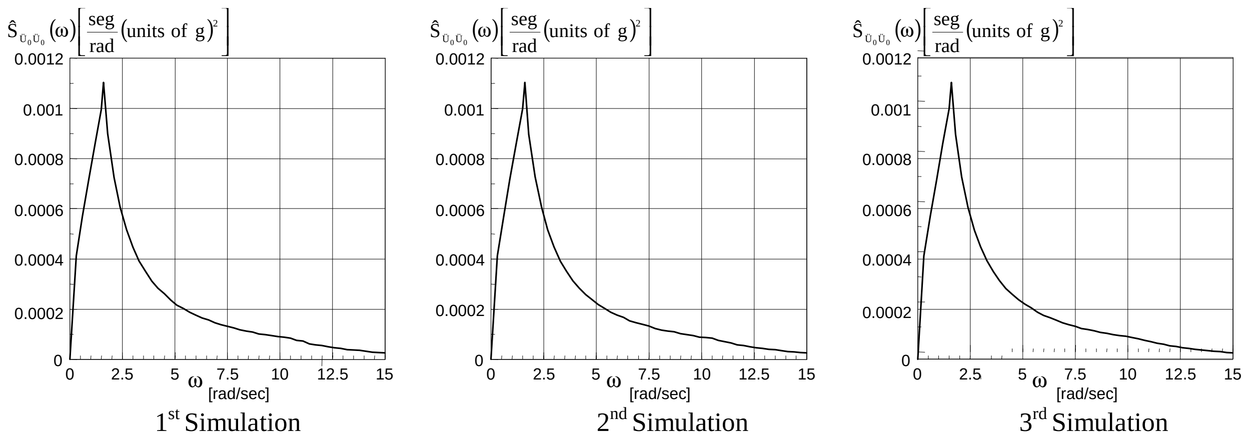

Figure 7. Estimates of spectral density functions for three ground acceleration simulations.

A stationary process is said to be ergodic if all averages taken over any individual sample are the same averages as of the assemble; then each sample represents the assemble forming the random process. The deterministic amplitude approach allows obtaining time histories for an ergodic process (Silva and Barranco, 1997), as long as the following conditions are fulfilled:

$$T_0 = \frac{2\pi}{\Delta\omega} \tag{8}$$

$$\Delta t \leq \frac{\pi}{N\Delta\omega} \tag{9}$$

For this work function $S_{\ddot{U}_0\ddot{U}_0}(\omega)$ was divided in 128 spectral bands (N), with a frequency step $\Delta\omega$ =0.3 rad/sec. Duration of the resulting time series is T_0 =20.9 sec., being the time increment $\Delta t \leq 0.081$ sec. To cover the maximum time length of the series considering the Δt value given by Eq. (9), N was taken as 256. With this consideration each one of the simulations is a sample of an ergodic process, and in this case each time series will have the same spectral density function (Fig. 7).

Figure (8) shows the estimates of ground acceleration SDF for the earthquake strong phase registered at Mexico City. It can be a narrow band process with characteristic frequencies around 3.2 rad/sec. The function is wider and its maximum intensity is 4.5 times greater than that obtained for soft soil area at Mexico City. The properties of both spectral functions can be explained taking into account the following. The record has a characteristic period that shows the site conditions and corresponds to an extraordinary earthquake. On the other hand, SDF computed has been obtained from a broad band design spectrum, in which the maximum ordinate includes expected extraordinary excitations.

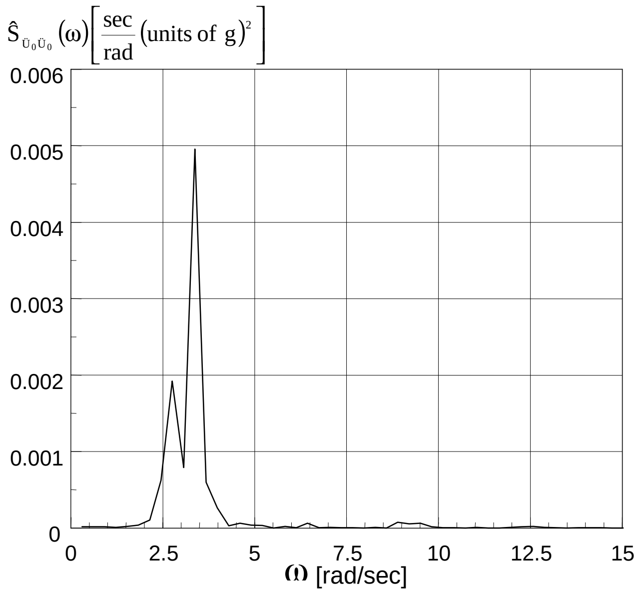

Figure 8. Estimates of SDF for earthquake registered at Mexico City in 1985.

RESPONSE SPECTRA

In this section response spectra obtained from real and simulated ground motion are studied

First, the displacement response on time domain can be evaluated through Duhamel integral:

$$x(t) = \frac{1}{\omega_D}\int_0^t \ddot{U}_0(t)e^{-\zeta\omega_K(t-\tau)}sin[\omega_D(t-\tau)]d\tau \tag{10}$$

Where ζ is the critical damping percentage, ω_k is the structure natural frequency and ω_D is the damped frequency.

Then, response spectrum is built with the period T_k of structures versus their maximum responses.

Acceleration response spectra for the three ground movement simulations are shown in Fig. (10), and Fig. (11) shows the spectrum corresponding to the earthquake recorded in Mexico City. It can be inferred from Figs. (10) and (11) that acceleration histories produced from design seismic spectrum, have much more influence on the whole structural period range of response than the actual acceleration signal except for structures with periods near to 2 sec. Therefore, using synthetic signals through the proposed methodology produces maximum results of the same order than those obtained using design seismic spectrum.

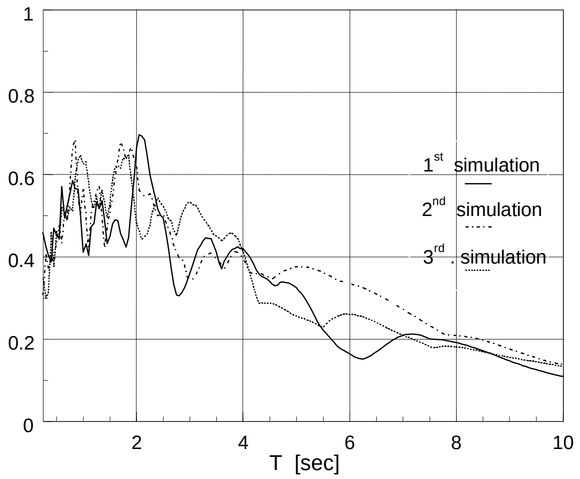

Figure 10. Response spectra from simulations

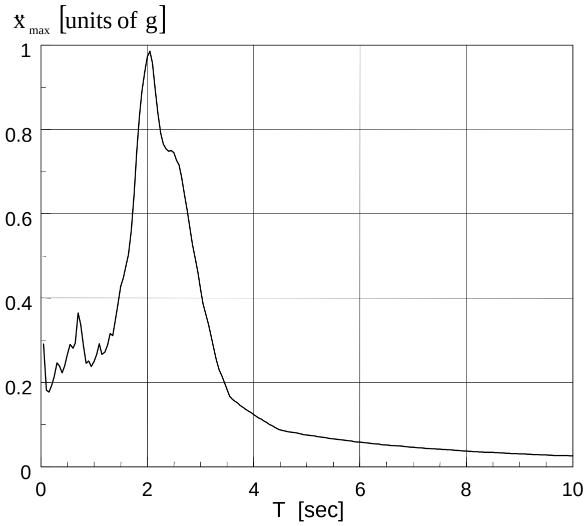

Figure 11. Response spectra from earthquake registered at Mexico City

Figure (12) shows the mean acceleration response spectrum after 1000 samples of ground movement simulations. This spectrum fits almost totally the design seismic spectra, with maximum intensities of 0.52 g for periods between 0.6 and 2.0 seconds. Notice that beyond 2.0 sec (in the structure response range of interest), both spectra are the same. It should be mentioned that differences are supposed to be produced due to numerical approaches, this subject is still under study.

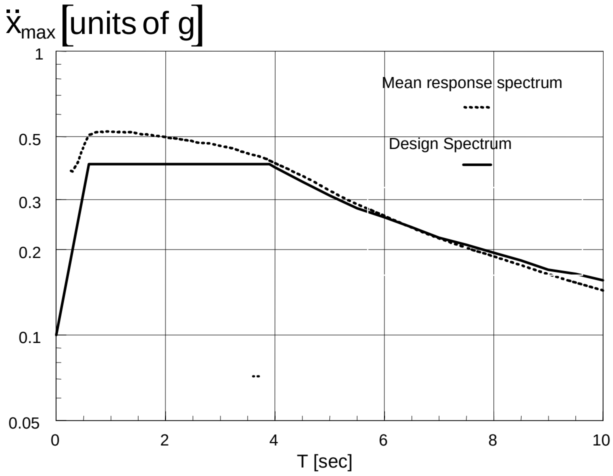

Figure 12. Mean acceleration response spectrum after 1000 ground movement simulation

CONCLUSIONS

A procedure to obtain ground acceleration time histories whose intensities are compatible with design seismic excitation recommended by the design codes was presented. It was found that the time series simulated for soft soil conditions of Mexico City give ordinate values comparable in magnitude to those in the recorded earthquake motion. It has been shown that acceleration time histories can be simulated by samples of ergodic processes containing the whole spectral frequency content. Structural response is similar using artificial series or design seismic spectrum, and these motions are unfavourable, except for buildings having periods near 2 sec.

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