*Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)*
 *ISBN 978-0-367-14328-2*

# Effect of soil-structure interaction on seismic performance of Tuned Mass Dampers in buildings

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ABSTRACT: Tuned Mass Dampers (TMDs) are aimed at mitigating vibrations of a structure under seismic or wind excitation by tuning the characteristics of the device to control specific resonance frequencies of the structure. However, the vibration modes of a structure can be considerably altered by the interaction with soil, leading to a loss of efficiency of the device.

This paper shows the preliminary results of a study aimed at formulating a methodology for the design of TMDs accounting for soil-structure interaction. Taking as a reference an illustrative case study of a timber building equipped with a TMD, the results of a parametric study on the effects of soil-structure interaction are presented. This is accomplished through finite element simulations in which soil-structure interaction is described by dynamic impedance functions, in order to have computationally efficient models to study the properties of the soil-structure system. The results are expressed in terms of non-dimensional performance curves of the TMD accounting for soil-structure interaction. The performance curve describes the progressive decay of the TMD efficiency as a function of the structure-to-soil relative stiffness, highlighting the main features of the response of the soil-structure system. This also allowed a clear quantification of the relative contributions of soil stiffness and TMD to the attenuation of the structural displacements.

## 1 A REVIEW OF DYNAMIC SOIL-STRUCTURE-TMD INTERACTION

A Tuned Mass Damper (TMD) can be conveniently used as a passive device to control vibrations of a structure under seismic or wind excitation. Several design criteria are available for optimal tuning of TMDs, aimed at maximising its vibration control efficiency, by relating the damping and stiffness of the device to the dynamic properties of the structure. The most used criterion was proposed by Den Hartog (1956), which provides the optimal analytical solution for a TMD applied to a single-degree-of-freedom (SDOF) system with fixed base and subjected to harmonic excitation. In that model, the TMD damping ratio is determined as $\xi_{TMD}=c_{TMD}/(2\times m_{TMD}\times\omega_{TMD}) = \{6\times\mu/[8\times(1+\mu)\times(2-\mu)]\}^{0.5}$ and the TMD frequency ratio as $\alpha=\omega_{TMD}/\omega_s=1/(1+\mu)\times[(2-\mu)/2]^{0.5}$, where $m_{TMD}$, $\omega_{TMD}$, $c_{TMD}$ are the TMD mass, circular frequency and damping coefficient, respectively, $\omega_s$ is the fundamental circular frequency of the structure and $\mu=m_{TMD}/m_s$ is the ratio between the masses of the TMD and of the structure, assumed as input in the design.

It is known, however, that the response of a structure to an earthquake can be influenced by its interaction with the foundation soil. Nonetheless, the available solutions for TMDs often neglect soil-structure interaction leading to possible detuning of the device from the resonance frequencies of the whole system. Detuning of TMDs due to soil-structure interaction was recognized in some analytical studies and verified through some experimental evidences. In Wu et al. (1999), a frequency-independent structural model was adopted to test the TMD efficiency including soil-structure interaction effects. The work highlighted that soil-structure coupling can influence the effectiveness of a damper system mounted on the top of the structure. A structural model with frequency-dependent soil-structure effects was proposed by Ghosh and Basu (2004), using the tabular solutions by Wong and Luco (1978) for the horizontal and rotational impedance functions and limiting the study to three values of the soil stiffness. It was therein proposed to tune the device to the fundamental frequency of the soil-structure system. Liu et al. (2008) developed a mathematical model for predicting wind-induced oscillations of a high-rise building with a TMD installed on top when soil-structure interaction is considered. The frequency-independent expressions proposed by Wolf (1994) were used to determine the swaying and the rocking springs and dashpots for three soil cases, and linear dynamic analyses were carried out in the time domain. Some optimisation methods were also developed for the design of TMDs accounting for soil-structure interaction (Bekdas and Nigdeli 2017, Salvi et al. 2018) and optimal configurations of the device were proposed for specific structural and geotechnical configurations. The first experimental studies were carried out through geotechnical centrifuge modelling of a two-degrees-of-freedom system, equipped with a single or double TMD, resting on a sandy soil (Jabary and Madabhushi 2015). It was demonstrated the greater efficiency of a double TMD to avoid detuning due to soil-structure interaction.

The present study is part of a wider research project whose main goal is to develop a robust design methodology for TMDs accounting for soil-structure interaction. As a first step, considering a well-documented case study of a timber building, this article focuses on the definition of non-dimensional performance curves of TMDs, which relate the efficiency of the device to the structure-to-soil relative stiffness. Large variability for the latter is considered, with soil-structure interaction effects reproduced in the numerical models through the frequency-dependent impedance functions proposed by Gazetas (1991). The TMD performance curves are obtained for the classical Den Hartog's design criterion, which considers fixed base, as well as for its modification as proposed by Ghosh and Basu (2004), and the improvement of the structural performance is then clearly quantified.

## 2 CASE STUDY

As a case study, the seven-storey timber building shown in Figure 1(a), tested on a shaking table in NIED Miki (Japan) within the SOFIE project (Ceccotti et al. 2013), has been considered as a reference structure for carrying out a parametric study on the effect of soil-structure interaction. The real full-scale timber structure was composed of six floors and the sloped roof, with a total mass $m_s$=262.72 Mg. In earlier studies, Poh'sie et al (2016a,b) found optimal solutions for a single- or multi-TMD installed in the building using genetic algorithms. In the following, we will investigate how the performance of such seismic device can be modified when soil-structure interaction is taken into account.

Poh'sie et al. (2016a) calibrated a simplified three-dimensional model of the building implemented in the finite element solver ABAQUS, suitable for efficient dynamic analyses. Each floor was modelled as a XY-translational and Z-rotational inertia element located at the floor height, restrained to move in the horizontal plane (shear-type model) and connected to the next upper and lower floor by XY-translational and Z-rotational elastic springs (simulating the effect of the wall and connectors stiffnesses). The roof was modelled similarly as a constrained inertia element and located at an average height between the lowest and the highest point of the roof (Figure 1(b)). The numerical model, characterised by the fundamental periods $T_{1,x}$=0.235 s and $T_{1,y}$=0.364 s, was shown to reproduce the main responses of the full-scale structure with a good level of accuracy. A bi-directional TMD was placed in correspondence of the sixth floor by means of a mass $m_{\mathrm{TMD}}$, equal to 1% the mass of the structure, connected to the structural mass $m_6$ through two springs of stiffnesses $k_{\mathrm{TMD,x}}$ and $k_{\mathrm{TMD,y}}$ and two dashpots of coefficients $c_{\mathrm{TMD,x}}$ and $c_{\mathrm{TMD,y}}$, in the X and Y directions respectively. A 2% structural damping was considered for the bare structure.

The model above was therefore modified to account for soil-structure interaction, shown in Figure 1(b). A reinforced concrete raft foundation was adopted for the building. The raft

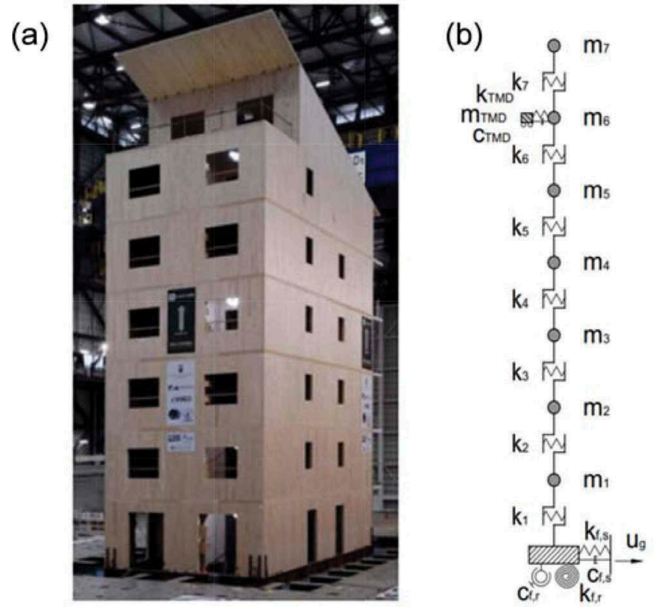


Figure 1. (a) View of the seven-storey building tested in the SOFIE project and (b) schematic representation of the simplified 3D numerical model accounting for soil-structure interaction.

extends in plan for the entire footprint of the building, with dimensions 14.0×8 $m^2$ in the X and Y directions, respectively, and has a thickness of 0.5 m. The mass of the foundation results equal to 0.5 times the total mass of the structure. Horizontal and rotational dynamic impedance functions were used in the X and Y directions to reproduce the frequency-dependent soil-structure interaction effects. The mechanical properties of the impedances were evaluated through the Gazetas's solutions (1991), calibrated on the first 10 modes of the structure (total mass participation greater than 98%) in each direction.

A wide range of the shear modulus of soil $G_{soil}$ was considered, varying from $10^7$ kPa to $10^2$ kPa, corresponding to the case of negligible soil-structure interaction effects (structure with fixed base) and extremely deformable soil (soil acts as a natural isolator), respectively. Note that $G_{soil} \leq 10^3$ kPa is extremely low for soil, that would be associated to a marked plastic response of the latter, but it was however considered in the parametric study in order to examine the case of very rigid structures compared to the soil, taking advantage of the non-dimensional representation of the results. To this end, the structural performance was related to the non-dimensional parameter $G_{SS}=h_m/(V_s{*}T_s)$, termed structure-to-soil relative stiffness as originally proposed by Veletsos and Nair (1975): the quantity $h_m$ is the first modal height of the structure, $V_s$ is the shear wave velocity of soil and $T_s$ the fundamental period of the structure with fixed base.

## 3 SEISMIC PERFORMANCE OF THE TIMBER BUILDING WITH TMD

A preliminary modal analysis of the reference structure with a compliant base was carried out. The fundamental periods of the soil-structure system $T_{SSI}$ are reported in Table 1 and the relative period elongation $T_{SSI}/T_s$ is shown in Figure 2. In both directions, the soil-structure interaction effects become not negligible for values of $G_{SS}$ greater than about 0.1, that is in agreement with the results obtained by Veletsos and Nair (1975). Beyond this value, the vibration period starts increasing more than linearly.

Table 1. Fundamental periods.

| $G_{soil}$ (kPa) | $G_{SS,x}$ (−) | $G_{SS,y}$ (−) | $T_{SSI,x}$ (s) | $T_{SSI,y}$ (s) |
|---|---|---|---|---|
| $10^7$ | 0.025 | 0.018 | 0.235 | 0.364 |
| $10^6$ | 0.079 | 0.056 | 0.235 | 0.365 |
| $10^5$ | 0.251 | 0.178 | 0.244 | 0.371 |
| $10^4$ | 0.794 | 0.562 | 0.299 | 0.431 |
| $10^3$ | 2.510 | 1.778 | 0.685 | 0.849 |
| $10^2$ | 7.939 | 5.623 | 2.264 | 2.748 |

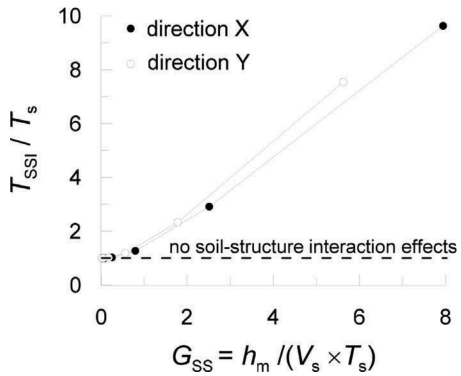


Figure 2. Period elongation plotted as a function of the structure-to-soil relative stiffness $G_{SS}$.

The dynamic performance of the structure was evaluated through the direct-solution steady-state dynamic analysis method available in ABAQUS, which provides the steady-state amplitude and phase of the response of a system due to harmonic excitation at a given frequency in terms of physical degrees of freedom. The effect of the TMD on the seismic performance of the structure can be summarised as a reduction of the maximum horizontal displacements, intended as relative displacements with respect to the foundation. Figure 3 compares the profiles of the maximum horizontal displacements obtained with and without the TMD, for three significant values of the soil stiffness. It can be observed that the TMD designed according to the Den Hartog's criterion is able to attenuate the maximum displacements of the structure for low values of $G_{SS}$, with consequent reduction of the inter-storey drift. This effect, however, tends to attenuate as $G_{SS}$ increases, until becoming null when the soil stiffness is sufficiently lower than the structural stiffness.

The results above can be represented in the semi-logarithmic non-dimensional space shown in Figure 4, where a performance factor $H$ (defined as the ratio of the maximum displacement of the mass $m_6$ connected to the TMD to the displacement of the same node without TMD) is plotted against $G_{SS}$. In this space, three regions can be identified. When the soil stiffness is much higher than the structural one ($G_{SS}$<0.08), the soil-structure interaction effects are negligible and the mitigating effect of the TMD can be maximised by using the Den Hartog's criterion for an equivalent SDOF structural system or, in general, optimal solutions for a structure with fixed base. Conversely, for sufficiently high values of $G_{SS}$ (>0.8), the soil response is completely decoupled from the dynamic amplification of the structure because of the high deformability of the former. It follows that the soil acts as a natural isolator for the structure which, accordingly, undergoes an essentially rigid motion, as it can be inferred looking at the profiles in Figure 3 for $G_{SS}$ greater or equal than 1.778. In this case (region 3), the TMD loses completely its effectiveness because it is no longer needed to attenuate the structural response. There is an intermediate region (0.08<$G_{SS}$ <0.8), instead, in which the dynamic

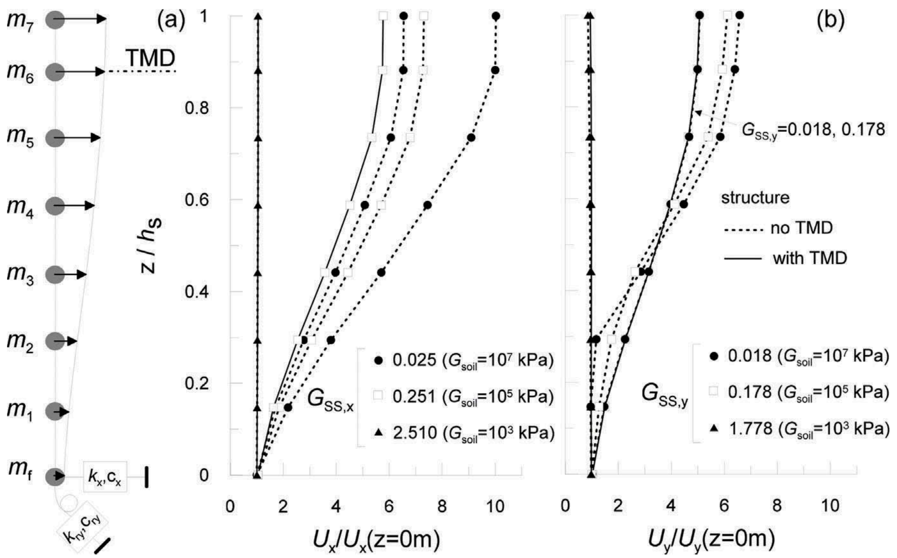


Figure 3. Profiles of the horizontal displacements of the structure in the X and Y directions, figures (a) and (b) respectively, obtained in correspondence of the relative fundamental periods.

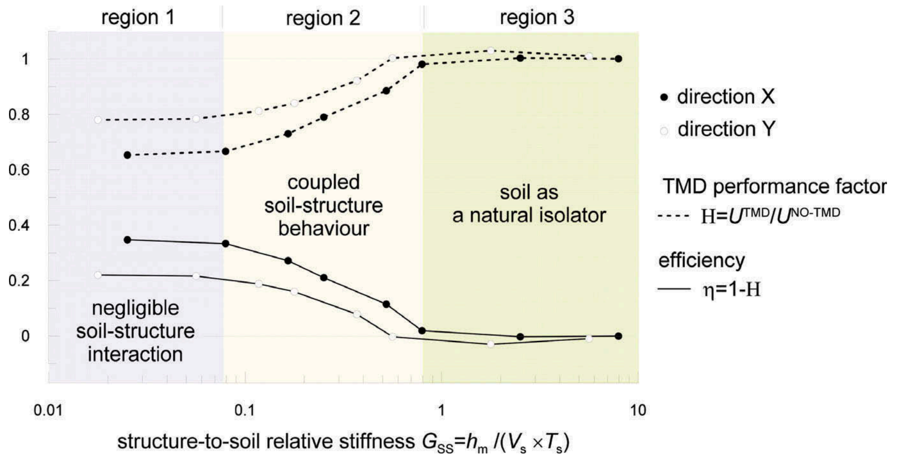


Figure 4. TMD designed according to Den Hartog's criterion: TMD performance factor $H$ and efficiency parameter $\eta$ plotted as a function of the relative stiffness $G_{SS}$ for the X and Y directions.

behaviour of the structure and that of the soil are coupled. In this zone, the performance factor of the TMD decreases progressively as the soil stiffness decreases with respect to the structural stiffness.

In addition to the performance factor $H$, the effect associated with the TMD response can be more directly expressed through the efficiency $\eta = 1-H$. This parameter, in fact, is equal to 0 in region 3, when the dynamic response of the structure is not activated by the large deformability of the foundation soil, while it reaches the maximum value in region 1, corresponding to the optimal solutions for TMDs in the case of a structure with fixed base. In region 2, the TMD and the soil concur to mitigate the displacements of the structure, and therefore this region appears as the target for an optimised design criterion for TMDs accounting for soil-structure interaction.

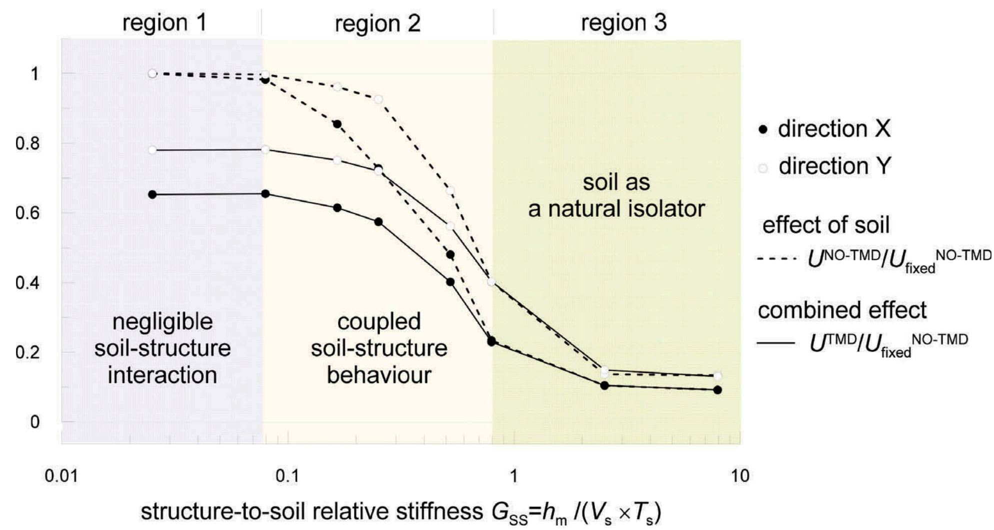


Figure 5. Effect of the soil deformability and of the TMD, the latter designed according to the Den Hartog's criterion, on the maximum displacement of the structure as a function of the structure-to-soil relative stiffness $G_{SS}$, in the X and Y directions.

The relative contribution between soil-structure interaction and the dynamic response of the TMD can be observed in Figure 5, looking at the maximum horizontal displacements of the structure with TMD $U^{TMD}$ and without TMD $U^{NO\text{-}TMD}$, compared to the maximum displacement $U_{fixed}{}^{NO\text{-}TMD}$ obtained with the fixed-base structural model without TMD. In this way, the ratio $U^{NO\text{-}TMD}/U_{fixed}{}^{NO\text{-}TMD}$ includes the sole effect of soil deformability and its distance from the trend $U^{TMD}/U_{fixed}{}^{NO\text{-}TMD}$ gives information about the role of the TMD in the dynamic performance of the soil-structure system. In the transition region with coupled soil-structure behaviour, it can be observed that, regardless the use of a TMD in the structural layout, the effective deformability of soil leads to a significant reduction of the maximum amplification. More in detail, in region 2 the contribution of the soil deformability increases more than linearly as the relative stiffness $G_{SS}$ rises, with a consequent rapid decrease of the mitigating effect produced by the TMD response.

## 4 MODIFIED TMD DESIGN CRITERION ACCOUNTING FOR SOIL-STRUCTURE INTERACTION

Based on the results above, the TMD of the reference structure was designed again using the criterion proposed by Den Hartog (1956) considering, however, the fundamental periods of the soil-structure system, as suggested by Ghosh and Basu (2004). The resulting structural response is illustrated in Figure 6, plotting the TMD efficiency as a function of the structure-to-soil relative stiffness. Compared to the Den Hartog's criterion (grey curves), the modified criterion for soil-structure interaction (SSI) leads to a moderate increase of the efficiency, with maximum values of 0.1 and 0.065 in the X and Y directions (peaks of the thick lines), respectively. This increase of efficiency of the TMD concentrates mainly in the transition region where a coupled soil-structure behaviour occurs. More in detail, the maximum gain, expressed by the difference between the efficiency $\eta^{DH}$ referred to a TMD designed according to the Den Hartog's criterion and the efficiency $\eta^{SSI}$ obtained considering the modified SSI criterion, occurs for values of the relative stiffness $G_{SS}$ of about 1, corresponding to the boundary between the regions 2 and 3. For higher values of $G_{SS}$, the SSI criterion loses completely its effectiveness, as it was found in the case of the classical Den Hartog's solution.

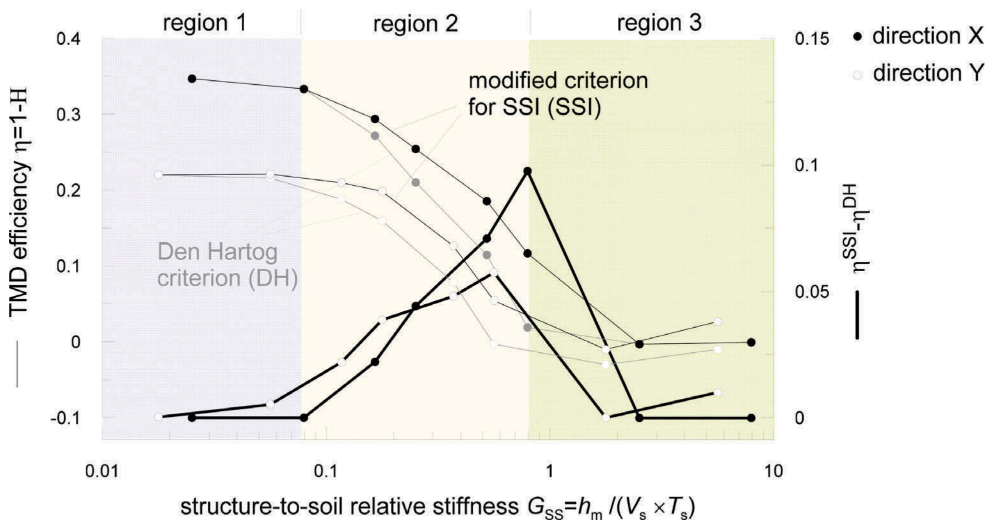


Figure 6. TMD designed considering the fundamental period of the soil-structure system: TMD efficiency $\eta$ plotted as a function of the relative stiffness $G_{SS}$ for the X and Y directions.

Focussing on the structural response in the region with coupled dynamic behaviour ($G_{SS}$=0.25), Figure 7 shows the variation of the maximum normalised displacement (mass $m_6$) in the X direction with the frequency $f$ of the input motion. It is evident that the main differences concentrate in correspondence of the first mode of the structure with fixed base (mass participation factors $M_x$ = 80 % and $M_{ry}$ = 100 %): in addition to the reduction of the maximum dynamic amplification of the structure, soil-structure interaction produces a decrease of the frequency at which the maximum value occurs, that is however not significantly altered by the design method used for the TMD since the small mass of the latter. For the higher modes, the contribution of the soil deformability becomes dominant compared to the dynamic response of the TMD and the amplification curves associated with the two design criteria of the TMD (Den Hartog and SSI) are essentially overlapped.

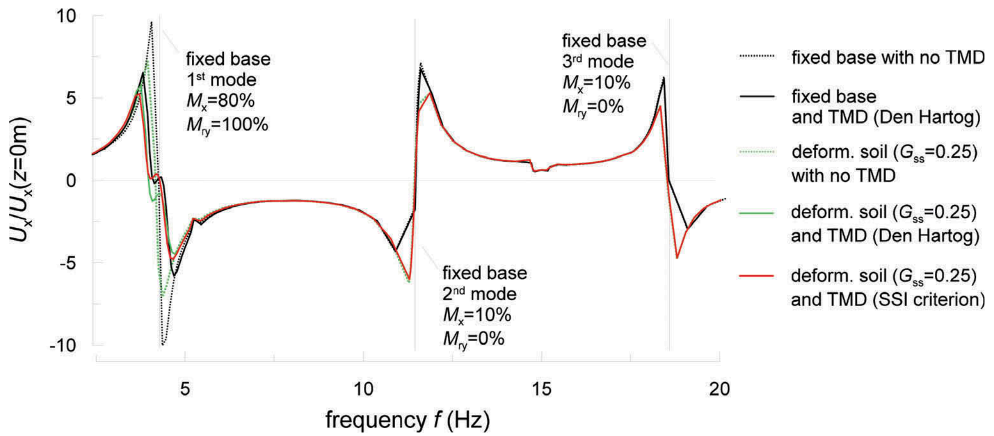


Figure 7. Amplification of the normalised displacement of the mass $m_6$ in the X direction plotted as a function of the frequency $f$: comparison between the Den Hartog and the SSI design criteria of the TMD.

## 5 CONCLUSIONS

In this paper, a numerical study on the efficiency of TMDs for mitigation of seismic effects on a building including soil-structure interaction was carried out. As an illustrative example, a timber structure already investigated in the literature was considered.

The results of the numerical study showed that both soil-structure interaction and the TMD application tend to attenuate the structural oscillations, but their relative contribution depends on the relative stiffness between the structure and the foundation soil. Accordingly, a performance curve of the TMD was defined, relating the TMD efficiency to the structure-to-soil relative stiffness. The performance curve is expressed in terms of non-dimensional quantities and highlights some peculiar aspects of the soil-structure-TMD interaction: it was found that the use of a TMD leads to an improved performance of the structure for medium to high values of the soil stiffness compared to that of the structure. More specifically, when coupled dynamic response occurs, the TMD loses partially its effectiveness and the classical design criteria for TMDs no longer appear as optimal solutions.

As a first attempt of optimised design of TMDs accounting for soil-structure interaction, the classical Den Hartog's criterion was modified considering the fundamental period of the soil-structure system. The resulting increment of efficiency of the device is however quite limited and it is appreciable only in the transition region of the dynamic response. This approach could therefore constitute a starting point towards a more efficient design solution, in which nevertheless some further modifications, currently under investigation, might be needed.

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