Simplified analysis of frame structures with viscoelastic dampers considering the effect of soil-structure interaction

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Abstract: In this study, simplified numerical models are developed to analyze the soil-structure interaction (SSI) effect on frame structures equipped with viscoelastic dampers (VEDs) based on pile group foundation. First, a single degree-of-freedom (SDOF) oscillator is successfully utilized to replace the SDOF energy dissipated structure considering the SSI effect. The equivalent period and damping ratio of the system are obtained through analogical analysis using the frequency transfer function with adoption of the modal strain energy (MSE) technique. A parametric analysis is carried out to study the SSI effect on the performance of VEDs. Then the equilibrium equations of the multi degree-of-freedom (MDOF) structure with VEDs considering SSI effect are established in the frequency domain. Based on the assumption that the superstructure of the coupled system possesses the classical normal mode, the MDOF superstructure is decoupled to a set of individual SDOF systems resting on a rigid foundation with adoption of the MSE technique through formula derivation. Numerical results demonstrate that the proposed methods have the advantage of reducing computational cost, however, retaining the satisfactory accuracy. The numerical method proposed herein can provide a fast evaluation of the efficiency of VEDs considering the SSI effect.

Keywords: viscoelastic damper; soil-structure interaction; MSE technique; frequency domain; simplified analysis

1 Introduction

In recent years, the use of energy dissipation devices to reduce structural vibration has received considerable attention. Various kinds of damping devices were developed, among which viscoelastic dampers (VED) have been widely used to reduce the excessive vibration of a structure under the action of dynamic loads. Many studies have been carried out to analyze the effect of VEDs on dynamic responses of structures excited by winds or earthquakes (Zhang and Soong, 1992; Mazza and Vulcano, 2007, 2011; Chang and Lin, 2004; Hwang et al., 2008; Lewandoski et al., 2012). However, due to the complexity of soil-structure interaction (SSI), these studies were based on the assumption of a rigid foundation and neglected the SSI effect on the seismic responses of structures equipped with VEDs. The studies of Veletsos and Meek (1974), Avilés and Pérez-Rocha (1996), Mylonakis et al. (2006), Medina et al. (2013) demonstrated that the SSI effect could significantly modify the structural dynamic characteristics, thus influence the responses of structures. Namely, the performance of VEDs which are related to the dynamic characteristics, especially the structural frequencies, are inevitably influenced by the SSI effect. Meanwhile, the stiffness and damping changes of the structure caused by the VED will affect the structural response and vice versa. When a structure with energy dissipaters is located on soft soil, the assumption of a rigid foundation may result in analytical inaccuracy and considerable deviation from the original design objective. Hence, the rigid base hypothesis is only reasonable for hard soil. In engineering practice, a number of structures equipped with VEDs are founded on soft soil bases, and a strong interaction between soil and structure occurs in these cases. Up until now, few studies (Takewaki and Uetani, 1999; Zhou et al., 2012) have explored the effect of SSI on the performance and effectiveness of dampers installed in frame structures. The research results of these studies indicate that the SSI effect may reduce the efficiency of the external dampers through numerical examples, but the analyses are limited and
do not provide a detailed discussion about the efficiency reduction extent of the dampers influenced by the SSI characteristic parameters. Therefore, it is worth studying the performance and quantifying the efficiency of VEDs when the SSI effect is considered through a simple and effective method, which will provide useful information for researchers and practicing engineers.

Due to the frequency-dependent dynamic properties of soil, the seismic analysis is mainly performed in the frequency domain. To obtain the exact solution of the pile impedance, complicated derivation of formulations and time consuming computation have to be done, which limits its application in engineering practice. For simplification, a widely used approach is to represent the soil with a frequency-independent lumped-parameter model (Nogami and Konagai, 1986; Wolf, 1991; Wu and Lee, 2002; Wang et al., 2013). The model consists of a few sets of connected springs, dampers and masses with unknown parameters, which are determined by minimizing the total square errors compared with the rigorous solutions. Another simple method to obtain the pile foundation impedance is to represent the pile-to-soil interplay as a dynamic Winkler beam based on frequency-dependent springs and dashpots (Gazetas et al., 1993; Mylonakis and Gazetas, 1999). The results from the method are in reasonable agreement with the more rigorous solutions, and due to its clear physical concept and low computational complexity, the method has become a popular application.

The substructure method (Kausel and Roesset, 1974; Gutierrez and Chopra, 1978; Wolf, 1989) has been successfully used to study the seismic behavior of a structure considering SSI effect, because it has the advantage of conveniently modeling the superstructure and the unbounded soil. Since the constitutive behavior of VED and the impedance function of the pile group foundation are both frequency dependent, the problem can be well studied in the frequency domain by modeling the structure-VEDs system and soil-pile system separately and then assembling.

To simplify the seismic response analysis of the SSI system, some papers by Bielak (1976), Veletos and Meek (1974), and Wolf (1989) introduce the analogy of a fixed-base replacement SDOF oscillator whose period and damping can accurately simulate the dynamic behavior of the original SSI system.

Integrating the latest studies of SSI and VEDs, the following analyses are carried out in this study. First, the equilibrium equations of SDOF and MDOF frame structures equipped with VEDs considering SSI effect are established in the frequency domain. Then simplification procedures are proposed to analyze the SDOF and MDOF coupled system. Numerical results demonstrate that the proposed methods have the advantage of reducing the computation cost while retaining accuracy.

In addition, the SSI effect on the performance of VED is studied and discussed in detail by parametric analysis through the simplification method. This demonstrates that the efficiency of VEDs decrease along with the soil softening, and the modal strain energy (MSE) technique works well with frequency dependent parameters for simplification of the SSI problem. The numerical methods proposed herein can provide a fast evaluation of the efficiency of VEDs within consideration of the SSI effect. The parametric analysis results can give a quantitative assessment of the need for additional damping in the existing structures or the design of new structures considering the SSI effect.

2 Fractional derivative Maxwell model for VED

The constitutive behavior of VED might be dependent upon the frequency, temperature, and amplitude. However, a mathematical model considering all these effects is very difficult to achieve. Therefore, for practical applications, isothermal conditions are usually considered in the simulation conditions. Thus, many mathematical constitutive models of VED just consider the frequency dependent constitutive behavior. The five-parameter Fractional derivative Maxwell (FDM) model is used herein to demonstrate the behavior of the general viscoelastic damper. The model was first proposed by Makris and Constantinou (1991) and validated by dynamic testing, and very good agreement between the predicted and experimental results was obtained over a wide range of frequencies. The general force-displacement constitutive equation of the model can be expressed as:

\[ P(t) + b_0D^\beta[P(t)] = k_0u(t) + c_0D^\alpha[u(t)] \]  

where \( t \) is the time, \( P(t) \) is the damping force and \( u(t) \) is the damper deformation; \( b_0, \alpha, \beta, k_0, c_0 \) are material constants with the constraint that \( 0 \leq \beta, \alpha \leq 1 \). The fractional derivative order \( D^\alpha[\cdot] \), \( D^\beta[\cdot] \) can be defined by an integral form as follows:

\[ D^\alpha[f(t)] = \frac{d^\alpha f(t)}{dt^\alpha} = \frac{1}{\Gamma(1-\alpha)} \frac{d}{dt} \left[ \int_0^t \frac{f(\tau)}{(t-\tau)^\alpha} d\tau \right] \]  

\[ D^\beta[f(t)] = \frac{d^\beta f(t)}{dt^\beta} = \frac{1}{\Gamma(1-\beta)} \frac{d}{dt} \left[ \int_0^t \frac{f(\tau)}{(t-\tau)^\beta} d\tau \right] \]  

The properties of the VED in the frequency domain are more commonly used in analysis by adopting Fourier transformation as follows:

\[ \hat{F}\left(D^\alpha[f(t)]\right) = (i\omega)^\alpha \hat{f}(\omega) \]