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An approach for synthesizing tri-component ground motions compatible with hazard-consistent target spectrum - Italian aseismic code application

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ABSTRACT

A versatile approach for synthesizing non-stationary multicomponent ground motions compatible with a given target response spectrum is presented. In conjunction with performance-based structural design, the proposed approach combines a scenario-based procedure to select the target spectra of the three components of the motion, and a stochastic scheme, with an iterative wavelet-based method to generate the artificial time histories. In this context, the selection of an appropriate target spectrum is mandatory to synthesizing accelerograms with proper frequency content, input-energy, effective duration, and inelastic demand. In the scenario-based assessments, the target spectrum is derived directly from an earthquake scenario defined by seismic hazard disaggregation and strong ground-motion attenuation relationships. Firstly, the design spectrum specified by aseismic code provisions is replaced by a set of conditional mean spectra (CMS) for each of the ground motion components. Subsequently, an inverse stochastic dynamics problem, defined by a set of parametric evolutionary power spectra (EPS), is formulated and solved in a point-wise format for each CMS and for the three components of the motion. To improve the matching between the response spectrum of the simulated records and the CMS, an iterative procedure involving the family of harmonic wavelets is then employed. Post-processing for a proper baseline correction of the records is performed to synthesize ground-motions yielding realistic velocity and displacement traces. To illustrate the effectiveness of the approach, extensive numerical results pertaining to the Italian aseismic code provisions are included in this paper. In this regard, Monte Carlo simulations are undertaken to relate the CMSs to the evolutionary power spectrum. In particular, non-constant peak factor expressions via regression analysis are derived for various ground-motion durations. Finally, the nonlinear responses of elasto-plastic SDOF oscillators with different values of the yield strength reduction factor are considered. The oscillators subjected to artificially generated records and a set of natural unscaled and spectrum-compatible accelerograms, are examined in terms of ductility demand and equivalent number of yield cycles.

1. Introduction

The assessment of the seismic collapse probability of a structure requires the evaluation of its response considering the range of potential earthquakes that may affect it. For this purpose, non-linear dynamic analysis can be performed. This approach is required by many aseismic code provisions (e.g. ICC [24]; EN-1998; [17], CS.LL.PP. [14]) for buildings with irregular configuration or for relevant lifeline infrastructures. These analyses are sensitive to the characteristics of the ground-motions (i.e. the inelastic demand), such as the amplitude, the frequency content, the input-energy and the duration of the accelerograms [8].

Usually, the input accelerograms are obtained by selecting real ground-motions or synthesizing artificial records that match in a certain way a design/target spectrum provided by the seismic regulation code or the Uniform Hazard Spectrum (UHS) obtained from Probabilistic Seismic Hazard Analysis (PSHA). A concern regarding the PSHA was recorded in a report of the USA National Research Council (1988). Indeed, since the PSHA combines the contributions of different earthquake scenarios that occur on different seismogenic zones, it has been pointed out that the UHS may be an improper target spectrum for the purpose of a non-linear dynamic analysis [42,32,35].

An alternative method, followed in this study, that leads to a more realistic and less conservative spectrum has been recently proposed

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[19]. In this context, it is possible to replace the UHS by a set of design earthquake spectra computed for a set of periods of interest by means of seismic hazard disaggregation. Examples of this procedure can be found in McGuire [35], Baker and Cornell [3] and FEMA P-58-1 [19]. In particular, Baker and Cornell have developed a tool to "decompose" the UHS in Conditional Mean Spectrum (CMS). Each CMS provides the expected response spectrum for a specific period of interest and for a given target spectral acceleration. The target spectral acceleration can be obtained from Probabilistic Seismic Hazard Analysis (PSHA), directly from the UHS or from the design spectra in building codes.

The selection of accelerograms from an historical database, using a narrow search window to consider most of the seismogenic characteristics of the location, yields, in general, a small number of available records. For this reason, it is a common practice to scale the real ground-motions by a constant factor (e.g. Naeim et al. [39]; Kottke and Rathje [30]; Iervolino et al. [27]; Das and Gupta [15]; Suarez and Montejo [51]) or to modify their frequency content (e.g. Karabalis et al. [29]; Mukherjee and Gupta [38]; Suárez and Montejo [50]). Alternatively, several techniques for generating artificial time histories have been developed [16]. Perhaps the first review of the spectrum compatible simulation methods can be found in Spanos [49]. These techniques can be considered as belonging to two classes. In the first one, the accelerograms are generated as realization of a stochastic process characterized by its power spectrum. This can be performed deriving stationary power spectra [22,44,18,13] or evolutionary power spectra [45,21,46] consistent with the response spectrum. The second approach is based on seismological source models [31,40]. The majority of these models require that a suite of real recorded accelerograms is used as seed for synthesizing new time histories. Further, most of these studies have focused on the generation of monocomponent earthquake records. Note, however, that in general aseismic building code provisions require the simultaneous use of three components of the excitation when a spatial model of the structure is analyzed.

In this paper an approach for synthesizing non-stationary tri-component ground motions compatible with a given target response spectrum is presented. The stages of the proposed approach are:

1. select a proper target acceleration spectrum consistent with the site geologic characteristics;
2. generate tri-component artificial time histories with appropriate frequency content, input-energy, duration and inelastic demand;
3. and make the mechanization procedure versatile as it does not require real earthquake records as seed for synthesizing the new ground-motions.

To address the problems related to the choice of target spectrum, a scenario-based procedure involving seismic hazard disaggregation is used to define the earthquake scenario at a specified magnitude and distance from the site. Then, the shaking hazards are represented by a median acceleration response spectrum obtained from the ground motion attenuation relationship. Thus, the design spectrum provided by the aseismic code provisions is replaced by a set of conditional mean spectra for the three orthogonal components of the motion. Next, based on the previous work of Spanos and Loli [45] and Spanos et al. [46], the parameters of the evolutionary power spectra (EPS) related to the target CMSs are obtained by solving the inverse stochastic dynamics problem in an approximate manner for each component. In particular, the frequency content of the EPS is captured by the Clough-Penzien spectrum [11]. The formulation of the problem involves the estimation of the peak factor [45,54]. In this regard, the solution of the so called first-passage problem is circumvented via Monte Carlo simulations. Specifically, a frequency and duration dependent peak factor is estimated to achieve a better agreement between the target CMS and the average response spectrum of the artificial generated time histories. Each non-stationary component of the motion is obtained by filtering a white-noise process through an ARMA digital filter and then multiplying it by an envelope function. Subsequently, an enhanced design spectrum compatible matching is achieved for each time history by means of an iterative procedure based on the use of the harmonic wavelets.

To elucidate the effectiveness of the approach, extensive numerical results pertaining the Italian aseismic code provisions (NTC2008: [14]) are included.

2. Background on conditional mean spectrum

Consider a structure with a period of interest T^*(e.g. its first natural frequency). For a given location it is possible to obtain, using hazard disaggregation, the pair mean causal magnitude ($\overline{M}$) and mean causal distance ($\overline{R}$) [35,6,8]. Thus, the associated median predicted spectrum can be computed using a ground-motion prediction model (often called attenuation relations); it estimates the probability distribution of ground motion intensity given the properties of the earthquake source (magnitude and style-of-faulting), distance, and site response (site class or V_{S30}). If the target spectral acceleration $S_a(T^*)$ is known (e.g from the UHS or building code spectrum), the parameter $\varepsilon(T)$ for $T = T^*$ is provided by the equation [2]:

$$\varepsilon(T^*) = \frac{\ln S_a(T^*) - \mu_{\ln S_a}(\overline{M}, \overline{R}, T^*)}{\sigma_{\ln S_a}(T^*)}, \tag{1}$$

where $\mu_{\ln S_a}(\overline{M}, \overline{R}, T^*)$ and $\sigma_{\ln S_a}(T^*)$ are the predicted mean and standard deviation, respectively, of spectral acceleration at a specific period T^* computed using an attenuation relationship, and $S_a(T^*)$ is the acceleration value of the target spectrum at the same period. The parameter $\varepsilon(T)$ is defined as the number of standard deviations by

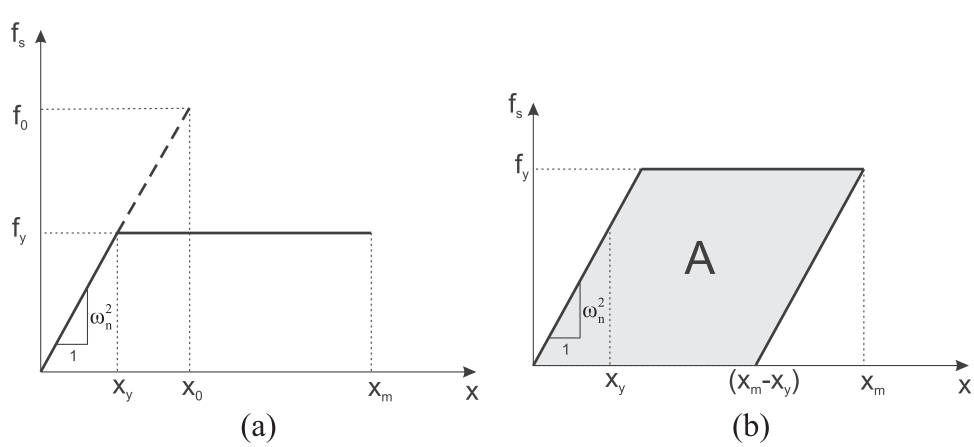

Fig. 1. (a) Elastic-plastic force-displacement relation; (b) parameters to determine the number of equivalent yield cycles for an elasto-plastic system.