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Structure–Soil–Structure Interaction effects on Seismic Response of Adjacent High-Rise Structures Equipped with Optimized Tuned Mass Damper

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ABSTRACT: Tuned Mass Damper (TMD) is amongst the simplest and, the most usable passive control tools, to improve the behavior of various structures. However, factors such as the characteristics of the soil beneath the structure and the presence of an adjacent structure could also affect the performance of that. This study investigates the effects of using a TMD in two 20-story steel moment frames with two different aspect ratios on the seismic response of them in fixed and flexible bases and considers the adjacency of two structures, known as Structure-Soil-Structure Interaction (SSSI). To apply the effects of SSSI, the reduced stiffness matrix of the foundation-soil-foundation system, considering as a plane strain problem, is obtained through analysis of a finite element model in Abaqus and is applied to the 2D models of the end frame of the structures using a set of springs and a newly developed element in OpenSEES. Furthermore, the particle swarm optimization (PSO) algorithm is used to optimize the design parameter of TMD. The average results obtained from time history analysis under ten far-field seismic records specifies that, exploiting a TMD with parameters optimized in a 20-story structure in both fixed-base cases and considering SSSI, can reduce the seismic responses in the form of the average of maximum drift and displacement. However, the SSSI effect can change the responses of structures equipped with dampers; in such a way that, in high-rise structures with a higher value of the height to dimension ratio (thinner structure), the response of structures is increased..

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1- Introduction

Tuned Mass Damper (TMD) is one of the most effective passive control methods for structures. This damper reduces the demand for energy dissipation in the main structure by absorbing part of the energy caused by dynamic loads such as earthquakes. The damper frequency is tuned based on structure frequency till the damper moves in the opposite direction of the structure when this frequency is excited. The energy is dissipated by the inertia force generated in the damper.

For the first time, the concept of TMD was introduced by Frahm [1] to reduce the effects of vibration caused by sea waves on the ship's body. Some of studies have tried to obtain optimized design parameters of TMDs in different structures [2-4]. Domizio et al. [5] optimized the parameters of three different TMD configurations using the particle swarm algorithm to control the seismic response of nonlinear structures. However, all of these studies considered a fixed-base structural system. They neglected the effects of soil on the design parameters of TMD. Due to the potential effects of Soil-Structure Interaction (SSI), Some researchers [6-9] considered them in the procedures of tuning TMD. The mentioned studies only considered the effects of soil beneath the structure. The condition of adjacent structures is one of the other important factors that can affect the modal response of structures and consequently TMD tuning and considering it can also change the design parameters of TMD. The initial phase of studies about Structure-Soil-Structure Interaction (SSSI) were performed at 1970s. Jabary and Madabhushi [10], using geotechnical centrifuge tests, studied the in-plane effects of SSSI for two close adjacent frames equipped with TMD.

This study investigates the effects of optimized TMD on seismic responses of two adjacent 20-story steel structures considering Structure-Soil-Structure Interaction (SSSI). The condensed stiffness matrix of soil is assembled in the global stiffness matrix of models in OpenSEES by a newly developed element. For control of structures against seismic load, the design parameters of TMD, including angular frequency, damping ratio, and mass, are optimized using PSO algorithm by minimizing the average of maximum drifts under ten far-field earthquake records in different cases. Finally, the designed TMDs are used in the structures considering SSSI effects and without them, and the results are compared in the form of the average of maximum drifts and the average of root mean square (RMS) of story drifts.

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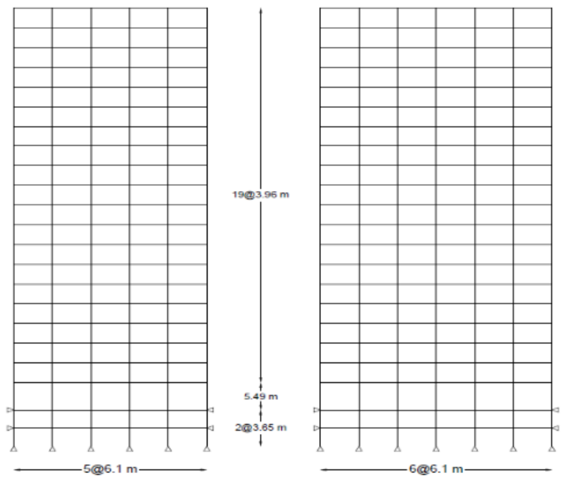

Fig. 1. The studied frames in this study

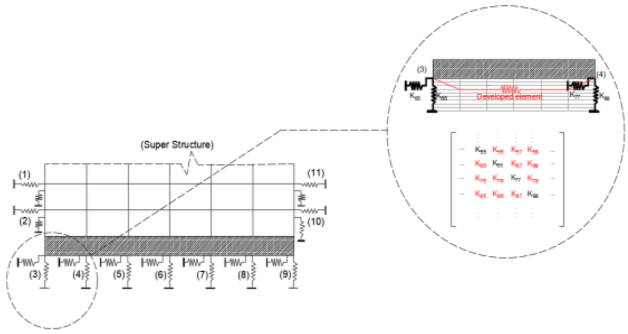

Fig. 2. Schematic diagram of soil and foundation proposed modeling method in this article

2- Modeling

2- 1- Modeling of Structures

This study uses 2D models of end frames of a benchmark 20-story steel building in Gupta and Krawinkler's research [11] in two directions. The building's lateral load-resisting system is comprised of steel perimeter moment-resisting frames. Both of the mentioned structures in this study are modeled in OpenSEES software. The behavior of the structures is considered linear. These frames are shown in **Fig.1**.

3- Modeling of SSI and SSSI

The effects of SSI and SSSI are considered using the substructure method. For this purpose, soil medium modeled in Abaqus software using the finite element method. Then, the condensed stiffness matrix of the foundation- soil- foundation system is evaluated using static analysis.

The schematic diagram of the springs under the foundation is shown in **Fig.2**. As shown in Fig. 2, the condensed stiffness matrix is included of two matrices. The first matrix is a diagonal matrix that is added to structural models in OpenSees by transitional springs as "zeroLength" element in two horizontal and vertical directions. In the second matrix, the sum of the elements of each column or row is zero. In other words, this matrix is related to the relative transition between the common nodes considered in the boundary of soil and foundation. This matrix is added to the structural models by a new developed element in the OpenSees framework. In fact, this element assigned a defined matrix to the global stiffness matrix of a model.

4- Modeling of TMD

For modeling TMD in OpenSEES, a lumped mass is placed at the center of the roof story of the 20-story structure. This damper connects to the structure and the mass from two sides using a spring. The damping and the stiffness of the spring are modeled using viscous and elastic materials, respectively. The design parameters of TMD are obtained using the Particle Swarm Optimization (PSO) algorithm.

5- Analysis process

In this study, the results of this study are discussed and presented as the comparison between the average of maximum story drifts and the average of root mean square (RMS) of story drifts obtained from time history analysis under earthquakes listed in **Table 1**. The earthquakes are chosen from PEER earthquake record database, considering soil type, earthquake intensity, and distance from the fault. The criteria for choosing these earthquakes are the shear wave velocity of 200 to 375 m/s at a depth of 30 m of soil, the intensities between 6.5 to 7.5 Richter, and a range between 20 to 50 km for the distance from the fault (far-field earthquakes). The selected earthquakes are scaled to ASCE-7 design spectrum for type-D soil in Los Angeles area.

Table 1. Parameters of earthquakes used in this study

No.	Earthquake Name	Station	PGA (g)
1	San Fernando	L.A. - Hollywood Stor FF	0.225
2	Loma Prieta	Hollister City Hall	0.246
3	Loma Prieta	Palo Alto - 1900 Embarc.	0.215
4	Landers	Yermo Fire Station	0.245
5	Northridge	L.A. - Baldwin Hills	0.239
6	Kobe	Abeno	0.221
7	Kobe	Morigawachi	0.214
8	Kocaeli	"Duzce"	0.312
9	El Mayor-Cucapa	El Centro Differential Array	0.507
10	Darfield	Pages Road Pumping Station	0.223

6- Conclusion

This article investigates the effects of SSSI on two 20-story buildings equipped with TMD. For this purpose, linear models of end frames of a benchmark 20-story structure in two directions are generated in OpenSEES software. The design parameters of TMD are calculated using PSO algorithm. The optimization aims to minimize the average maximum drifts of the structures under ten far-field earthquake records. Finally, the seismic responses are discussed in the form of the average of maximum drifts, and the average root mean square (RMS) of story drifts. The results show that considering SSSI leads to the significant increase of responses in both structures, especially in the structure with a higher dimension ratio. However, the application of optimized TMDs can decrease the responses in both 'fixed-base' and 'with SSSI' conditions which reveals the appropriate performance of this damper.

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