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The influence of soil-structure interaction on the overall damping of structures with high damping

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Abstract

The influence of the soil-structure interaction on the overall damping of buildings with energy dissipation devices is described. A new lumped parameter model that effectively represents the dynamic stiffness of the foundation-soil system over a wide range of frequencies has been developed. The energy dissipation devices are assumed to be interstory viscoelastic type. A generalized modal superposition method is used to analyze buildings with low, medium and high natural periods. It is found that increasing damping through the energy dissipation devices results in increasing the overall damping, and soil-structure interaction makes this effect less pronounced. The overall damping in the first two modes of vibration decreases with the increase of the building height to foundation width (H/a) ratio, regardless of the amount of damping. Soil-structure interaction makes this effect more pronounced. The building to foundation mass (MR) ratio has very little influence on the overall damping in the first mode of vibration, regardless of the amount of damping. However, in the higher modes of vibration, the overall damping of buildings with energy dissipation devices increases with the MR ratio.

Introduction

There has been a growing interest in using energy dissipation devices for earthquake resistant design of new and existing buildings. Many types of energy dissipation devices have been developed. These devices have very strong potential for improving the dynamic performance of building systems [7]. Meanwhile, soil-structure interaction has been recognized as an important influence on the dynamic response of the building systems, especially when the building systems are situated on soft soil. Therefore, it is desirable to study the influence of soil-structure interaction on the dynamic behavior of building systems with energy dissipation devices. This paper reports the influence of soil-structure interaction on the overall damping of building systems with energy dissipation devices. Information concerning the influence on the natural frequencies of these building systems can be found in Reference [4]. Detailed analysis and results along with studies of the influence on other dynamic responses of these systems can be found in Reference [3].

Modeling of the Building Systems

Building and Damping Devices

In this study, building systems with low, medium, and high fundamental periods of vibration are represented by four-, eight-, and sixteen-story building systems, respectively. Each building consists of ductile moment frames with linearly varying stiffness and mass. These buildings are assumed to be shear-type, with building weights being concentrated at the floor levels. Column stiffnesses are assumed to be unaffected by column axial loads. The building systems remain elastic throughout the analysis. The inherent building damping is assumed to be 5% of critical viscous damping for every mode of vibration. Viscoelastic energy dissipation devices are added diagonally between each story of the building frame, where large relative displacements are expected. Using the geometry of the building and typical properties of a viscoelastic material, it was determined that the relationship between the incremental story stiffness k_d and incremental story damping coefficient C satisfies the formula $k_d = 1.8C\ w_n$, where w_n is the natural frequency of the system [3]. Different amounts of additional damping from the energy dissipation devices are combined with the inherent building damping to achieve total first mode damping of 10%, 20% and 30% of critical damping of the fixed-base systems.

Foundation-Soil Systems

In this study, foundation-soil system consists of a surface strip-foundation resting on a cohesionless homogeneous elastic half-space soil. The Poisson's ratio of soil is equal to 1/3 and the unit weight is equal to 18.5 kN/m^3 ($118pcf$) [2]. The water level is assumed to be much below the foundation level.

A new lumped parameter model, called the 7-parameter model, has been developed to represent the horizontal and rotational stiffness of the foundation-soil system [3]. See Figure 1. As its name suggested, this model has seven parameters: two equivalent lumped masses (M_o, M_1), two damp-

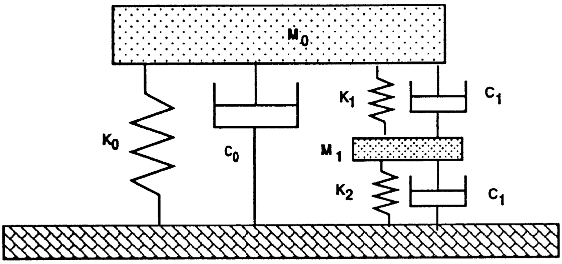


Figure 1: Seven-Parameter Model

ing constants (C_o, C_1), and three spring constants (K_o, K_1, K_2). The model effectively represents a very wide range of dynamic stiffnesses for horizontal, rotational, vertical and torsional motion. Comparing with the "exact" data, dynamic stiffnesses are better estimated by this model than by the well-known 5-parameter model [1, 8]. The comparison and mathematical details for developing this model can be found in Reference [3].

Method of Analysis

Several techniques have been developed to analyze the dynamic response of structures. Among these methods, the classical modal superposition method has been accepted as one of the most powerful and economical methods for the transient analysis of linear large scale systems. It is an effective method for computing natural frequencies, modal shapes, and overall modal damping of building systems, which gives physical insight of the system behavior. However, this classical method cannot directly be used to analyze building systems when soil-structure interaction is taken into consideration. Therefore, many researchers have extended this method to handle soil-structure interaction. Among these extended methods, the generalized modal superposition method [5, 6] was selected as method of analysis in this study because it is the only method that can provide the exact solution for free vibration analysis.

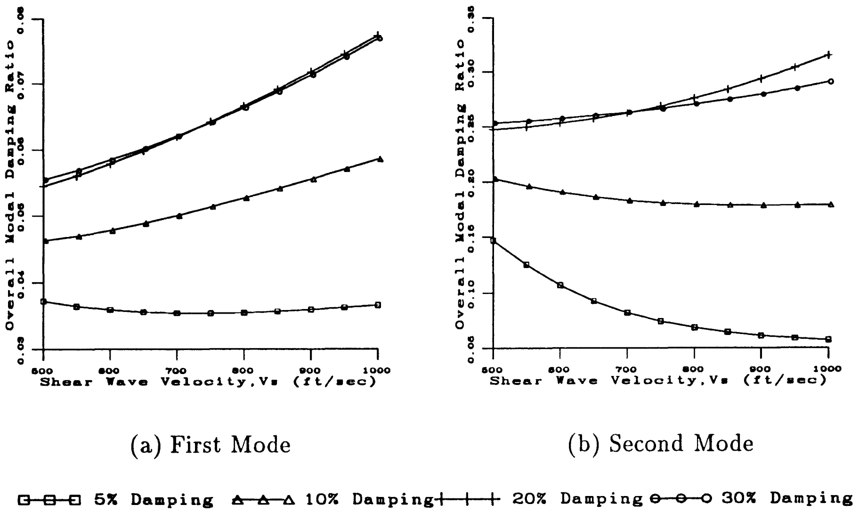
Results

This study uses three key parameters: the soil shear wave velocity (V_s), the building height to the foundation characteristic width ratio (H/a ratio), and the building mass to the foundation mass ratio (MR ratio). The soil shear wave velocity V_s represents soil-structure interaction. Parameters' ranges for this study are summarized in Table 1. The reasons for selecting these ranges and the methods to calculate them are given in Reference [3].

The four-, eight-, and sixteen-story building systems behave in a very

Table 1: Ranges of Parameters Used in This Study

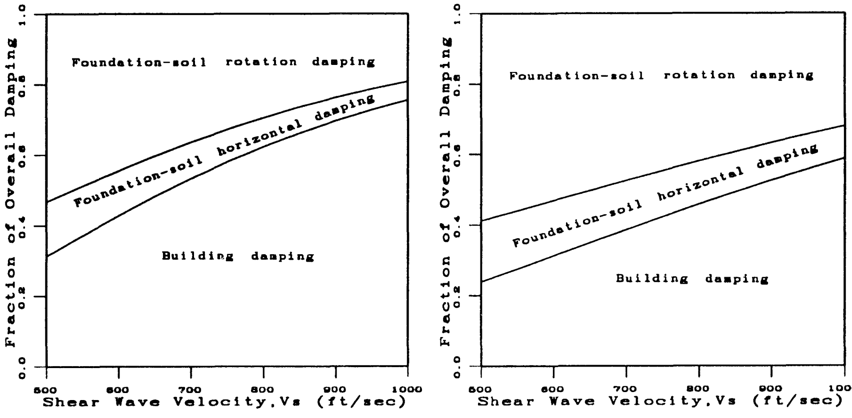
Building system	V_s (m/sec)	H/a	MR
4-story	160.0-300.0	5.0-7.0	3.5-4.5
8-story	160.0-300.0	7.0-9.0	2.0-3.0
16-story	190.0-300.0	9.0-11.0	1.5-2.5



(a) First Mode

(b) Second Mode

Figure 2: Overall Damping of the 8-Story Buildings with H/a = 4.0, and $MR = 2.5$



(a) 10% Damping

(b) 30% Damping

Figure 3: Damping Contribution in the First Mode of Vibration of the 8-Story Buildings with $H/a = 4.0$, and $MR = 2.5$

similar way, regardless of their different fundamental periods. In this paper, only analysis results for the eight-story building systems are shown. More extensive results of all cases are reported in Reference [3].

For fixed-base building systems, it is found in this study that the overall modal damping ratio, which is the ratio of the overall system damping to the system critical damping, increases with damping from the energy dissipation devices, and the increase is more significant in the higher modes of vibration.

For flexible-base building systems with low and moderate damping, the overall damping also increases in the first two modes of vibration. However, soil-structure interaction makes this effect less pronounced. For building systems with high damping, the overall modal damping may increase or decrease with the increase of damping. As examples, Figures 2 (a) and (b) show the influence of damping from energy dissipation devices and soil-structure interaction on the overall damping of the 8-story buildings in the first and second modes of vibration, respectively.

Although the decrease of the soil shear wave velocity increases the internal energy dissipation in the soil and from the radiation of waves away from the foundation, it decreases the inherent building damping and damping contribution from the energy dissipation devices to the overall damping by reducing the building curvature. As examples, Figures 3 (a) and (b) show the influence of soil-structure interaction on the contribution of damping from foundation-soil, building, and energy dissipation devices to the overall damping ratio in the first mode of vibration. Note that building damping in these figures is the inherent building damping combined with the damping provided by the energy dissipation devices.

In conclusion, soil-structure interaction reduces the effectiveness of energy dissipation devices in increasing the overall damping. The devices effectiveness is greater reduced in systems with higher damping than in systems with lower damping.

Influence of the H/a ratio

The overall modal damping ratio in the first two modes of vibration decreases when H/a ratio increases, regardless of the amount of damping in the building systems. The decrease is more pronounced when soil shear wave velocity decreases. As examples, Figures 4 (a) and (b) show the influence of the H/a ratio on the overall damping in the first mode of vibration of the eight-story building systems with 5% and 30% damping, respectively. As the H/a ratio increases, the foundation width decreases. Consequently, the dynamic stiffness, mass and damping coefficients in the rotation motion of foundation-soil system decreases [3], and the mass and moment inertia of the foundation is also decreases. When the damping contribution of foundation-soil systems in the rotation motion to the overall damping is

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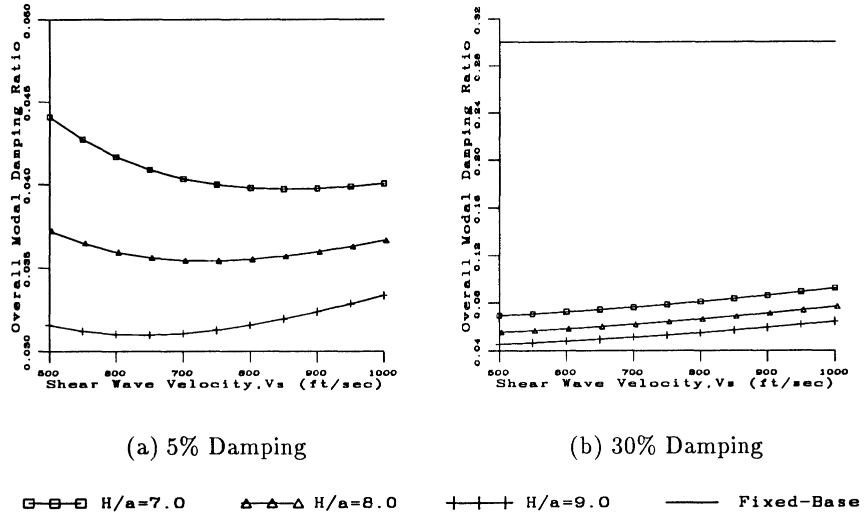

(a) 5% Damping

(b) 30% Damping

Figure 4: Influence of the H/a Ratio on the Overall Modal Damping of the 8-Story Buildings in the First Mode of Vibration

high, especially in the first mode of vibration (see Figure 3), the decrease of system damping due to the decrease of foundation-soil damping coefficient in the rotation motion is more than the decrease of critical damping due to the decrease of foundation-soil stiffness and mass coefficients in the rotation motion, and the decrease of foundation mass and moment inertia. Thus, the overall damping ratio, which is the ratio of the system damping to the system critical damping, decreases with the increase of the H/a ratio.

Influence of the MR ratio

In the first mode of vibration, the MR ratio has little influence on the overall modal damping ratio, regardless of the amount of damping [3]. As an example, Figure 5 (a) shows the influence of the MR ratio on the overall modal damping ratio in the first mode of the eight-story building systems with 30% damping. In the higher modes of vibration, the overall damping ratio of building systems with energy dissipation devices increases with the MR ratio. When the ratio increases, the foundation mass and inertia decreases, resulting in the decrease of the critical system damping. Since the overall modal damping ratio is the ratio of the overall system damping to the critical system damping, thus, the overall modal damping ratio of buildings with energy dissipation devices increases with the increase of the MR ratio. As an example, Figure 5 (b) shows the influence of the MR ratio on the overall modal damping ratio in the second mode of the eight-story building systems with 30% damping.

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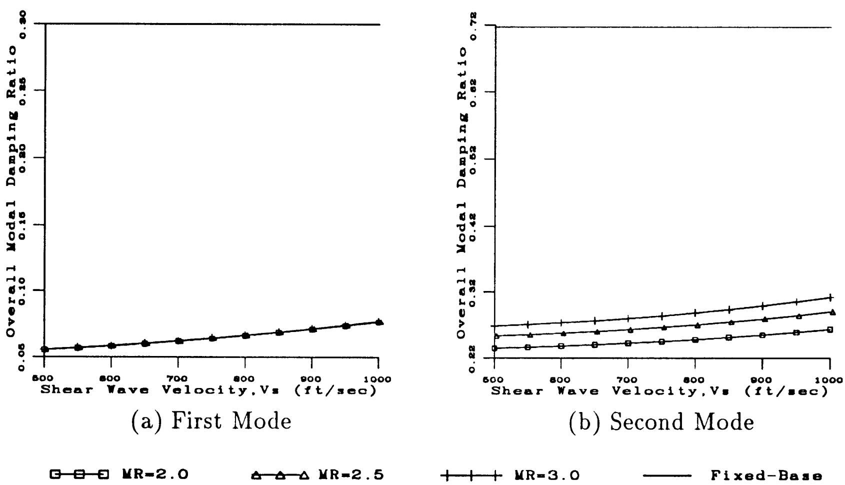

(a) First Mode

(b) Second Mode

Figure 5: Influence of the MR Ratio on the Overall Modal Damping of the 8-Story Buildings with 30% Damping and $H/a = 8.0$

Conclusion

The influence of soil-structure interaction on the overall damping of building systems with damping devices is presented in this paper. Detailed analysis and results are reported in Reference [3]. The influence of soil-structure interaction can be briefly summarized as follows:

1. For fixed-base building systems, the overall modal damping increases with damping from the energy dissipation devices, especially in the high modes of vibration.

2. Soil-structure interaction reduces the effectiveness of the energy dissipation devices in increasing the overall damping of building systems. The reduction is greater in systems with higher damping.

3. The overall modal damping in the first two modes of vibration decreases with the increase of the H/a ratio, regardless of the amount of damping. Soil-structure interaction makes this effect more pronounced.

4. In the first mode of vibration, the MR ratio has very little influence on the overall damping, regardless of the amount of damping. In the higher modes of vibration, when the MR ratio increases the overall damping of buildings with energy dissipation devices increases.

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It can be concluded from this study that the influence of the soil-structure interaction to the overall damping of buildings increases when energy dissipation devices are used.

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