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A GLANCE AT OPTIMAL CONFIGURATIONS OF LARGE MASS TUNED MASS DAMPERS IN SOIL-STRUCTURE SYSTEMS

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Abstract

The use of Tuned Mass Dampers featured by a Large Mass ratio (LM-TMDs) can represent an efficient solution for the seismic risk mitigation of structures, especially for seismic retrofitting of existing buildings in which a LM-TMD is conceived as a superelevation of the structural body. Although several studies in this field have dealt with optimization and technological developments, there is a lack of design criteria for LM-TMDs contemplating the influence of the soil-foundation interaction which can play a key role on the structural performance. Therefore, this study proposes a preliminary view to optimal configurations of LM-TMDs in soil-structure systems. To this end, a simplified interpretative model is used to carry out an extensive parametric analysis in the finite element framework OpenSees, considering a large variety of soil-structure layouts. Optimal solutions for the LM-TMD are identified, showing promising correlations between the non-dimensional quantities characterizing the LM-TMD and the soil-structure system.

Keywords: Large Mass Ratio TMD, Parametric Analysis, Optimisation, Existing Buildings, OpenSees

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1 INTRODUCTION

A Tuned Mass Damper (TMD) consists of a viscous damper and a mass that, through appropriate tuning, can dissipate energy of unwanted vibrations of the structure. In recent decades, the use of TMDs to counteract damage and excessive deformations induced by seismic actions on buildings has been extensively studied with reference to various types of structures, such as bridges, buildings, towers, and wind turbines, and is still a debated topic in research. Many tall structures were indeed equipped with a TMD to counteract the effects induced by wind or seismic excitation [1-3,4]. In addition, medium- to low-rise buildings can benefit from this technology in terms of seismic risk reduction [5, 6]. In the latter cases, it is possible to adopt a large mass ratio for the TMD (LM-TMD), i.e., the ratio of the mass of the TMD to the one of the existing structural layout, that proven to be more robust and efficient than traditional systems [7-9].

Despite the numerous developments achieved over the years regarding optimised design criteria for TMDs, some important issues affecting unfavourably the TMD performance are still under discussion, such as the nonlinear structural behaviour and the interaction of the structure with the foundation soils. As per the latter, recent studies demonstrated that the TMD performance can be substantially altered by the dynamic response of the soil-foundation system, detuning the seismic-resistant device from the design tuning frequency of the superstructure, commonly evaluated neglecting the soil compliance.

In fact, a TMD is typically tuned to a specific frequency that matches the dominant vibration frequency of the structure. This frequency is aimed at minimising structural vibration. The presence of soil-structure interaction can alter the dynamic response of the structure, thus changing its dominant vibration modes. This, in turn, causes detuning of the TMD from the new dominant frequency of the soil-structure layout. As a result, the TMD can be less effective at dissipating seismic energy in the structural system, or can even worsen the structural performance.

Detuning can occur due to several factors related to soil-structure interaction, such as the soil-structure relative stiffness, the soil damping, and the coupling of the dynamic features of the foundation system and of the superstructure [10]. By contrast, the use of a large mass ratio for the TMD can partly compensate detuning induced by the soil response [11]. In this regard, however, there is a lack of standardised design guidelines accounting for the effects above. In recent years, some studies were oriented towards the definition of a clear framework describing the soil-structure-TMD interaction [12, 13, 14, 15, 16, 17]. A useful contribution was provided in [10], where a fully non-dimensional formulation was used in conjunction of global sensitivity analysis methodologies to point out the dominant factors controlling this complex interaction, that is identifying for which types of structures it is legitimate to neglect the interaction phenomena and when, instead, a significant unfavourable error is committed in design if soil-structure interaction is not considered.

In light of the above, this work presents an extensive parametric analysis on a practice-oriented soil-structure-TMD model to highlight the existence of optimised configurations of the LM-TMD for a variety of soil-structure layouts. The entire procedure was implemented in the open-source finite element analysis framework OpenSees [18], while visualisation of the results was carried out in Matlab [19].

2 INTERPRETATIVE MODEL AND DOMINANT PARAMETERS

The present study takes the two-dimensional interpretative model developed in [10] as a reference to carry out a large number of time-domain analyses on different soil-structure-TMD layouts. The model is illustrated in Figure 1: it is composed of a mass m_2 placed on top and connected to a lower mass m_1, placed at height h_1, through the parallel combination of a translational linear spring and a dashpot; the mass m_1 is in turn rigidly connected to the foundation of mass m_f and a rotational inertia I_{rg} is applied at the top of the rigid body. The foundation mass is supported by the parallel combination of a linear spring and a dashpot along the horizontal and rotational global degrees of freedom of the foundation. The mass m_2 is equipped with a TMD, whose elevation is taken equal to 1.5 times the fundamental modal height, h_m, of the superstructure since a LM-TMD represents a superelevation of the existing layout.

A previous study [10] revealed that the linear soil-structure-TMD interaction is controlled by the non-dimensional parameters listed in Table 1. In addition to the parameters featuring the TMD, G_1 to G_3 (mass, frequency and damping ratio of the TMD, respectively), and the structural damping, there are some other governing factors directly related to soil-structure interaction, such as the relative stiffness between structure and soil, G_6, and the mass distribution in the structural layout affecting rocking at the foundation level, G_7 to G_{13}. In detail, soil-structure interaction effects become negligible when G_6 is lower than about 0.08, it couples the dynamic response of the entire soil-structure system for $0.08<G_6<0.8$, whereas the structural response is dominated by the soil compliance when $G_6>0.8$ [10].

#	Group name	Equation
G_1	Mass ratio	m_{TMD} / m_m
G_2	Frequency ratio	ω_{TMD}/ω_s
G_3	Damping ratio of TMD	ξ_{TMD}
G_6	Structure-to-soil rel. stiffness	$h_m / (V_s \cdot T_s)$
G_7	Slenderness ratio	$h_m / L_{f,x}$
G_9	Foundation aspect ratio	$L_{f,x} / L_{f,y}$
G_{10}	Damping ratio of the structure	$c_{\phi s} / (2\omega_s m_m)$
G_{13}	Normalised radius of gyration	$h_m^2 m_m/(r_G^2 m_s)-(h_{G,s}m_s-h_m m_m)^2/[r_G^2 m_s(m_m-m_s)]$

Table 1: Dominant parameters of the linear soil-structure-TMD interaction

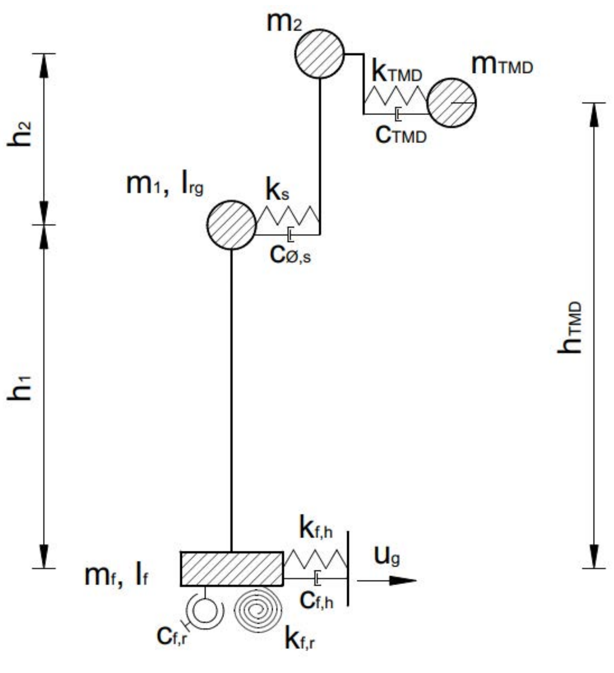

Figure 1: Interpretative soil-structure-TMD model (reproduced from [10]).

The above model was first calibrated on an existing eight-storey reinforced concrete building [11], from which reference values for the dominant parameters were computed. Then, in the parametric study board ranges of variability for the parameters were defined to cover a variety of conditions for the soil-foundation system and the superstructure, as recounted in the following.

3 PARAMETRIC ANALYSIS

The parametric analysis was implemented in OpenSees, comparing, for each soil-structure layout, two configurations of the reference numerical model in Figure 1, i.e., the model with compliant base (CM) with and without LM-TMD. The ranges of variability of the dominant parameters are listed in Table 2. Note that the mass ratio of the seismic-resistant device assumes much greater values than conventional TMDs (G_1 typically not greater than 3%) since the focus of the present study is on LM-TMD that can reasonably reach a mass ratio of about 40% in the case of low- to medium-rise buildings. For each permutation of the parameters, a series of dynamic analyses were carried out by applying a horizontal, harmonic displacement time history to the base node of the spring with stiffness $k_{f,h}$ (see Fig. 1), varying its period. The input motion has unitary amplitude and a period varying from $0.1 \cdot T_1$ to $4 \cdot T_1$, where T_1 is the fundamental vibration period of the reference structural model in the longitudinal direction. From each analysis, the maximum relative displacement (drift) and absolute acceleration of mass m_2 was computed for both models. As a result, the effectiveness of the LM-TMD in the CM models, η_{CM}, is determined as:

$$\eta_{CM} = \frac{drift_{CM}^{(NO\,TMD)} - drift_{CM}^{(TMD)}}{drift_{CM}^{(NO\,TMD)}} \quad (1)$$

Group	Lower value	Upper value
G_1	0.1	0.4
G_2	0.4	2
G_3	0.15	0.25
G_6	0.07	0.8
G_7	0.5	2
G_9	0.5	1
G_{10}	0.03	0.05
G_{13}	0.1	0.3

Table 2: Groups and relative ranges

The discussion of the results is here limited to some preliminary correlations between the sole drift-based effectiveness η_{CM} and fundamental parameters, such as the ones controlling i) the tuning of the LM-TMD and ii) the coupling of the dynamic responses of the structure and soil, namely G_2 and G_6 respectively. This relationship is illustrated in Figure 2, considering for the remaining parameters the values relating to the reference structure (see Section 2). The LM-TMD effectiveness attains the maximum for $G_6<0.07$, that is when soil-structure interaction leads to negligible effects on the structural performance. The effectiveness reduces remarkably as soil-structure interaction effects rise, $G_6>0.2$, with even the occurrence of a detrimental effect associated with the seismic-resistant solution for G_6 greater than about 0.3

(dynamic response controlled by the foundation soil). The optimum performance line of the LM-TMD (Fig. 2) corresponds to optimum tuning frequency ratios $G_{2,opt}$ and is strictly a function of the structure-to-soil relative stiffness, G_6.

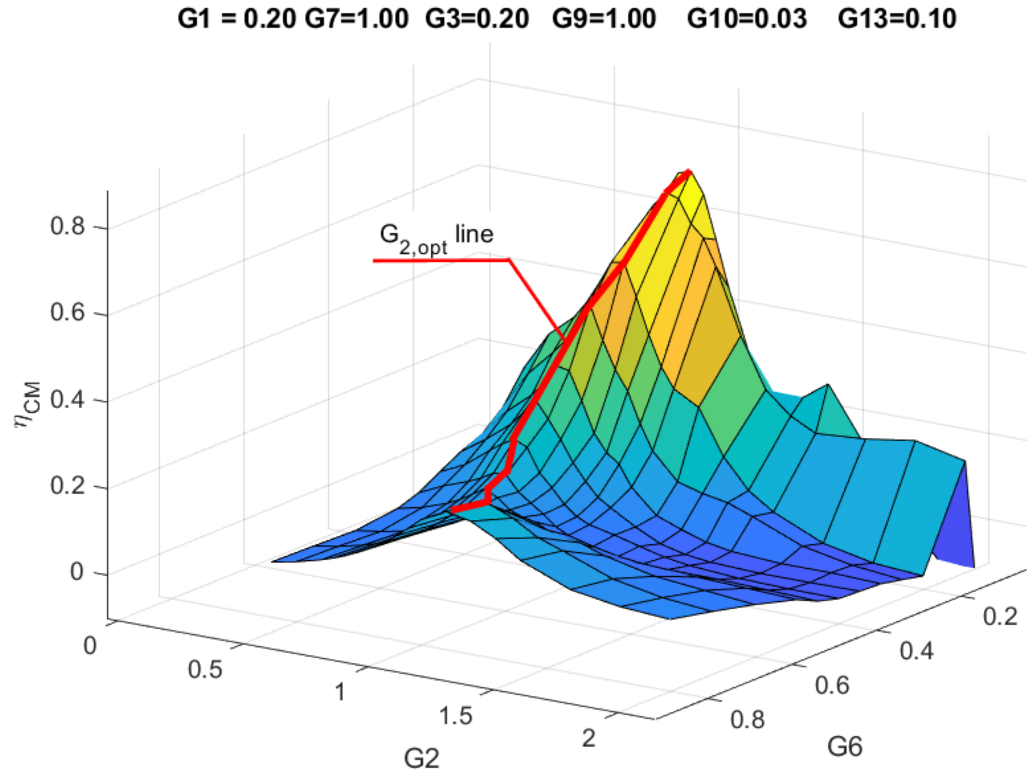

Figure 2: Effectiveness η_{CM} plotted as a function of G_2 and G_6.

Further useful insights on the optimum tuning frequency can be inferred by looking at its variation with another pertinent parameter, the foundation aspect ratio, G_9, assumed in Figure 2 equal to one (square foundation). Figure 3 shows the variability of η_{CM} with the tuning parameter G_2 for G_9=1 and 0.5, referring to boundary values of G_6 equal to 0.07 and 0.8 (i.e., no soil-structure interaction effects and dynamic response dominated by the soil, respectively). It can be observed that, regardless the role of soil-structure interaction, the LM-TMD can exhibit a better performance in structural systems having an elongated shape of the foundation (G_9=0.5) in the direction normal to the one of application of the seismic input compared to square footings (G_9=1). The optimal tuning occurs for G_2 less or greater than 1: a distinct dynamic response of the soil-foundation system (G_6=0.8) lengthens the optimum frequency ratio of the LM-TMD, reaching a value of 1.1 in the case of square foundations. This is a direct consequence of the rise of dominant rocking modes at the foundation level, induced by the high deformability of the soil compared to the structure, that are enhanced by a compact shape of the foundation in plan. In these cases, the optimal performance can be achieved by tuning the LM-TMD to the fundamental rotational mode of the whole system instead of the commonly used fundamental vibration mode of the structure in the horizontal direction.

Far from the optimal frequency, the performance of the LM-TMD reduces radically, as it is evident from the significant slope of the trends in Figure 3. The LM-TMD can be even detrimental when G_2>1.5 in structures having a much lower stiffness than the soil (G_6=0.08), effect that is avoided when the foundation system participates in the dynamic response of the superstructure mitigating the unfavourable inertial contribution offered by the anti-seismic device.

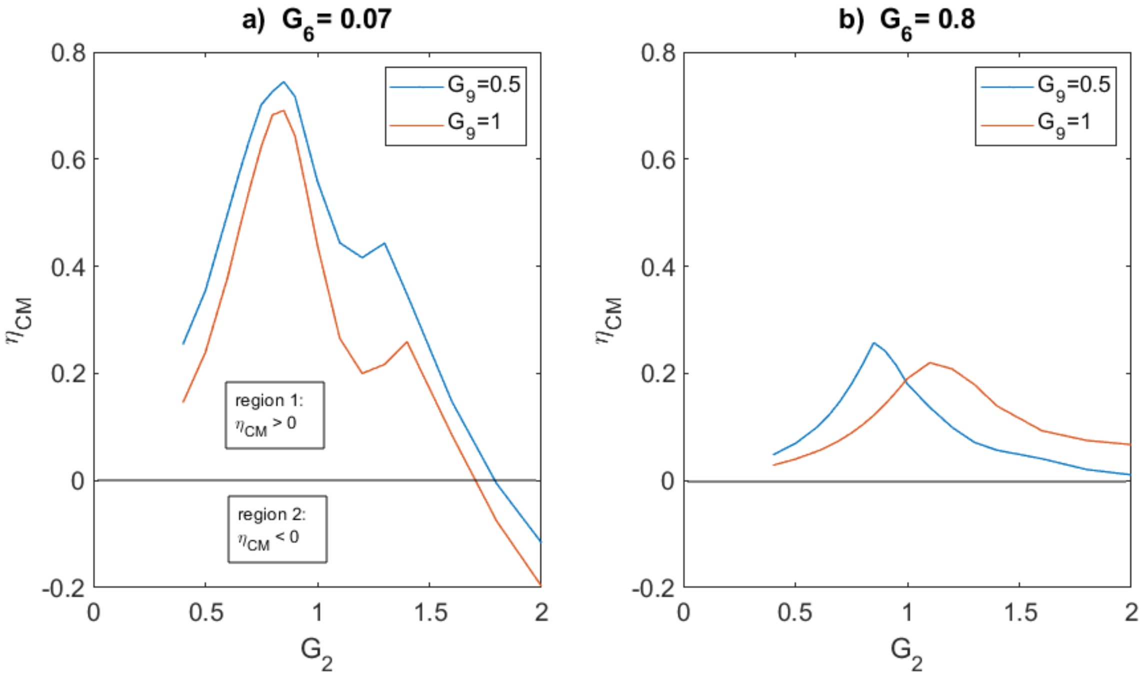

Figure 3: Sections at fixed G6 values, different foundation aspect ratios

4 CONCLUSIONS

Preliminary results of a large parametric analysis on the performance of LM-TMDs in soil-structure layouts have been presented. First, it is highlighted the need to investigate in more detail the configurations of best tuning between structure and TMD when the compliance of the foundation soils is not negligible. In fact, with respect to the case with fixed-base, the optimum frequency ratio of the LM-TMD changes with the relative stiffness between soil and structure, so neglecting this aspect a priori can lead to erroneous design evaluations. For high structure-to-soil relative stiffness, the LM-TMD tends to lose completely its effectiveness but never worsen the structural performance compared to the case with no anti-seismic device.

For many years, the optimal design of TMDs have been sought neglecting soil-structure interaction. The results discussed in the present paper, instead, open the way to an integrated design criterion for LM-TMDs considering the dynamic features of the whole soil-structure system, as the final aim of this ongoing research path.

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