# Numerical Study on the Effectiveness of Using Viscoelastic TMD to Mitigate Seismic Response of Above-Ground Pipelines

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## Abstract

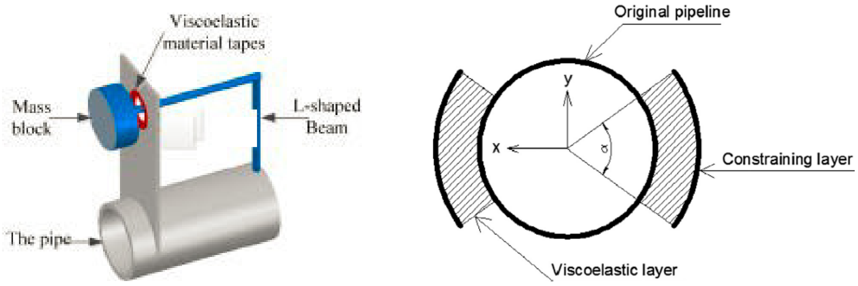
Above-ground pipelines often have long unsupported spans. They are therefore very flexible and vulnerable to vibrations induced by different vibration sources such as wind, earthquake, vortex shedding, etc. Ensuring the safety of these pipeline systems is crucial to the economy and environment. This paper proposes using viscoelastic tuned mass damper (TMD) to mitigate seismic induced vibrations of an above-ground pipeline system. In the viscoelastic TMD, a lumped mass is attached to the end of a sandwich beam, which provides stiffness and damping to the TMD system. In the present study, the viscoelastic TMD is firstly designed and the effectiveness of the proposed method is investigated through numerical simulations. Numerical results show that viscoelastic TMDs can effectively suppress seismic induced vibrations of above-ground pipelines.

**Keywords:** viscoelastic TMD, vibration control, suspended pipeline, seismic response

## 1. INTRODUCTION

Pipeline systems are commonly used to transport water, oil, natural gas, sewage and other materials. These pipelines often include long unsupported spans, and are very flexible and low damped. They are therefore susceptible to vibrations induced by different sources such as wind, earthquake, vortex shedding, etc. For example, wind or vortex shedding can lead to fatigue damage to pipelines, and severe earthquakes may result in excessive stress and strain in the pipe wall and therefore cause serious damage to the pipelines (Bai and Bai 2014). It is therefore important to mitigate these adverse vibrations and ensure the safety of these lifeline pipeline systems.

Previous studies on pipeline vibration control mainly focused on the vortex-induced vibrations (VIV) of subsea pipelines and various vibration control devices have been developed. Kumar et al. (2008) provides an extensive review on these devices. Very recently, Bi and Hao (2016a) proposed using a pipe-in-pipe (PIP) system to control seismic induced vibrations of subsea pipeline with free spans. The inner and outer pipes are connected by connecting devices, and the inner pipe acts as the TMD in the concept. For the above ground pipelines, Song et al. (2016) proposed using pounding tuned mass dampers (PTMDs, Fig. 1(a)) for pipeline vibration control. Tuned mass is used to absorb kinetic energy and the absorbed energy is dissipated through collisions. Bi and Hao (2016b) proposed attaching constrained viscoelastic materials to increase the damping of above-ground pipelines and mitigate their vibrations (Fig. 1(b)). It should be noted that continuous poundings may damage the viscoelastic material and therefore decrease the energy dissipation capability of PTMD as shown in Fig. 1(a). Moreover, a relatively long viscoelastic material and constraining layer are required in order to effectively increase the damping of the pipeline system, which makes adding constrained viscoelastic material to the pipeline expensive.




(a) (b)

**Fig. 1**. Recently proposed methods for above-ground pipeline vibration control (a) PTMD (after Song et al. (2016)) and (b) constrained viscoelastic material (after Bi and Hao (2016b))

An innovative viscoelastic TMD was proposed by Saidi et al. (2011) to attenuate the excessive floor vibrations. A viscoelastic TMD is composed of a tuned mass and a sandwich beam. The lumped mass is attached to the end of the sandwich beam and the sandwich beam provides stiffness and damping to the TMD system. Experimental results revealed that this innovative system can effectively reduce excessive floor vibrations. This paper proposes using viscoelastic TMDs to mitigate seismic-induced vibrations of above-ground pipelines, which has never been reported in previous studies. Numerical simulations are carried out to examine the effectiveness of the proposed method by using the finite element code ANSYS.

## 2. ABOVE-GROUND PIPELINE SYSTEM

A typical above-ground pipeline system adopted by Bi and Hao (2016b) is used again in the present study as an example. The key information of the pipeline system is briefly introduced here for the sake of completeness of the paper. More detailed information can be found in Bi and Hao (2016b).

The pipe is made of steel and the span length is 16 m. It is simply supported in the vertical direction, while it is not fully fixed to the supports in the transverse direction. The outer diameter of the pipe cross section is 0.35 m and the wall thickness is 3 mm. The Young's modulus, density and Poisson's ratio are 210 GPa, 7800 kg/m$^3$ and 0.3 respectively.

It is impossible to model the whole length of a pipeline system, taking one span of the entire pipeline for analysis is more practical. In the present study, the pipeline is modelled by SOLID186 elements in ANSYS. To simulate the restraining effects from adjacent spans on the single-span model, rotational springs are added at both ends of the analysed span, and they are modelled by COMBIN14 elements. Trial and error tests are used to determine the rotational spring stiffness so that the vibration characteristics of the pipeline system can be represented by the one-span model. The transverse restraint provided by the supports is again modelled by the spring elements COMBIN14. Fig. 2 shows part of the pipeline model.

The mass of the one-span model is 408 kg. In the present study, only the seismic loading in the transverse direction is considered, which will result in the vibrations in the transverse direction of the pipeline. The vibration frequency of the fundamental vibration mode in the transverse direction is 3.8556 Hz from eigenvalue analysis. A damping ratio of 1.2% is assumed for the pipeline in the analysis.

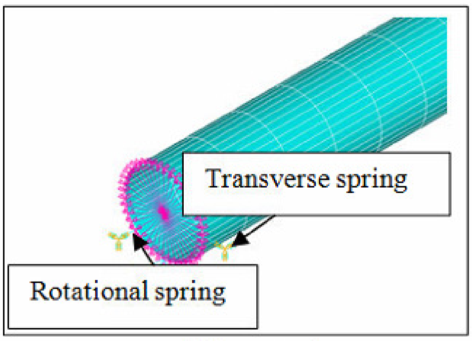



**Fig. 2**. FEM of the pipeline system

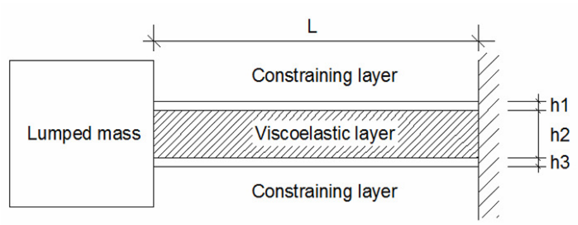



**Fig. 3**. A typical viscoelastic TMD

## 3. VISCOELASTIC TMD DESIGN AND NUMERICAL MODELLING

To effectively supress the transverse vibration of the pipeline due to earthquake loading, a viscoelastic TMD is applied at the middle of the pipeline, where the largest displacement is expected. The tuned mass is assumed as 2% of the total mass of the pipeline, which is therefore 8.16 kg. With the above-mentioned information, the optimal natural frequency and damping ratio of the damper can be estimated. In the present study, the formulas proposed by Sadek et al. (1997) are used, and it is estimated that the optimal natural frequency of the damper is 3.7736 Hz and the optimal damping ratio is 0.1518.

Fig. 3 shows the side view of a viscoelastic TMD. In the present study, steel is used for the constraining layer and a commercially available rubber is used for the viscoelastic layer. The density and shear modulus of the rubber are 550 kg/m$^3$ and 650 kPa respectively. The dissipation loss factor $\beta$ determines the energy dissipation capability of the rubber, $\beta$=0.32 for the selected rubber. To meet the optimal natural vibration frequency and damping ratio calculated above, the viscoelastic TMD needs to be designed. Particularly, the length ($L$ in Fig.3), width ($b$, which is not directly shown in Fig. 3) and the thickness of each layer ($h_1$, $h_2$ and $h_3$) should be determined. Saidi et al. (2011) suggested the detailed design procedure for the viscoelastic TMD system and it is adopted in the present study. The following parameters are estimated based on the method proposed by Saidi et al. (2011): $L$=500 mm, $b$=100 mm, $h_1$=$h_3$=1.8 mm and $h_2$=37 mm.

To check if the designed viscoelastic TMD can meet the optimal requirement, the finite element (FE) model of the viscoelastic TMD is developed. The constraining layers and viscoelastic layer are modelled with the solid element SOLID186, which supports viscoelasticity. Perfect contact between the layers is assumed, i.e., the constraining layer and the viscoelastic layer share nodes at the interface. The lumped mass at the end of the sandwich beam is modelled by MASS21 element. Fig. 4 shows the FE model of a viscoelastic TMD system. It should be noted that MASS21 is a point element, the dimension of the element cannot be directly shown in the numerical model. It is at the middle of the cross section and shares the node with the constraining layer as shown in Fig. 4.

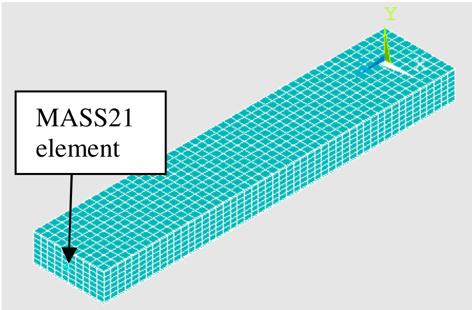



**Fig. 4**. Viscoelastic TMD system

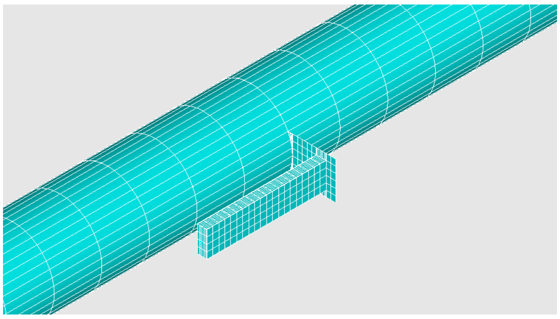


**Fig. 5**. Pipeline-viscoelastic TMD system

The constraining layers are assumed to be linear elastic, while the viscoelastic layer is assumed to be hyperelastic (Bi and Hao 2016b). The damping is modelled in ANSYS for each material as a constant stiffness multiplier (DAMP command in ANSYS), which can be calculated as $\alpha_2=\xi/\pi f$ (Saidi et al. (2011), Bi and Hao 2016b), in which $\alpha_2$ is the stiffness multiplier; $f$ is the fundamental vibration frequency of the viscoelastic TMD, which can be obtained by carrying our an eigenvalue analysis; $\xi$ is the damping ratio of the material. For the viscoelastic material, $\xi$ is related to the dissipation loss factor $\beta$ and can be estimated as $\xi= \beta/2$ (Nashif 1985). For the constraining layer, a damping ratio of 0.3% is assumed.

To obtain the natural frequency and damping ratio of the system, a free vibration test is simulated and the wavelet transform method proposed by Ruzzene et al. (1997) is used to estimate the vibration frequency and damping ratio of the system. It is estimated that the vibration frequency of the viscoelastic TMD is 3.7212 Hz and the damping ratio is 14.9%, which are very close to the required optimal values of 3.7736 Hz (frequency) and 15.2% (damping ratio) given above. The accuracy of the numerical model is therefore validated. Maximum responses occur at the middle of the pipeline and the viscoelastic TMD is therefore installed at the middle of the pipeline to mitigate the transverse vibration of the pipeline. Fig. 5 shows the pipeline-viscoelastic TMD system.

## 4. NUMERICAL RESULTS

Without loss of generality, three different earthquake loadings which have different frequency contents are considered in the present study. Fig. 6(a) shows a simulated earthquake. Fig. 6(b) shows the NS component recorded at Sylmar station during the 1994 Northridge earthquake. This earthquake loading is characterised by the long-period pulse-like waves, and it is used to represent a near-fault ground motion. Fig. 6(c) shows a recording during the 1971 San Fernando earthquake and it is used to represent a far-field earthquake.

Fig. 7 shows the transverse displacements at the middle span of the pipeline under different seismic excitations. It can be seen that viscoelastic TMD can obviously decrease the vibrations of the pipeline system. Moreover, this viscoelastic TMD is quite robust and it is effective for different earthquakes loadings.

To further appreciate the benefits of the proposed method, the results from Bi and Hao (2016b) are also plotted in Fig. 7 for comparison. These results were calculated based on the following initial conditions: the thicknesses of the constraining layer and viscoelastic layer are 3 and 20 mm respectively, the constraining length is 8 m and the constraining angle is α=72° (see Fig. 1(b)). It can be seen that the method proposed by Bi and Hao (2016b) results in slightly better control effect. However, the materials used in the present study are much less, only 1.5% of constraining layer and 2.5% of viscoelastic material are required in the present study compare to those in Bi and Hao (2016b). It should be noted that a 8.16 kg mass block is also required in the present study. Overall, the proposed method will be much cheaper than that proposed by Bi and Hao (2016b) to achieve a similar control effect.

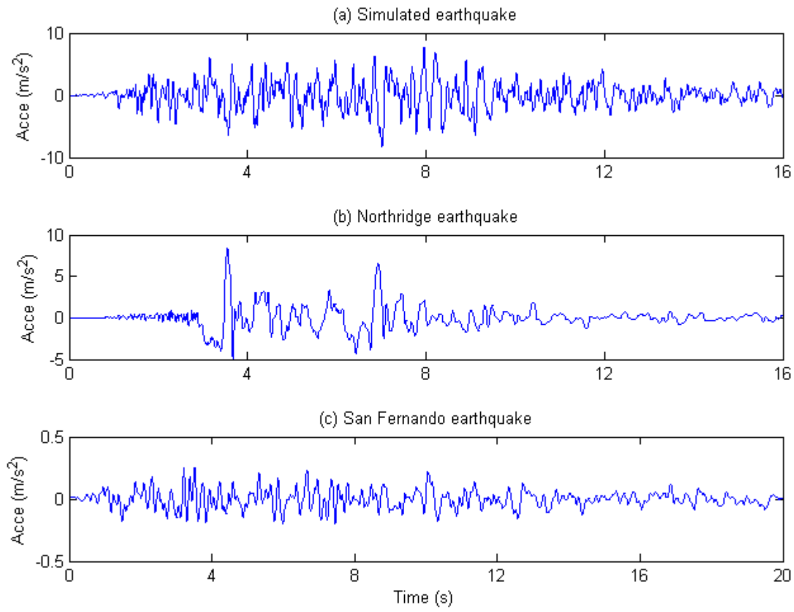



**Fig. 6**. Different earthquake loadings

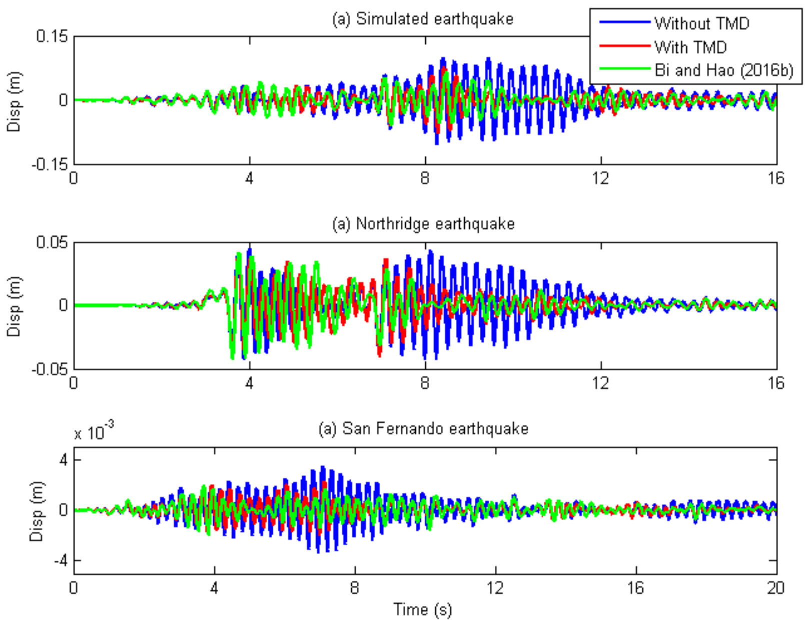



**Fig. 7**. Transverse displacement time histories at the middle of the pipeline for the uncontrolled and controlled systems

## 5. CONCLUSIONS

This paper proposes using viscoelastic tuned mass dampers (TMDs) to mitigate seismic induced vibrations of above-ground pipelines. Numerical simulations are carried out to examine the effectiveness of the proposed method. Numerical results show that viscoelastic TMDs can obviously reduce the vibrations of above-ground pipeline systems when they are subjected to seismic excitations.

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