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Influence of soil type on damping reduction factor: A stochastic analysis based on peak theory

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ABSTRACT

Damping reduction factor plays a central role both in scientific literature and seismic codes, but still now proposed formulations show a quite large scatter. The main goal of the present work is to explore a new definition of the damping reduction factor. The concept of stochastic response spectrum is adopted in order to predict the earthquake response of a linear SDoF system, on the basis of the random vibration theory for non-stationary process. The peak of the response of a SDoF system under a non-stationary stochastic process is used to define the stochastic displacement spectrum. The damping reduction factor is thus evaluated as the ratio between the maximum displacement of systems with a given damping and a conventional one subject to the same earthquake.

1. Introduction

Seismic design and assessment of ordinary structures are generally based on response spectrum analyses in which a 5% damping ratio is adopted. Actually two types of damping can be recognized in structures, one of which comes from structures themselves and the other from the added energy dissipation devices. Within this classification, high-damping elastic response spectra should be applied in the case of structures equipped with seismic isolation or energy dissipation systems. In this context the Damping Reduction Factor (DRF) represents an effective tool for design purposes in order to estimate response spectra characterized by damping ratio different from 5%. Namely the DRF is a scaling factor applied in response spectrum analyses to translate spectral ordinates at 5% damping into ordinates corresponding to other values of damping ratio.

In the last decades several studies for the formulation of the DRF have been carried out by many researchers, the outcomes of which have been adopted by the main seismic codes [1–7]. Until now researchers were mainly oriented to estimate the DRF by the observation of the effects of viscous damping on the maximum displacement response of elastic SDOF systems subjected to artificial or natural earthquakes [1,2,4,6,7]. In addition to its obvious dependence on damping and period, recent investigations, based on real acquisitions, showed the dependence of the scaling factor on seismological parameters such as magnitude, distance from the source and local site conditions [6]. In a recent paper, Palermo et al. [8] used a stochastic approach with stationary input to provide insight into the observed trends and to identify the key parameters which govern the damping reduction factor. Practically all the aforementioned studies, except for the latter one, are based on statistical analyses of the time-history response of SDOF damped systems subjected to real earthquake records. Nevertheless, despite the great quantity of studies dedicated to the problem, an evident understanding of the observed trends is still missing.

The study herein proposed deals with a stochastic approach to obtain the DRF and to identify the fundamental parameters which govern it. The adopted methodology is based on a stochastic approach with non-stationary input, contrarily to the study from Palermo et al. [8] dealing with a stationary input. Moreover, in the presented study, a formulation based on the peak theory of stochastic processes is utilized and the concept of Seismic Spectrum in stochastic meaning is introduced. The DRF is defined as the ratio between the displacement spectrum of a system with a given value of the damping ratio and the displacement spectrum of a system with a conventional value of the damping ratio (equal to 5%) subject to the same earthquake. In this framework, the peak theory represents the most rigorous way to translate the concept of spectral value, i.e. of the maximum value of the system time response, in stochastic meaning.

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2. Description of the model and of the seismic ground motion

2.1. Damping reduction factor

The equation of motion for a linear-viscous SDOF system subjected to a seismic ground acceleration action $\ddot{X}_g(t)$ can be written as:

$$\ddot{X}_0(t) + 2\xi_0\omega_0\dot{X}_0(t) + \omega_0^2 X_0(t) = -\ddot{X}_g(t) \tag{1}$$

where X_0 is the system-ground relative displacement, ξ_0 the damping ratio and ω_0 the system natural frequency, defined as follows:

$$\omega_0 = \sqrt{\frac{k}{m}} \text{ and } \xi_0 = \frac{c}{2\sqrt{km}}, \tag{2}$$

k and m being the stiffness and the mass of the system, respectively.

Displacement spectrum and Pseudo-acceleration spectrum for the system are defined as:

$$S_d = |X_0(t)|_{max}\ displacementspectrum;\ PS_a = \omega_0^2 S_d\ pseudoaccelerationspectrum; \tag{3}$$

The Damping Reduction Factor (DRF) η is introduced to get an approximate estimate of the high damping elastic response spectra from their 5% counterpart, adopting the following equations:

$$S_d = \eta S_{d,\xi=5\%};\ PS_a = \eta PS_{a,\xi=5\%} \tag{4}$$

where $S_{d,\xi=5\%}$ and $PS_{a,\xi=5\%}$ are the elastic displacement and pseudo-acceleration response spectra for damping ratio equal to 5%, while S_d and PS_a are the corresponding quantities for damping ratios ξ greater than 5%. The same reduction factor η is used for both displacement and pseudo-acceleration response spectra, since they are mutually related through the relationship given by Eq. (3).

On the basis of Eq. (4), if the DRF is known, the high-damped response spectra can be evaluated from the response spectra with damping ratio equal to 5%.

2.2. Earthquake ground motion modelling and site soil conditions

In this study, a stochastic-based approach is used to evaluate the DRF, assuming a non-stationary model for the seismic action. More in detail, the seismic acceleration $\ddot{X}_g$ is modeled as a uniformly modulated non-stationary stochastic process, obtained by multiplying a time modulation function $\varphi(t)$ for a stationary process. An extensively applied stochastic approach was proposed by Clough and Penzien [9] who considered a linear fourth order filter, obtained from a series of two linear oscillators, forced by a modulated white noise process. Accordingly, ground acceleration $\ddot{X}_g(t)$ can be expressed as:

$$\begin{cases} \ddot{X}_g(t) = -\omega^2{}_c X_c(t) - 2\xi_c\omega_c\dot{X}_c(t) + \omega^2{}_p X_p + 2\xi_p\omega_p\dot{X}_p(t) \\ \ddot{X}_c(t) + \omega^2{}_c X_c(t) + 2\xi_c\omega_c\dot{X}_c(t) = \omega^2{}_p X_p + 2\xi_p\omega_p\dot{X}_p(t) \\ \ddot{X}_p(t) + 2\xi_p\omega_p\dot{X}_p(t) + \omega^2{}_p X_p = -\varphi(t)W(t) \end{cases} \tag{5}$$

where: $X_p(t)$ is the response of the first filter, having frequency ω_p and damping coefficient ξ_p; $X_c(t)$is the response of the second filter characterized by frequency ω_c and damping ratio ξ_c; $W(t)$ is the white noise stochastic process, whose constant bilateral Power Spectral Density function is S_0. Finally, $\varphi(t)$ is the modulation function [10]; the function proposed by Jennings et al. [11] is herein adopted, by assuming $t_1 = 5$ s, $t_2 = 12$ s, $\vartheta = 0.4$ (see Eq. (11) in [12]). By varying the Kanai-Tajimi parameters and the parameters of the modulation function, it is possible to represent all site conditions, earthquake durations, magnitudes, epicentral distances, etc., i.e. properly selecting the parameters involved in the stochastic model of the earthquake [13].

2.3. Stochastic-based DRF

Let us consider a SDoF freedom subject to a seismic motion modeled by the non-stationary Clough and Penzien (CP) stochastic process. Expressing Eq. (5) in the state-space, the motion equation of the system becomes:

$$\dot{\mathbf{Z}}(\mathrm{t}) = \mathbf{AZ}(\mathrm{t}) + \mathbf{F}(\mathrm{t}). \tag{6}$$

In Eq. (6) **Z** is the state-space vector and **F** is the force vector, given by:

$$\mathbf{Z} = (X_0\ , X_c\ , X_p\ , \dot{X}_0\ , \dot{X}_c, \dot{X}_p)^T;\ \mathbf{F} = (0\ , 0\ , 0\ , 0\ , 0\ , -\varphi(t)W(t))^T \tag{7}$$

while **A** is the state matrix:

$$\mathbf{A} = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -\omega_0^2 & \omega_c^2 & -\omega_p^2 & -2\xi_0\omega_0 & +2\omega_c\xi_c & -2\omega_p\xi_p \\ 0 & -\omega_c^2 & +\omega_p^2 & 0 & -2\omega_c\xi_c & +2\omega_p\xi_p \\ 0 & 0 & -\omega_f^2 & 0 & 0 & -2\omega_f\xi_f \end{pmatrix} \tag{8}$$

The stochastic response of the system excited by the non-stationary modulated CP process can be obtained by solving the following matrix Lyapunov differential equation [12,14]:

$$\dot{\mathrm{R}}(t) = \mathrm{AR}(t) + \mathrm{R}(t)\mathrm{A}^T + \mathrm{B}(t) \tag{9}$$

where $\mathrm{R}(t) = \langle \mathbf{ZZ}^T \rangle$ is the covariance matrix and $\mathrm{B}(t)$ is a square matrix with all zero elements except for the last one, equal to $2\pi S_0\varphi(t)^2$. The solution of Eq. (9) can be performed by adopting different numerical approaches [15–17].

3. Peak response and stochastic response spectrum evaluation

A seismic response spectrum is defined as the plot of the maximum response (displacement, acceleration) of a SDoF system to a recorded earthquake versus its natural period for any assigned value of structural damping. In stochastic meaning, in the same way, the seismic response spectrum is the plot of a stochastic evaluation of the maximum system response to a stochastic model of the ground motion versus the natural period for any assigned value of structural damping.

In this study, in order to obtain the DRF by Eq. (4), the displacement spectrum is evaluated in stochastic terms by mean of the peak theory of stochastic process [18,19]. More in detail, the maximum displacement $X_0{}^{max}$ is defined as the system displacement which is not exceeded with a given probability P^*. Consequently, the central matter now is to evaluate this maximum displacement that in a mathematical formulation is the displacement threshold b that will not be exceeded with a probability P_f^* during the system lifetime [13]. By applying the procedure described in [19], the spectrum is obtained by varying the natural period of the SDoF. The maximum displacement such that the probability that $X(t)$ will leave the domain $[-X_{\max}^P, +X_{\max}^P]$ is equal to an assigned value P^*, is defined as $X_{\max}^{P^*}(t)$. This inverse problem can be approached by a numerical procedure. It starts with a first tentative value of the maximum displacement $X_{\max}^0$ and iterates i-times until the following stop condition is verified:

$$\|P(\pm X_{\max}^i, t) - P^*\| \le \varepsilon \tag{10}$$

ε being a small enough value. At the end of this iterative procedure the maximum displacement can be assumed as $X_{\max}^{p*} = X_{\max}^i$. After the maximum displacement has been evaluated, a stochastic measure of the displacement spectrum can be obtained and finally the DRF η is achieved by Eq. (4). In the following analyses P^* is assumed equal to 10^{-3}.

4. Results and discussion

In this section, some sensitivity analyses are carried out in order to evaluate the influence of the different involved parameters on DRF.