Soil Dynamics and Earthquake Engineering 89 (2016) 100–115

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic control of irregular multistory buildings using active tendons considering soil–structure interaction effect

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ARTICLE INFO

Article history:
Received 22 August 2015
Received in revised form
23 February 2016
Accepted 10 July 2016

Keywords:
Seismic control
Irregular multistory buildings
Active tendons
Soil–structure interaction

ABSTRACT

Much research has been conducted in recent decades on structural control to improve the performance of different towers and high-rise buildings against severe earthquakes and strong winds. Most studies on building vibration control have been considered just two-dimensionally using shear frame models. In reality, most of the buildings might have irregular plans and thus experience torsion when subjected to earthquakes. Such torsion would further increase the structural response. On the other hand, some buildings are located on soft soil that would trigger the soil-structure interaction (SSI) effects required to be considered for design purposes. The main dynamic behavior parameters like natural frequencies, damping ratios and mode shapes would depend on construction site conditions and thus the SSI effects must be taken into account for buildings on soft soil. In this paper, a mathematical model is developed for calculating the seismic response of an irregular multi-story building equipped with active tendons. The SSI effect is then introduced by changing structure mass, stiffness and damping matrices. The model is employed to obtain the seismic response of 10-story buildings using active tendon with LQR algorithm. The building is modeled as a structure composed of members connected by rigid floor diaphragms with three degrees of freedom at each story; i.e. lateral displacements in two perpendicular directions and a rotation with respect to a vertical axis. Results showed that active tendons have low effects on the reduction of structural response when the building has been located on soft soils.

1. Introduction

There have been numerous studies on the structural vibration control to improve the safety or serviceability of different towers and high-rise buildings against strong earthquakes and winds during the last few decades [1–4]. The various vibration control strategies used to prevent structural damage in structures subjected to dynamic loads can be classified as active, passive, hybrid and semi-active control. The active control methods are effective for a wide frequency range as well as for the transient vibrations. One of the most important active control devices is active tendon system. The control forces are transmitted to the structure through two sets of diagonal pre-stressed tendons mounted on the side frames.

There are several categories of control algorithms applied to active tendon controllers; such as LQR [5–8], LQG [9,10], fuzzy logic control [11], sliding mode, PID control [12], fuzzy sliding mode control [13,14], and H_∞ control [15,16]. Among them, the LQR control theory has generated many interests and is more common. An energy-based technique to find gain matrices in classical linear control regulator (LQR) was developed by some researchers like Alavinasab et al. [17]. Chang and Lin [18] used an active tendon system installed at the first story of a multi–story building subjected to earthquake excitations with optimal H_∞ control algorithm to reduce inter-story drifts. Park et al. [19] studied a fuzzy supervisory control method for improving the seismic performance of the active control system in the earthquake-excited building structures. The method has a hierarchical structure consisting of a supervisor at the higher level and several sub-controllers at the lower levels. Each sub-controller is implemented to reduce the story-drift by using a LQR method while the fuzzy supervisor continuously tunes the sub-controllers.

Park et al. [20] used an adaptive modal-space reference-model-tracking fuzzy control technique for the seismic control of structures under earthquake excitation. The proposed method consists of a basic controller, a reference model and a fuzzy tuner. The fuzzy logic was introduced to update optimal control force so that the controlled structural response can follow the target response of a reference model. To easily and practically conduct, the reference model was adopted by assigning the target damping ratios to the first few dominant modes in modal space. Thenozhi and Yu [21] analyzed the stability of the active vibration control system

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http://dx.doi.org/10.1016/j.soildyn.2016.07.005

for both linear and nonlinear structures by Proportional-derivative (PD) and proportional-integral-derivative (PID) controllers and used Lyapunov theory for deriving sufficient conditions of stability to tune the PD/PID gains.

Most studies on building vibration controls have been considered just two-dimensionally using the shear frame models. The torsion effect is ignored in two-dimensional frame. In reality, most of the buildings have irregular plans experiencing torsion about vertical axis when subjected to earthquakes that would increase the structural response. In such a model, in addition to the lateral displacement in both x and y directions, there is torsion about the z direction [22]. Yanik et al. [23] proposed a new active control performance index for vibration mitigation of three-dimensional structures. They considered the minimization of the mechanical energy of the three-dimensional structure, control and seismic energies. To create the control force, it does not require the solution of the nonlinear matrix Riccati equation and a prior knowledge of the seismic excitation. Nigdeli and Boduroglu [24] used active tendons to control torsion in irregular single story and multistory structures under the effect of bidirectional near fault ground motion excitation. The control forces were obtained by Proportional-Integral-Derivative (PID) type controllers.

However, some buildings are located on soft soil for which the soil-structure interaction (SSI) effect must be taken into account. The dynamic characteristics of structures such as natural frequencies, damping ratios and mode shapes would change by the SSI effects [25]. The natural complexity in the behavior of in-situ soils has conducted to the development of many idealized models of soil behavior based on the classical theories of elasticity and plasticity for the analysis of soil-foundation-structure interaction problems. Models of soil behavior which exhibit purely elastic characteristics are considered here. The simplest type of idealized soil response is to assume the behavior of supporting soil as a linear elastic continuum. The deformations are thus assumed as linear and reversible. Several types of soil models can be expressed as, Winkler's Model [25], Elastic Half-Space Models [25], two-parameter elastic models like Pasternak [26] and so on. Lin et al. [27] investigated the SSI effect on the vibration control effectiveness of active tendon systems of a one-story irregular building subjected to earthquake excitations. In this model, in addition to the lateral displacement in both x and y directions, there is torsion about the z direction. An H_∞ direct output feedback control algorithm is used by minimizing the entropy to reduce the seismic responses of torsionally coupled structures. Farshidianfar and Soheili [28] studied the optimized parameters for tuned mass dampers for seismic vibration mitigation of multi-story buildings consisting SSI effects.

Few researchers studied the active control of irregular buildings with SSI effect. Even Lin et al. [27] limited their study to one-story buildings. The authors have found no study on the active tendon control of irregular multi-story buildings with SSI effects. Here in this research, while considering multi-story buildings with SSI effect, the reaction of active tendons in the perpendicular direction to the earthquake in irregular buildings is under investigation. In this paper, a mathematical model is developed for the control of the earthquake response of an irregular multi-story building with active tendons. By trial and error, the locations of tendons are obtained such that they produce the lowest force versus the greatest reduction in structural response. The SSI effect is then introduced by changing structure mass, stiffness and damping matrix. For SSI effect, the soil is modeled as spring and dashpot. The model is employed to obtain the time response of a 10-story building using active tendon with LQR algorithm. The building is modeled as a structure composed of members connected by a rigid story diaphragm so that it has three degrees of freedom at each story; i.e., lateral displacements in two perpendicular directions and torsion about z direction.

2. Mathematical model of the building

Fig. 1 shows the first story of a multi-story building with SSI effect as spring and dashpot. The whole multi-story building can be seen from the side view in Fig. 2. The floors are considered as

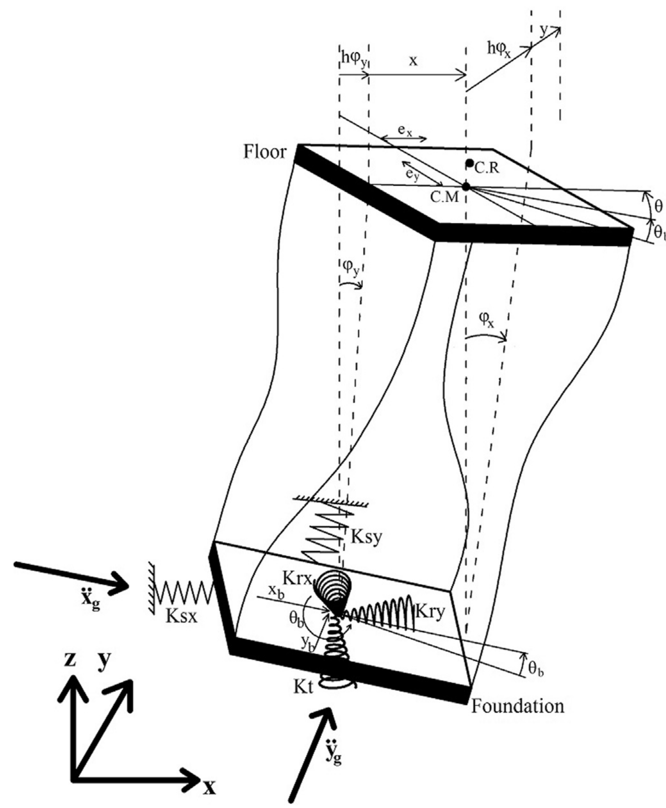

Fig. 1. First story of a multi-story building with SSI effect (Adapted from Ref. [29] and edited).

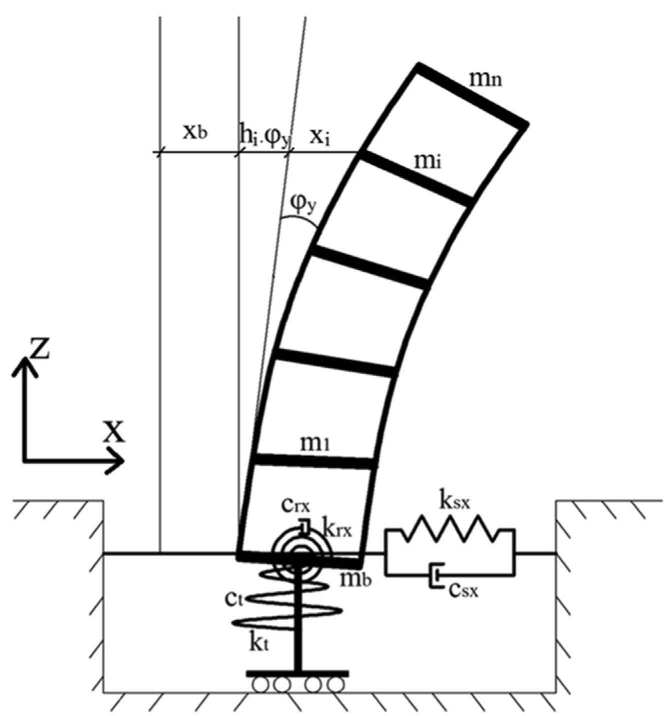

Fig. 2. A multi-story building from the side view.