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Reflection on Analytical Characterisations of TMD Performance using Dynamic Centrifuge Tests

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ABSTRACT

A series of geotechnical centrifuge tests was conducted to investigate single tuned mass damper (STMD) and multiple tuned mass damper (MTMD) positioning effects on the seismic response of a multiple-degrees-of-freedom structure undergoing soil-structure interaction (SSI). The dynamic centrifuge tests were conducted to overcome the limitations of numerical and parametric analyses on MTMD effectiveness. It was found that a MTMD configuration tuned to one mode frequency is overwhelmingly the most effective in attenuating structural response. Contrary to findings from past optimisation studies in the field, a MTMD configuration in a MDOF structure tuned to multiple mode frequencies was also found to be consistently effective in damping and, depending on the input motion considered, could lead to significant attenuation of structural response beyond what could be achieved with the use of alternative STMD and MTMD configurations.

Introduction

A tuned mass damper (TMD) is an effective vibration control device widely used in many buildings around the world in the event of wind and/or seismic loading. It operates through dissipating the vibrational energy of a structure (Liu et al., 2008). To ensure effective operation its natural frequency requires tuning to a value (near-)identical to the pre-dominant modal frequency of the structure under fixed-base conditions or that of the soil-structure system in the presence of significant soil-structure interaction (SSI) (Dutta et al., 2004; Lin et al., 2010).

Conventional TMD (also: single tuned mass damper, STMD) design is based on the control and reduction of the largest modal structural response (Ghosh & Basu, 2004). However, the use of a STMD in a multi-modal structure is limited to the control of only one mode. Multiple tuned mass dampers (MTMDs) could potentially be used to control multiple modes. Early studies into SDOF structure-MTMD systems by Igusa and Xu (1991), and, Xu and Igusa (1992) found MTMDs to be more effective and robust than a STMD of equal mass ratio. Numerical and parametric studies on similar systems performed by Yamaguchi and Harnpornchai (1993), Kareem and Kline (1995), and, Zuo and Nayfeh (2005) showed that MTMDs with natural frequencies tuned to the frequency of the dominant mode of excitation are more effective in response control than a STMD and yield better robustness to uncertainties in frequency and damping. However, parametric studies by Rana and Soong (1998) showed that MTMDs deployed to control multiple modes do not cause a significant response reduction in addition to what can already be achieved with the use of a STMD, and may even lead to response amplification.

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The overwhelming majority of past TMD studies have focused on the optimisation of TMD parameters through the development of simplified analytical expressions based on only a limited number of defined structural (and soil) variables. Results from optimisation studies vary widely, depending on specific model characteristics, simplifications, input motions and assumptions used by researchers. One such assumption is soil linearity (Ghosh & Base, 2004), whereas there is ample evidence of non-linear soil behaviour under cyclic loading. Another notable drawback of analytical optimisation studies is that the efficiency with which TMDs operate in practice is often considerably less than in theoretically developed responses (Weber & Feltrin, 2010). Xu and Kwok (1992), Takewaki (2000) and Liu et al. (2008) are among many who studied the response of structures considering their interaction with the foundation soil and TMD. However, the bulk of TMD optimisation studies have considered the long-established use of TMDs in wind-excited structures, with their use in seismically-excited structures not being as extensively explored.

In a recent study by Jabary and Madabhushi (2015), use was made use of geotechnical centrifuge modelling to investigate STMD performance in a multi-storied structure under a range of soil conditions and damper configurations. The present study will follow the same experimental approach, with the aim of investigating the performance of a wide range of TMD configurations which incorporate variations in the use of STMD vs MTMD and damper positioning within a multi-storied structure undergoing dynamic SSI. To the authors' knowledge, very few experimental studies have been performed in this area using geotechnical centrifuge testing. The authors hope to overcome the limitations of numerical and parametric analyses on MTMD effectiveness and in so doing verify the efficacy of the results from such studies. A dense dry sand deposit was considered to maintain stable soil conditions throughout testing.

Geotechnical Centrifuge Testing

The behaviour of real-sized geotechnical structures in a centrifuge is replicated by subjecting models to increased gravitational fields (Madabhushi, 2014). Scaling laws relate the gravity field level at which models are tested to the dimensions and response parameters of the idealised field prototypes. Unless otherwise stated, all dimensions and parameters mentioned or shown in this paper imply those of the prototype structure. For more on centrifuge scaling laws the reader is referred to Schofield (1980).

Centrifuge tests for the purpose of this study were conducted at 50 g using the 150 g-ton Turner beam centrifuge at the Schofield Centre in Cambridge. The model container used was the equivalent shear beam (ESB) which minimises reflected energy from boundary walls to simulate seismic energy that radiates away into the field (Teymur & Madabhushi, 2003). The stored angular momentum (SAM) actuator was used to simulate earthquakes. More details of the Turner beam centrifuge and its testing facilities may be found in Madabhushi (2014).

Centrifuge Model

Structure and Dampers

In light of anti-nodes associated with multiple mode frequencies, a 2DOF model structure (shown schematically in Figure 1) was used to enable investigation of TMD storey positioning.

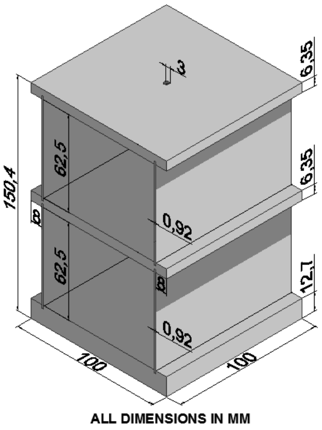

Figure 1. Sway frame structure dimensions

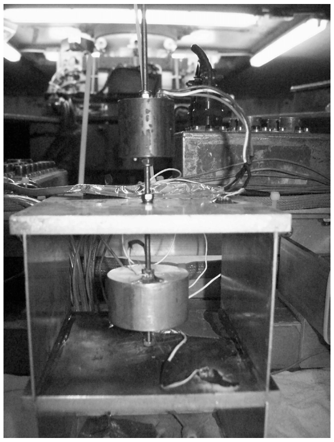

Figure 2. Sway frame structure fitted with a MTMD configuration

The model structure considered is a linear-elastic sway frame with slots in both storeys for the positioning of TMDs. The frame constitutes an idealised form of a two-storey building of 7.5 m in height and replicates its horizontal sway behaviour. Figure 2 shows TMDs fitted to the model to a particular MTMD configuration. The side walls and storeys of the structure are comprised of aluminium alloy 6082-T6 ($E=70$ GPa, $\sigma_y=255$ MPa and $\rho=2700$ kg/m^3) and fixity holds between them. The bearing pressure of the structure is $q=38$ kPa. Two passive (non-externally driven) TMDs were designed with different masses to experiment with multiple mass ratios (μ). Optimised mass ratios are usually high and rarely found in practice due to economic reasons. Real structures typically have $\mu<10$ % (Warburton, 1982). To replicate optimised conditions as much as possible the mass ratios used within this study were $\mu=13$ % and $\mu=27$ %. The linear-elastic TMD studdings were made of steel grade 43 ($E=210$ GPa, $\sigma_y=275$ MPa and $\rho=7840$ kg/m^3). Linear-elastic passive TMDs are practical because they are well understood, effective and reliable. As such, they represent the overwhelming majority of TMDs in use around the world today (Bekdaş & Nigdeli, 2011).

Soil

A homogeneous bed of dry fine-grained siliceous Hostun HN31 sand ($d_{10}=0.315$ mm, $d_{50}=0.480$ mm, $d_{60}=0.525$ mm, $G_s=2.65$, $e_{min}=0.555$ and $e_{max}=1.041$) was considered in this study. The sand was pluviated to a high relative density of $D_r=85$ %. The reasons for this rigid foundation are twofold: (I) to clearly demonstrate TMD effects on structural response while allowing for the incorporation of soil effects, and; (II) to achieve a stable soil foundation which would not experience drastic changes in stiffness as multiple earthquakes are fired in succession. The prototype soil depth considered was 18.5 m.

Test Set-Up

Alterations in structure-TMD configurations considered in this study are classified into three categories: (I) the number of TMDs used (STMD or MTMD); (II) TMD positioning in the structure (lower or upper storey), and; (III) TMD tuning frequency (by varying the damper position). The testing set-up and configurations used are shown in prototype scale in Figure 3.

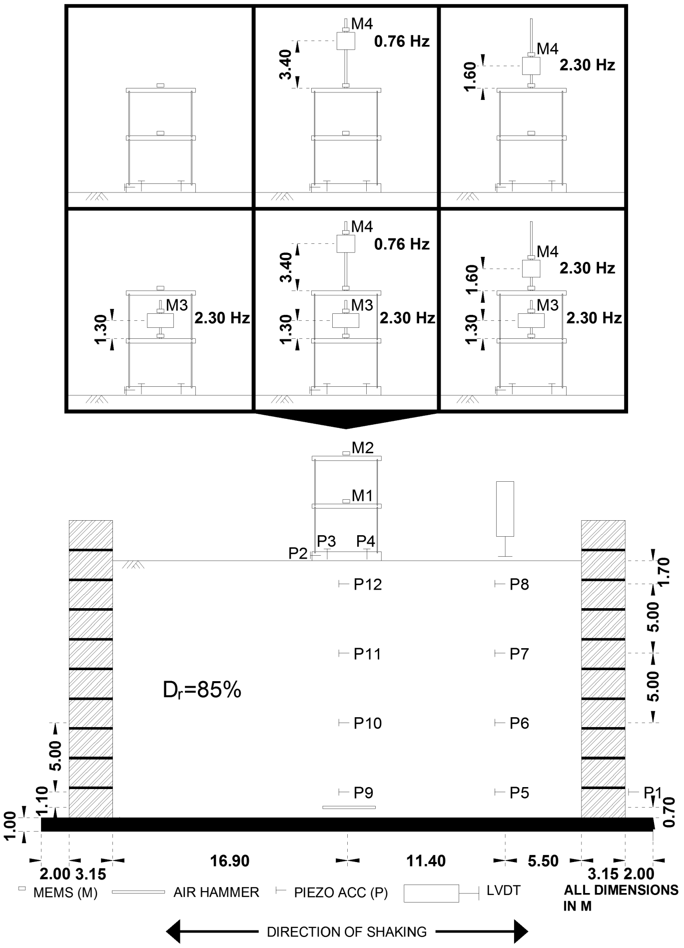

Figure 3. Centrifuge test set-up and configurations (prototype scale)

The most effective position of a TMD tuned to a mode frequency is usually the anti-node of that mode (Rana & Soong, 1998). This is the storey which undergoes the largest deflection. Accordingly, modal analysis of the fixed-base structure reveals that a TMD tuned to the first-mode frequency should be positioned on the upper storey and that a TMD tuned to the second-mode frequency should be positioned on the lower storey. The mass matrix ($\underline{M}$) and stiffness matrix ($\underline{K}$) conventions are shown in Figure 4 along with Equations 1 and 2. The normalised mode-shape matrix is given in Equation 3.

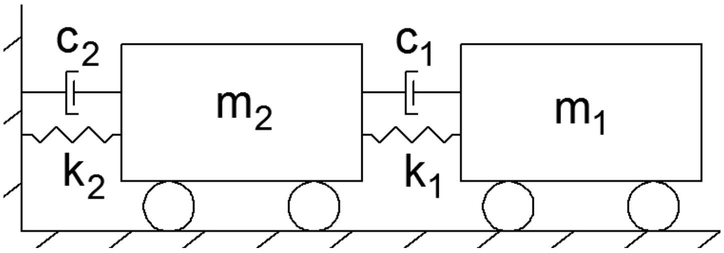

Figure 4. Parameter convention used

$$\underline{K} = \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_{1+}k_2 \end{bmatrix} \tag{1}$$

$$\underline{M} = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \tag{2}$$

$$\underline{\varnothing} = \begin{bmatrix} \varnothing_{11} & \varnothing_{12} \\ \varnothing_{21} & \varnothing_{22} \end{bmatrix} = \begin{bmatrix} 1.00 & 1.00 \\ 0.62 & -1.62 \end{bmatrix} \tag{3}$$

The model structure was positioned in the centre of the ESB container to minimise boundary effects and ensure the same boundary conditions apply throughout testing. Data from piezo-electric and MEMS accelerometers was used to obtain the results presented in this study.

The value of the optimum tuning frequency generally prescribed by TMD optimisation studies lies within a multiple of 0.9-1 of the pre-dominant modal frequency of the system (Joshi & Jangid, 1997; Bandivadekar & Jangid, 2013). These slight differences in tuning frequency ratio (f^{opt}) are attributed to differences in mass ratio, damping ratio, the number of TMDs and the optimisation approach considered. Given the small scale of the centrifuge model, an offset of even a millimeter in the positioned height of the damper along the studding would result in a notable change in tuning frequency. For this reason, along with the absence of a comprehensive universal optimisation procedure able to consider specific soil and structural conditions and their interaction, TMDs were consistently tuned to the first- and second-mode frequencies in accordance with $f^{opt}=1$. Due to geometrical restrictions on the model (to enable the realistic representation of a prototype building's storey height) combined with concerns for non-linear studding behaviour, configurations involving a TMD tuned to the first-mode frequency and positioned on the lower storey were not tested.

The structural responses are investigated in terms of peak accelerations, which are normalised with respect to peak bedrock accelerations to overcome potentially slight differences in soil properties (over time as multiple earthquakes are fired) and input motion characteristics (from one earthquake to another) as well as to enable direct comparisons between the system responses under different configurations and to different earthquakes. Both storey responses were computed to rule out that the presence of a TMD fitted to a storey for which the response is computed influences damping effectiveness. Two types of simple sinusoidal input motion of the same magnitude were considered: (I) single burst frequency earthquake of 1.0 Hz (prototype), and (II) sine-sweep frequency earthquake of 1.2→0 Hz (prototype). The first- and second-mode prototype system frequencies were experimentally determined to be 0.76 Hz and 2.30 Hz respectively, with significant Fourier components associated with each of the mode frequencies.

Results

Given that the main aim of this research is the investigation of the effectiveness of a range of STMD and MTMD configurations in damping peak structural response, six centrifuge tests were conducted to investigate two case scenarios: (I) the effects of positioning a STMD on different storeys, and; (II) the effects of positioning an additional TMD in parallel. The latter may be further classified into: (i) the effects of MTMDs tuned to the same mode frequency, and; (ii) the effects of MTMDs tuned to the first- and second-mode frequencies. Figure 5 shows a typical input motion and the upper storey acceleration response to a sine-sweep earthquake (1.2→0 Hz). Figure 6 shows the upper storey acceleration response under different structure-TMD configurations to a sine-sweep earthquake (1.2→0 Hz) normalised with respect to the peak bedrock acceleration. Figure 7 shows the upper storey acceleration response under different structure-TMD configurations to a single burst earthquake (1.0 Hz) normalised with respect to the peak bedrock acceleration. Due to an obstruction in testing, the isolated (no TMD) structural response to the single burst earthquake could not be obtained. Table 1 shows the normalised peak accelerations.

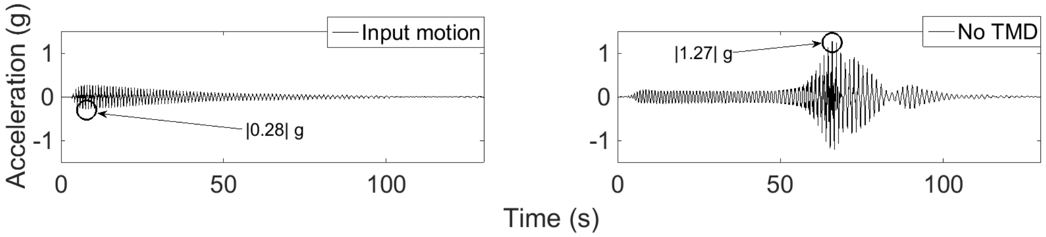

Figure 5. Input and upper storey accelerations to 1.2→0 Hz sine-sweep earthquake (prototype)

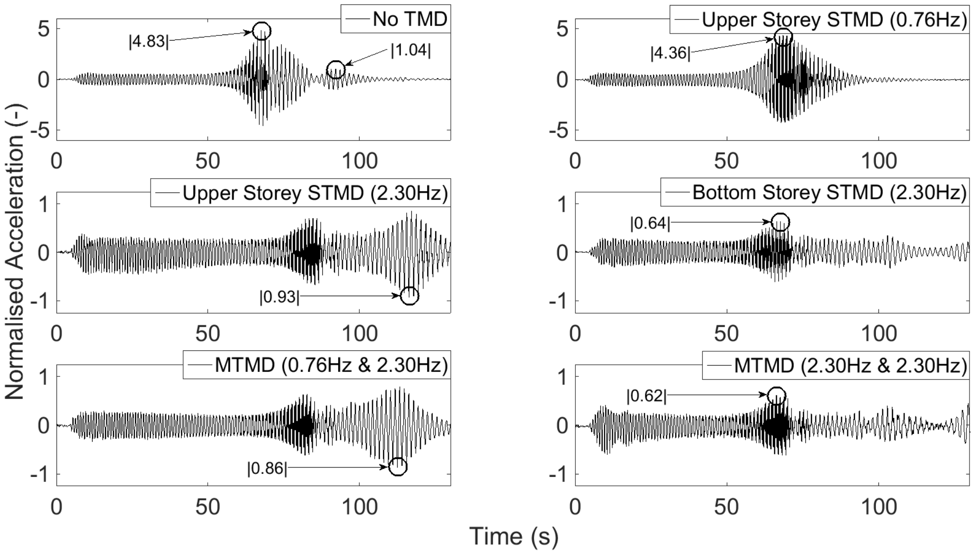

Figure 6. Normalised upper storey accelerations to 1.2→0 Hz sine-sweep earthquake (prototype)

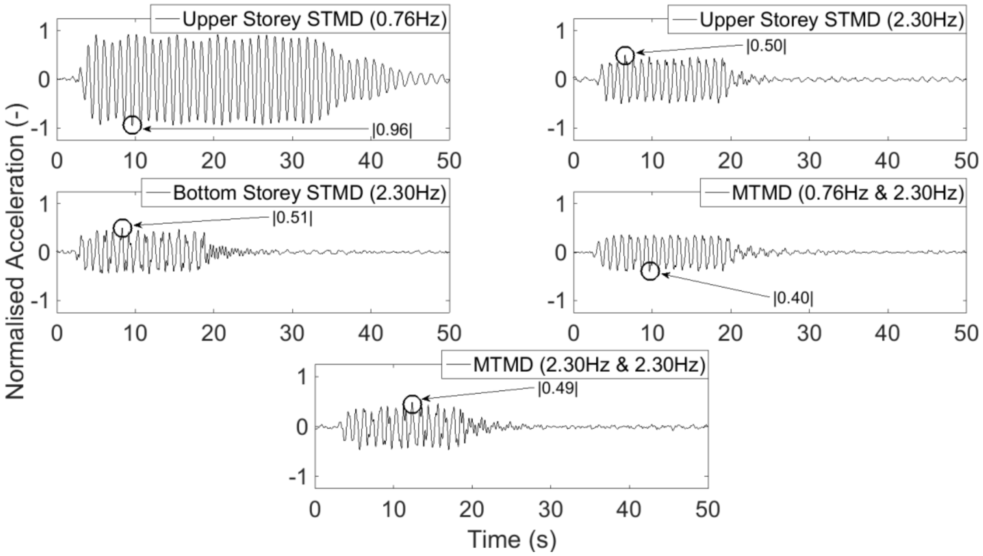

Figure 7. Normalised upper storey accelerations to 1.0 Hz single burst earthquake (prototype)

Table 1. Peak structural accelerations normalised with respect to peak bedrock accelerations.

	Lower stor. response to 1.2→0 Hz	**Lower stor. response to 1.0 Hz**	**Upper stor. response to 1.2→0 Hz**	**Upper stor. response to 1.0 Hz**
Configuration	Peak	Peak	Peak	Peak
No TMD	4.89	-	4.83	-
MTMD (2.30 Hz & 2.30 Hz)	**0.63**	**0.47**	**0.62**	0.49
MTMD (0.76 Hz & 2.30 Hz)	0.82	0.53	0.86	**0.40**
Upper stor. STMD (2.30 Hz)	0.73	0.47	0.93	0.50
Lower stor. STMD (2.30 Hz)	0.74	0.61	0.64	0.51
Upper stor. STMD (0.76 Hz)	6.35	0.90	4.36	0.96

Discussion

The results in Table 1 show that the MTMD configuration with both TMDs tuned to the same mode frequency is usually the most effective in attenuating peak structural acceleration. This is in line with findings from Yamaguchi and Harnpornchai (1993), Kareem and Kline (1995), and, Zuo and Nayfeh (2005). MTMD effectiveness observations made by Rana and Soong (1998) who determined that MTMDs deployed to control multiple modes do not cause significant response reduction in addition to what can already be achieved with the use of a STMD largely hold in Table 1. However, the MTMD configuration tuned to differing frequencies is actually found to be the most effective in attenuating the peak upper storey acceleration in the case of the single burst earthquake. This stands in contrast to the findings from the parametric study by Rana and Soong (1998). Table 1 shows that a STMD may be effective in response attenuation but could also cause response amplification depending on the specific configuration used. Evaluation of the results in Table 1 highlights that consideration of the fixed-base structure's anti-nodes for optimal TMD placement(s) does not necessarily hold for a soil-structure system.

The upper storey STMD (2.30 Hz) and MTMD (0.76 Hz & 2.30 Hz) configurations in Figure 6 show greater structural response following the earthquake than during the earthquake. However, in both instances the configurations attenuate the structural response peaks during as well as following the earthquake, albeit far more effectively during the earthquake. This demonstrates the practicality of TMDs throughout earthquake events.

Conclusions

Considering different earthquake motions and specific structure-damper configurations for the soil-structure system dealt with in this study, it was experimentally shown that a MTMD configuration tuned to one mode frequency is overwhelmingly the most effective in attenuating peak structural accelerations both during and immediately following an earthquake event. However, depending on the input motion considered, a MTMD configuration in a multiple-degrees-of-freedom structure tuned to first- and second-mode frequencies is also consistently effective and could even be more effective than a MTMD configuration tuned to one mode frequency and various STMD configurations. A MTMD configuration tuned to first- and second-mode frequencies may therefore lead to significant response reduction beyond what could be achieved with the use of alternative STMD and MTMD configurations.

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