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Experimental study on damping characteristics of soil-structure interaction system based on shaking table test

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ABSTRACT

Soil-structure interaction (SSI) system is composed of soil and structure that are two materials with quite different damping behaviors and it is regarded as non-classical damping system in conventional concept. Based on the analysis of motion state of SSI system, the paper presents the damping characteristic of SSI system via shaking table test. The results of transfer function, acceleration response time histories and equivalent viscous damping ratio and so on indicate that under certain conditions, SSI system shows approximate classical damping characteristic. In practical projects, dynamical analysis of SSI system can be viewed as approximately classical damping system once the synergistic effect of soil is considered.

1. Introduction

Damping system represents the pattern and characteristic of energy dissipation in a dynamical system [1]. The damping system of a dynamical system with viscous damping model can be divided into classical damping system and non-classical damping system [2]. In classical damping system, motion equations can be decoupled in modal space due to the consistent pattern of energy dissipation in each part of the system. The real mode shapes can be obtained, so that modal superposition method is available for dynamic analysis [2,3]. In non-classical damping system, motion equations cannot be decoupled because of significant sources of localized energy dissipation. Therefore, the mode shapes become complex valued numbers rather than real valued numbers [4,5]. To solve dynamic response, alternative methods, such as complex modal Lanczos method [6], approximate decoupling method [7] and the real modal approximation method [8] etc. are proposed, which turns out to be more complex and time-consuming.

The selection of dynamic analysis method is correlated to damping system. For different damping systems, the method could be totally different and the results can also vary greatly. Consequently, the correct identification of damping system is the cornerstone to select a reasonable dynamical analysis method and conduct an accurate analysis.

Nowadays, as the effect of SSI is taken into consideration for structural response analysis in practical projects, the damping system of SSI has received increasing attention [9–11]. However, the standard to identify damping system of SSI system is absent. Current identification is merely based on properties of different materials and different material damping, without any substantive and fundamental studies. It has been widely believed that systems composed of similar material are classical damping system, such as structure located on a rigid soil [12,13]. In contrast, those systems with different materials is non-classical because of different damping characteristics of each material. However, some experiments have illustrated that SSI system with soft soil underneath could be approximately classical damping system or referred to engineered classical damping system [12].

Nowadays, once the effect of SSI is considered to analyze structural response, the selection of dynamical analysis method becomes a multi-criterion problem, without an accurate reference or evaluation. In practical applications, some scholars assume that SSI system can be treated as classical damping system, so they apply modal superposition method by giving a comprehensive damping ratio [2], while others took the differences of damping characteristic among different materials into consideration and applied complex modal Lanczos method [6–8,11], but the analysis results differed. As for damping system of SSI system, there has been no substantive and fundamental study [12,13]. The study on mechanism of coordinated motion, characteristics of energy transfer on the interface and an evaluation method in practical projects have been rarely reported. The motion characteristics of soil and the upper structure, especially the motion coordination mechanism between soil and upper structure and characteristics of energy transfer on the interface, are crucial to the identification of the SSI damping system.

In this paper, based on analysis of damping system and the motion state, the damping characteristics of SSI system are investigated via a small-scaled shaking table test. Under different magnitudes of the dynamical excitations, coordination process between soil and upper

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Fig. 1. Test model and loading system.

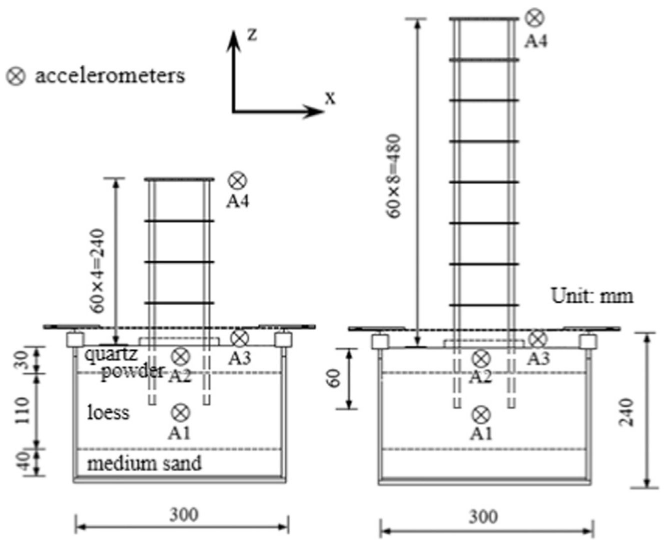

Fig. 2. Arrangement of measuring points.

structure are observed from the shape of transfer function, peak frequency, amplitude of transfer function, acceleration response at the interface, modal damping ratio and other measured data. Then, the category of SSI damping system and the transformation conditions of different categories are analyzed. Acceleration responses on the both sides of the interface between soil and structure are further investigated. Finally, the conclusions are verified by SSI system with different soil.

2. Damping system and characteristics of motion

Classical/Non-classical damping system is correlated to motion state of the system, and the identification is based on the continuity of motion state [14–18]. Since one of the major concerns of motion state is dynamic characteristics, this paper starts with investigating dynamic characteristics and motion state of the system.

For a single-degree-of-freedom (SDOF) system, its kinetic equation is shown as below.

$$[M]\{\ddot{u}(x,t)\} + [C]\{\dot{u}(x,t)\} + [K]\{u(x,t)\} = \{P(x,t)\} \tag{1}$$

The main difference of dynamics analysis between classical and non-classical damping system is whether the motion equation can be decoupled. If it can be decoupled, the motion state can be represented by a linear combination of several order decoupled modes. However, an arbitrary decoupled mode is obtained by assuming that the system has a unique deflection curve. If the deflection curve of the mode is assumed to be shape function, and the motion state of reference point in modal space is expressed by the generalized coordinates, then any decoupled modal motion can be expressed by shape function and generalized coordinates:

Table 1
Test program of the shaking table tests.

Experiment no.	Wave form	Peak acceleration	Duration	Load step
E1	White noise	0.07*g*	20 s	0.0005 s
E2	Sinusoidal	0.07*g*	30 s	0.005 s
E3	Small EQ (El Centro)	1.0*g*	30 s	0.005 s
E4	Sinusoidal	1.0*g*	30 s	0.005 s
E5	White noise	0.07*g*	20 s	0.0005 s
E6	Moderate EQ (El Centro)	2.0*g*	30 s	0.005 s
E7	White noise	0.07*g*	20 s	0.0005 s

$$\begin{cases} u_i(x,t) = \phi_i(x)Z_i(t) \\ \dot{u}_i(x,t) = \phi_i(x)\dot{Z}_i(t) \\ \ddot{u}_i(x,t) = \phi_i(x)\ddot{Z}_i(t) \end{cases} \tag{2}$$

where $u_i(x,t)$, $\dot{u}_i(x,t)$, $\ddot{u}_i(x,t)$ are the i^{th} ordered modal displacement, velocity and acceleration with respect to coordinate x at time of t, respectively; $\phi_i(x)$ is the shape function, which is correlated with coordinate x; $Z_i(t)$, $\dot{Z}_i(t)$, $\ddot{Z}_i(t)$ are the displacement, velocity and acceleration in the generalized coordinate respectively, which is correlated with time t.

If both shape function $\phi_i(x)$ and acceleration of reference point $\ddot{Z}_i(t)$ are continuous, the mode shapes of system are real valued number. The system can be analyzed by modal superposition method and the synthetized motion state of each point under excitation is continuous. Eq. (2) illustrates the necessary and sufficient condition for the classical damping system.

3. Tests on damping characteristics of SSI system

To make a further investigation on damping system of SSI system, the damping characteristics of SSI system under different dynamic excitations and its variation laws as well as the mechanism of coordinated motion between soil and structure are explored via a small-scale shaking table test.

3.1. Test model and verification of test system

The test models of SSI damping system are a four-storey and an eight-storey frame structure with four piles. To simulate the soil in the free field and the consolidation of the soil, a flexible circular container