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Selection of the optimal frequencies of viscous damping formulation in nonlinear time-domain site response analysis

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ABSTRACT

Viscous damping is commonly employed in a nonlinear time-domain site response analysis to capture soil damping at small strains. In contrast to the generally accepted concept of the frequency-independent behavior of soil damping, the viscous damping employed as Rayleigh damping is frequency dependent and can overdamp or underdamp wave propagation. This study revisits the issue of selecting the target value of viscous damping frequencies to minimize the effect of frequency-dependent damping. The proposed criterion considers both the site frequency (SF) and frequency characteristics of input motion (e.g., predominant frequency (PF) or mean frequency (MF)) and is more accurate than the widely used protocol in practice. In the Rayleigh damping, the low optimal frequency can be selected as SF but the high optimal frequency should be selected as the maximum between the PF/MF of the input motion and 5SF.

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1. Introduction

One-dimensional site response analysis is routinely performed to assess local site amplification effects during a seismic event [1,2]. The vertical propagation of horizontal shear waves allows the approximation of ground motion, whereas horizontal soil layers represent the site stratigraphy. The solution of the wave propagation equation is performed in either the frequency domain (FD) or time domain (TD). Nonlinear analysis is becoming widely used because it can accurately simulate the nonlinear behavior of the soil and perform effective stress analysis, wherein the development of the seismic pore pressure is modeled. In contrast to laboratory tests that demonstrate the limited influence of the loading frequency [3], nonlinear analysis is limited by the uncontrolled loading frequency dependence of small strain viscous damping.

Viscous damping formulation, which is usually modeled by Rayleigh damping or simplified Rayleigh damping, requires one or two defined frequencies that control the shape and frequency dependence of small strain damping (Fig. 1). For Rayleigh damping, the target damping ratio is matched only at two frequencies, f_0 and f_1 (hereafter called the optimal frequencies). The Rayleigh damping formulation underestimates the damping at frequencies between f_0 and f_1 and overestimates the damping at frequencies lower than f_0 and higher than f_1. The defined frequencies have an important influence on the propagated ground motion [4–8]. Thus, one of the major difficulties in performing nonlinear site response analysis is the selection of formulation frequencies.

In this study, we revisit the aforementioned issue of selecting the optimal frequencies for viscous damping to resolve some of the ambiguities in the current practice. We initially conduct a comprehensive review of previous recommendations. Thereafter, some analyses with bounding cases are performed to assess the recommendations and explore whether they work or not. A solution applicable for general cases is suggested to form the basis of the specifications of viscous damping parameters for most TD codes. The recommendation is verified with a set of analyses that cover a wide range of cases.

2. Selection of optimal frequencies

A few formal protocols are available to guide analysts in selecting the model type and parameters of Rayleigh damping. Most practitioners use simplified or full Rayleigh damping, whereas extended Rayleigh damping [6] is seldom applied in practice. The target damping level ξ is considered the small strain damping (1–5%).

With regard to the optimal frequencies for the full Rayleigh damping, a low frequency f_0 is generally selected as the

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fundamental site frequency (SF), which can be calculated as follows:

$$SF = V_s/4H, \tag{1}$$

where V_s is the elastic shear wave velocity, and H is the thickness of the soil column. A large frequency f_1 is selected as the predominant frequency (PF) or an odd-integer multiple of the fundamental SF. Hudson et al. [4] proposed the use of SF and PF. Hashash and Park [9] showed that favorable matches with FD can be obtained when SF and 8SF are used. However, Park and Hashash [6] found that the conventional guideline in using the first and high mode of the soil column or the PF of the input motion does not always result in a good match with the linear FD solution, particularly for deep soil columns. They concluded that the two significant frequencies should be selected through an iterative process "depending on the input motion". Kwok et al. [7] recommended that when the option of using more than one optimal frequency is available, such as the full Rayleigh damping formulation, this option should be applied in lieu of the simplified Rayleigh damping because significant bias at high frequencies can occur with the latter. The two optimal frequencies in the full Rayleigh damping formulation should be set to SF and 5SF. Their recommendation is based on three selected sites ($SF==0.45$, 1.06, and 6.4 Hz) that represent a wide range of site conditions. However, the control motion for the evaluation is only one broadband synthetic acceleration history calculated for an outcropping rock site condition.

Phillips and Hashash [10] introduced an approach to constructing a frequency-independent viscous damping matrix and implemented it in DEESPOIL [11]. Rathje and Kottke [12] reported that the frequency-independent damping improves the agreement between TD and FD linear analysis, but TD analysis still present approximately 5–15% underestimation relative to the FD method at frequencies greater than approximately 5 Hz. A potential reason for this difference, according to their explanation, is the time stepping method used in TD analysis (Newmark β method with $\beta==0.25$), which introduces frequency shortening [13]. However, the transfer function (TF) by TD analyses with frequency-independent damping not only shows frequency shortening but also exhibits additional amplitude decay at a high frequency compared with that by FD analyses. This result indicates that the proposed frequency-independent viscous damping matrix is still frequency independent. The difference between TD and FD results increases with an increase in the small strain damping ratio.

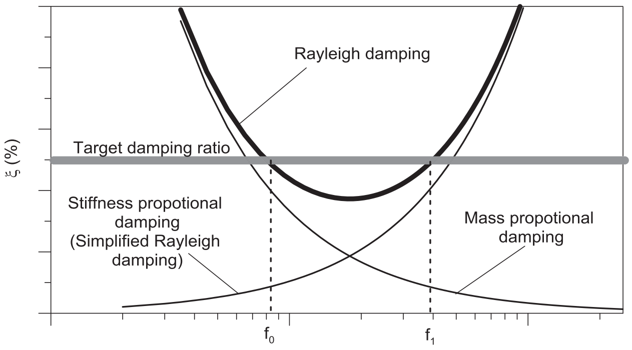

Fig. 1. Simplified and full Rayleigh damping.

The damping parameters should be selected through an iterative process depending on the characteristics of input motion. Thus, the FD and TD elastic solutions can match within a reasonable degree of tolerance over the frequency range of interest. The procedure has been implemented through a user interface in the code DEEPSOIL [11] but is unavailable for other codes. The frequency-independent viscous damping [10] employed in DEEPSOIL still exhibits a frequency-dependent behavior and has not been implemented in any 2D and 3D finite element/finite difference analysis programs. Therefore, the recommendation by Kowk et al. [7] has been mostly adopted by later analyses (e.g., [8,12]) because of its simplicity. However, as discussed previsouly, their guideline neglects the influence of input motion on optimal frequencies.

3. Analysis procedure

3.1. Evaluation approach

A series of analyses is performed to examine the selection of the frequencies/modes of the Rayleigh damping formulations on the site response analysis and to illustrate how the frequency-dependent Rayleigh damping affects the analysis results. Evaluation is performed by comparing the results of the linear TD analyses by using alternative specifications of viscous damping with the exact solution from the linear FD analyses. The FD analyses are exact because of the use of linear soil properties and frequency-independent damping. DEEPSOIL V5.1 [11], which is capable of performing TD and FD analyses, is adopted for all analyses.

3.2. Analysis cases

Three analysis cases listed in Table 1 are performed to investigate how the motion characteristics (as indicated by PF or mean frequency (MF) [14]) coupled with SF affect the optimal frequencies/modes in the Rayleigh damping.

Case 1. Single-frequency motion: One harmonic motion ($PF==MF==5$ Hz) is propagated through 50 and 500 m constant V_s profiles.

Case 2. PF and MF of broadband motion lower than SF: One broadband motions of the strong event ($M> >7.0$) recorded at long distances ($R> >100$ km) is propagated through the 30 m constant V_s.

Case 3. PF and MF of broadband motion higher than SF: One motion of the moderate event ($M==\sim 6.5$) recorded at short

Table 1
Input motions and soil columns for three analysis cases.

Case	Motion						Soil column			
	Type	Event	Station	PF (Hz)	MF (Hz)	PGA (g)	Thickness (m)	V_s (m/s)	ξ (%)	SF (Hz)
1	Harmonic	–	–	5	5	0.3	50	450	1	2.25
							500	450	1	0.23
2	Broadband	Chi-Chi	TAP090	0.86	0.95	0.13	30	250	3.5	2.10
3	Broadband	Northridge	LA00	2.62	2.59	0.39	1000	450	5	0.11

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