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Technical Note

Soil damping influence on seismic ground response: A parametric analysis for weak to moderate ground motion

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ABSTRACT

Small-strain stiffness and damping ratio are the key parameters for modeling the dynamic behavior of soils, but they are often problematic and onerous to obtain under field conditions. This is particularly true for the attenuation characteristics. As an alternative to classical laboratory tests, that are costly and prone to inaccuracies due to scale and sampling issues, recent studies stress the opportunity of using in situ measurements, and particularly surface-wave methods. However, while these methods are often used to provide shear wave velocities, they are more rarely used to give in situ estimates of damping parameters. Similarly, it is uncommon to extract attenuation information from down-hole tests. In practice, the usual anti-earthquake design is confronted with a scarcity of laboratory test measurements and with the intricacies of obtaining reliable in situ attenuation measurements. Consequently, shaking simulations commonly use literature values of the damping coefficient. This choice is often motivated by the assumption that damping does not have a critical role in ground shaking evaluations, especially for weak-moderate motion cases. The purpose of this work is to provide, for these conditions, an analysis of when an accurate characterization of the damping coefficient is needed to produce reliable shaking predictions. We performed a stochastic analysis of synthetic seismic response for different realistic subsoil conditions using as input several real ground motion records. For completeness, we also compared linear-equivalent to fully non-linear shaking simulations, showing that, for the moderate-strain conditions we consider, the linear-equivalent approach is adequate. In our simulations we fixed the subsoil structures and material deformation properties while we adopted a Monte Carlo approach to explore the effects of randomly variable damping coefficient values. Our results show how an accurate knowledge of the attenuation coefficient is of minor importance in absence of strong impedance contrasts in the shallow subsurface.

1. Introduction

The importance of the local site response and ground shaking amplification on building damages is well known [46]. Several advanced approaches have been proposed by the scientific community for virtual seismic scenarios [6,7,49,40]. For a common theoretical seismic response analysis, the input parameters must be a selection of accelerograms and realistic subsoil models. These models, regardless of their being one-, two- or three-dimensional, need to be populated by physical properties such as layer structure, seismic waves propagation velocities, materials densities as well as their capability of dissipating energy. The last parameter takes the various forms of an attenuation coefficient α [dB/m], a quality factor Q [dimensionless] or damping ratio D [dimensionless]. Quality factor (Q) and dissipation factor (Q^{-1}) are usually preferred in the geophysics and seismology literature. In soil dynamics and geotechnical earthquake engineering, the parameter that traditionally measures the soil energy dissipation during harmonic excitation is the damping ratio (D), defined as:

$$D = \frac{\Delta E}{4\pi E} \tag{1}$$

where ΔE represents the energy dissipated during one cycle at circular frequency ω, and E is the maximum strain energy stored during the cycle. Note that, due to mathematical convenience, the visco-elastic behavior of soils is generally modeled using a Kelvin–Voigt approach [35]. The damping ratio defined in this manner is, in general, frequency-dependent [41,4,17]. However, at small

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strain levels (weak-moderate motion), soil damping ratio is considered to be hysteretic and therefore frequency independent [34,40]. Frequency-independent damping ratio is also called rate-independent or hysteretic damping, as it causes the cyclic stress–strain curve to exhibit a hysteretic loop. As suggested by Knopoff [32], the dissipation factor [Q^{-1}] is equal to two times the damping ratio [D]:

$$Q^{-1} = \frac{\Delta E}{2\pi E} = 2D \quad (2)$$

Laboratory measurements of the damping ratio are commonly carried out using the resonant column or the torsion shear tests. These measurements are very well established and usually their interpretation assumes that a linear visco-elastic constitutive soil model applies. The damping ratio D is computed using approaches such as the free vibration decay, half-power bandwidth methods or the random decrement method [17]. In cyclic-triaxial tests the damping is calculated directly from the hysteresis in the stress strain curve [53]. Accurate laboratory tests have been used extensively to characterize soil deposits especially for research aims [27,31], but unfortunately they are not often performed for usual in situ engineering characterization. Given the limited availability of in situ estimates, classical laboratory experimental results are often taken from the literature [39,36,14,54] as reference damping values.

On the other hand, in situ soil parameter characterization is getting more and more common today. In particular, in situ shear wave surveys are geophysical tools of increasing application in earthquake engineering. Estimates of shear wave velocity V_s [m/s] can be obtained using several techniques, from borehole investigations [3] to SH reflection prospecting [16]. Over the past decades surveys based on the analysis of surface-wave dispersion (i.e., variation of phase or group velocity with frequency) have been intensely developed, leading to a number of affordable methodologies [50,49,41,51,9,11]. In situ experimental estimation of shear velocity relationship with important parameter as resonance frequencies were recently carried out by Hall and Bodare [22].

Many recent pieces of work claim that in situ measurements shall be used also to gain a solid understanding of attenuation characteristics in soil deposits. In situ energy attenuation measurements potentially provide a means to estimate low-strain material damping, free from the problems of specimen representativeness [22,29,13]. After the seminal work of Rix et al. [43] many others tackled the in situ attenuation measurement problem [35,20,44,5]. These studies suggest a simultaneous determination of stiffness and damping ratio. One approach is based on the measurements and joint inversion of the dispersion and attenuation curves of Rayleigh waves. The damping ratio is computed from particle motion attenuation measurements using several approaches, such as amplitude decay with distance, spectral slope, waveform inversion and pulse rise methods [24,28,42,38,21]. Despite these progresses regarding in situ damping measurements, only limited applications of these techniques have been observed. Part of the problem lies in the scarce interest for the identification of damping characteristics in the usual practice of seismic response site analysis, probably because the importance of damping is not fully appreciated. As a matter of fact, damping is often a neglected input parameter in seismic amplification analysis.

Note that the case of a uniform damped soil on rigid or elastic rock is well known from the literature [36] and from this simple case it is apparent how material damping is indeed very important for such cases, at it affects, together with radiation damping, the amplitude at resonance. However, little is known of how important damping is in the presence of weak impedance contrasts between soil and bedrock, and what are the characteristics of the relevant transition towards the extreme case of a very stiff bedrock.

The goal of this paper is to help define the cases where an accurate identification of the damping characteristics is needed in weak-moderate motion conditions, as opposed to cases where literature values can be used with no major detriment to the prediction accuracy. Our investigation is based on 1D linear-equivalent analyzes, and a comparison with fully non-linear shaking predictions is made for completeness. We considered a common moderate seismicity condition and explored it using:

- different synthetic soil stiffness profiles with growing impedance contrasts;
- several different real input seismograms;
- a Monte Carlo sampling of damping values, taking into account a number of damping literature data for typical soil deposits.

2. Selection of the damping parameter set

The first step in our analysis is the identification of a realistic distribution of damping values for several soil types. We first considered a number of literature damping estimates for earth deposits, from coarse gravel to clay, given as a function of shear strain ξ. We took into account particularly the laboratory damping measurements by Seed and Idriss [47]; Hardin and Drnevich [23]; Kokusho [30,31,33]; Idriss [25]; Bolton and Wilson [12]; Vucetic and Dobry [52]; Field and Jacob [18]. As a result of considering the ensemble of these dataset, we elaborated an average damping curve with confidence intervals (computed as +/− one time the standard deviation at each strain level), as shown in Fig. 1a. Since damping cannot have negative values, we fitted the data using a

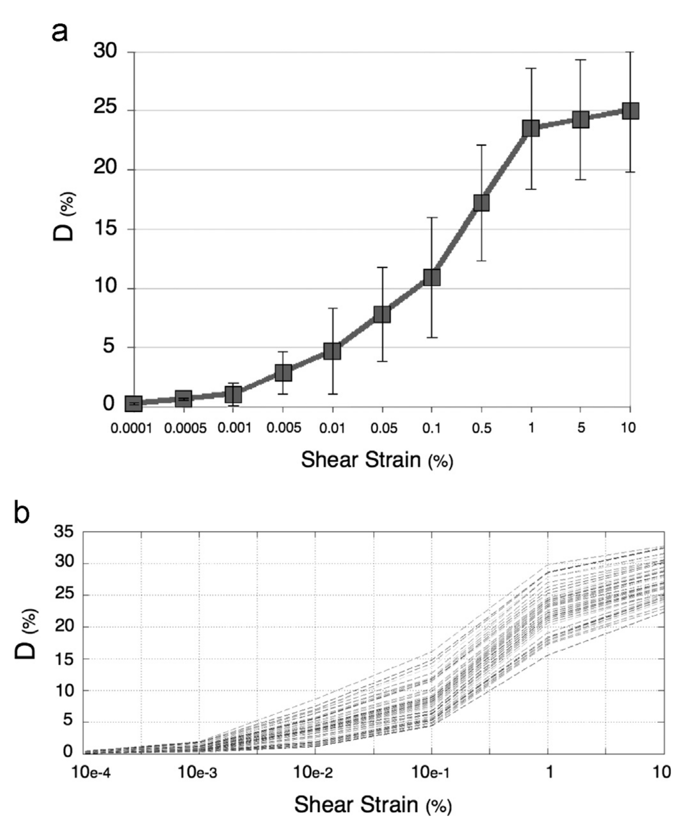

Fig. 1. (a) Average and confidence intervals of damping coefficient D as a function of shear strain, derived from the analyzed literature. Note that the shear strain axis is log-normal. (b) The 50 damping curves obtained from random sampling of the distributions in Fig. 1(a), and used for the Monte Carlo ground shaking simulations.