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Impacts of soil-structure interaction on the structural control of nonlinear systems using adaptive control approach

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ABSTRACT

Though there is no doubt that soil-structure interaction (SSI) effects could significantly impact on the response of structures under seismic loads, this phenomenon is often neglected in control of structures. In the present research, the simple adaptive control (SAC) algorithm is utilized in conjunction with the magnetorheological (MR) damper to control the responses of a nonlinear structure based on soft soil analytically and the results are compared with passive-on and passive-off states. As the prototype structure is from an experimental test, a reliable framework is established by validating the accuracy of the structural model. The SSI effects are investigated from several aspects such as effects on control forces and performance of SAC in control of soil-structure systems. In addition to using conventional evaluation criteria in control problems, fragility analysis is carried out to study the structural behavior and SSI effects in-depth. It is observed that the SAC algorithm is capable of controlling the responses of structures and the outcomes are satisfying comparing to the passive approaches. The results show that neglecting SSI could completely underestimate damage to controlled structures especially structures based on soft soil and it will lead to error in the first estimation of control forces during design.

1. Introduction

One of the major challenges for structural engineers is design and construction of structures with acceptable performance under dynamic loading conditions induced by strong wind or earthquakes [1,2]. For this purpose, using structural control methods has been proved to be an efficient approach compared to the traditional design practice based on strength and ductility. Structural control approaches can considerably mitigate damage effects on structures under seismic loads and therefore they are widely adopted in seismic design or rehabilitation of existing structures. In order to have a better performance along with improvements in efficiency, a wide variety of supplemental control devices and algorithms have been proposed and utilized during the past decades. The control devices are generally divided into three types, namely passive, active, and semi-active devices [3]. Passive control devices do not need power supply and they have been considered reliable by not destabilizing the structure. This type of devices, however, lacks adaptability to changes in seismic excitations and cannot be systematically controlled under seismic loads [4]. Active devices input energy into controlled structures and they can be controlled using different algorithms during seismic excitations. Although active control devices provide adaptability, they can destabilize the structure and require a large power source [5,6].

Semi-active devices have been of great interest to researchers, because they are versatile and capable of offering the adaptability of active devices within the reliable framework of passive devices [7,8]. Magnetorheological (MR) dampers are among the most efficient semi-active devices. These dampers use the MR fluid and its behavior can be changed from linear viscous to viscoplastic by applying a magnetic field [9]. As a reason of insensitivity to ambient temperature, MR dampers can be employed in both indoor and outdoor environments. From an economical point of view, they have numerous advantages due to costs involved in manufacture, maintenance, and the required power source. Because of their inherent merits and mechanical simplicity, these devices have been the main focus of many studies.

On the other hand, a large number of algorithms have been suggested and implemented to control the response of structures using semi-active control devices and MR dampers. For instance Lyapunov-

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based methods which calculate the minimal differences of a Lyapunov function [10], decentralized bang-bang control for decreasing the total energy of the structure [11,12], clipped-optimal control [13], and linear quadratic regulator control [14]. Each of these algorithms has its own advantages and disadvantages which depend on its usage and expected responses. It should be noticed that none of the above algorithms considers the possibility of changes in the characteristics of the controlled structure [15]. Among the other algorithms for control of structures using MR dampers, the simple adaptive control (SAC) method was employed efficiently [15–18]. The main objective of SAC is to minimize the discrepancy between the behavior of the structure or system and an ideal pre-defined reference model which has the proper behavior [19]. For this purpose, the states of the reference model and the response of the structure are enough and there is no need to know the entire details of the structure and its properties [i.e., mass, stiffness, and damping] [17]. Owing to the simplicity and computational efficiency, SAC has been known as a proper tool for controlling structures with a large degree-of-freedom and uncertainties in loading conditions [17,18]. Bitaraf et al. employed the SAC algorithm for seismic protection of a wide variety of structures including structures with nonlinear behavior, base-isolated structures, and damaged structures [15–17,20,21]. The results showed that the SAC algorithm and MR dampers can improve the seismic behavior of structures significantly. Amini and Javanbakht [18] compared the effectiveness of acceleration feedback-based SAC with other algorithms to improve the performance of a three-story structure using MR dampers. They showed that SAC is a reliable and effective algorithm in reducing acceleration responses of structures equipped with MR dampers. However, neglecting soil-structure interaction (SSI) effects has been a common assumption in previous research contributions [22], especially when the nonlinear behavior of the structure is present.

Although there is no denying that SSI can considerably affects the response of controlled structures based on soft soil, less attention has been paid to this aspect. In previous studies, the soil-structure system has been defined in either frequency domain or time domain [22,23]. In frequency domain the soil-structure system has been defined using a specific frequency. This approach also involves further dimensions of computational complexity in online control. On the contrary, the soil effects in time domain have been modeled by equivalent springs and dampers with one or two degree-of-freedoms [24]. Moreover, the soil-structure system has been assumed to be linear, while the soil behavior is nonlinear under severe seismic loads.

In the present research, efforts are made to investigate and control the responses of a soil-structure system using the SAC algorithm considering the nonlinear behavior of the soil and structure. To this end, a nonlinear two-story aluminum frame on clay soil from the experimental work of Liu et al. [25] is used as the structural model. Firstly the modeling approaches of the frame and soil are described in detail and validated by comparing the results from the simulation and experimental data. Subsequently the proper MR damper is modeled numerically and added to the structural model to control the frame under seismic loads using the SAC algorithm. The SSI effects on responses of the structure are investigated from several aspects. In addition to evaluation criteria, the fragility analysis is conducted to gain a better insight into the damage of the structure under uncertainties in seismic loads.

2. Representation of prototype structure

The structural model employed here is from the MAH02 test series which was conducted at UC Davis [25]. This test series was performed to evaluate the behavior of soil-structure systems, considering the foundation rocking and nonlinear behavior of the structure. Specimen str_A from this test series is selected in which the yield strength of foundation rocking and structural fuses were balanced. This three-dimensional specimen was a two-story scaled frame which was tested with an approximate centrifuge acceleration of 30g at soil-structure interface. The test specimen consisted of two one-span frames which were connected by a mass plate. The sections of the first and second story columns were 38.1 mm and 19 mm square hollow tube respectively. In order to have nonlinear behavior in columns of the second story, structural fuses were considered at the bottom of these columns. The beams were assembled U sections with welded beam plates. The remaining dead load was considered as lead mass blocks bolted to the end of the beams. All of the structural elements were made of aluminum 6063 with an identical yield strength of 206.8 MPa. The test specimen is demonstrated in Fig. 1 and dimensions of the structural elements are summarized in Table 1.

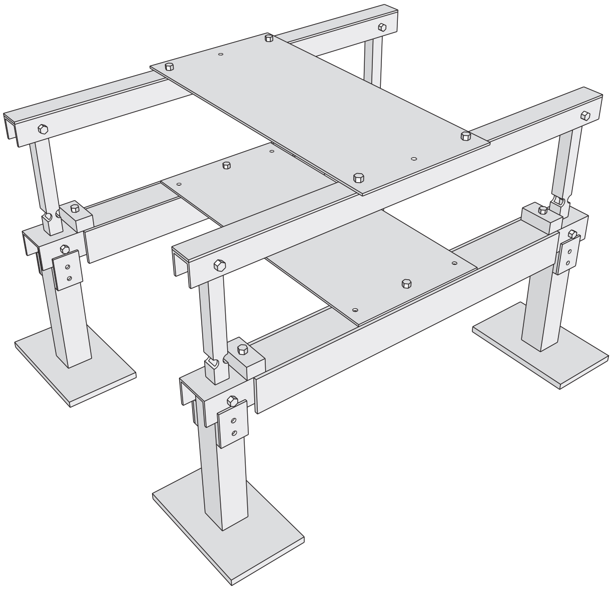

Fig. 1. Representation of prototype structure.

The footings were made of aluminum 6061 with the length, width, and thickness of 106.9 mm, 176 mm, and 9.5 mm respectively. The soil considered in the test was a combination of clay and sand which was placed in a rigid container. A drainage path was created first by filling the bottom and sides of the rigid container with 20 mm Nevada sand. After filling the container with a layer of 141 mm preconsolidated Yolo Loam clay, the container was then filled with 10 mm Monterey 0/30 sand with the aim of creating a drainage path. Soil properties considered in the structural model along with other assumptions are described in the next section. Detailed description of the experimental test and specimen can be found in [25].

3. Modeling approach and control method

In this section, modeling approaches for the structural model, MR damper, and implementation of the SAC algorithm are described. Because of numerous capabilities such as different materials, elements, and programming capability in the TCL environment, the Open System for Earthquake Engineering Simulation (*OpenSees*) [26] is utilized in the present study. In this section, the structural model is described in detail and its response accuracy is validated by comparing the results with experimental data to establish a reliable basis for the research. Subsequently the numerical model of a large-scale 200 kN MR damper and the implementation of the SAC algorithm are explained.

3.1. Frame model

Since the out-of-plane deflection of the specimen was reported to be negligible, a two-dimensional (2D) frame model is considered in this study. To model the beam-column elements which have elastic