Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Vic

Preliminary Study on the Effectiveness of Using Sandwich Pipe to Mitigate Seismic Induced Vibrations of above Ground Pipelines

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Abstract

This paper investigates the efficiency of using sandwich pipe (SP) to mitigate seismic induced vibrations of above ground pipelines. The simplification of a SP to a tuned mass damper (TMD) system is presented in detail. The effectiveness of using SP for pipeline vibration control is discussed based on the simplified model.

Keywords: sandwich pipe, TMD, vibration control

1. INTRODUCTION

Pipeline systems are commonly used to transport oil, natural gas, water, sewage and other materials. They are normally regarded as important lifeline structures. Guaranteeing the safety of these pipeline systems is crucial to the economy and environment. There are many reasons that may result in the damages to pipelines and these damages are often associated with pipeline vibrations. Therefore, it is important to control pipeline vibrations to reduce the possibility of catastrophic damages.

Three types of control, i.e., active, semi-active and passive controls, can be used in structural vibration resistance design (Soong and Spencer 2002). Considerable attention has been paid to research and development of structural control devices, with particular emphasis on the alleviation of wind and seismic induced responses of buildings and bridges. Among the numerous control methods available, the tuned mass damper (TMD) is one of the simplest and most reliable control devices. A TMD, consisting of a mass, damping and a spring is commonly attached to a vibrating main system for suppressing undesirable vibrations induced by wind or earthquake loads. It can be illustrated in Fig. 1, where m_T, k_T and c_T are the mass, stiffness and damping of the tuned system, the corresponding parameters for the main system are m_S, k_S and c_S respectively. The natural frequency of a TMD is tuned in resonance with the fundamental mode of the main structure, so that a large amount of the structural vibration energy is transferred to the TMD and then dissipated by the damper as the primary structure is subjected to external disturbances. Consequently, the safety of the main system will be greatly enhanced. The TMD has been widely applied since the 1970's in many engineering structures such as tall buildings, towers and bridges, etc (Soong and Spencer

2002). More recently, TMDs were also introduced to control wind (Norris *et al*. 2000) or vortex-induced vibrations (VIV) (Norris *et al*. 2013) for pipelines. Fig. 2 shows a photo of an installed TMD on an Arctic pipeline to mitigate wind induced vibration.

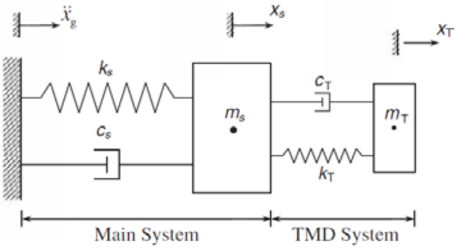

Fig. 1. A TMD system

Fig. 2. A photo of an installed TMD on a pipeline

More recently, sandwich pipe (SP), a composite structure consisting of two concentric steel tubes and a polymeric or cement-based core, has been developed as an effective design alternative especially when the pipe is going to be used in deep water applications. Fig. 3 shows the cross section of a SP. Compared to a single-wall steel pipe, a SP has many obvious advantages such as the reduction of weight, better corrosion resistance, higher thermal insulation capacity, larger buckling capacity and higher strength capacity, etc (Castello and Estefen 2008). A SP is a three layered composite structure. It can be simplified as a TMD system as shown in Fig. 1, where m_T and m_S are the masses of the internal and external pipes, the stiffness and damping of the tuned and main systems are provided by the core material and surrounding environment (support, soil etc) respectively. With carefully designed core material, a SP is believed to be able to suppress the vibrations induced by different sources. This makes it have great application potential in both onshore and offshore pipeline systems to control VIV and vibrations induced by earthquake and wind etc. It should be noted that in most pf previous studies, because of the large mass of the primary structures (e.g. buildings and bridges), a TMD is designed as an auxiliary device with a very small mass, typically in the order of a few percentage of the primary structure. Using internal pipe of a SP as the tuned mass, the mass ratio of the tuned and primary structure will be much larger, the dynamic behaviour of the auxiliary mass in such a case would be very different from those with small mass ratio. Hoang et al. (2008) found that, for a large mass ratio, TMD becomes very effective in minimizing the primary structural response and robust against uncertainties in the parameters of the system. With this property, using SP for pipeline vibration control might be even more efficient to control the vibrations induced by different sources.

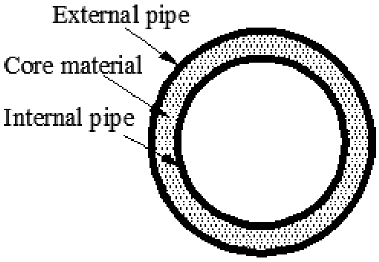

Fig. 3. Cross section of a sandwich pipe

The aim of this paper is to investigate the efficiency of using SP to mitigate seismic induced vibrations of above ground pipeline. The simplification of a SP to a TMD system is presented in detail. The effectiveness of using SP for pipeline vibration control is discussed based on the smiplified model.

2. ABOVE GROUND PIPELINE AND EARTHQUAKE LOADING

2.1. Above ground pipeline

Fig. 4 shows a typical above ground pipeline supported by different supports. To study the efficiency of using SPs to mitigate seismic induced vibration, the cross section of the pipeline is designed to have a sandwich shape as shown in Fig. 3. The external and internal pipes are assumed to be API36 and API28 pipes with the diameters of 914.4 and 711.2 mm respectively. The thicknesses for both pipes are both 7.9 mm. To effectively suppress seismic induced vibration of the pipeline, the core material should be optimally designed. The parameters for the optimized core material will be discussed in Section 3. The distance between each support is 40 m. Normally the pipe is not fully fixed to the supports, the transverse restraint provided by the support can be considered to be a spring (Powell 1978). The stiffness of the spring can vary from 7.5×10^5 N/m to 6×10^6 N/m (Powell 1978). In the present study, the stiffness is assumed to be 10^6 N/m, which represents a relatively flexible restraint.

Fig. 4. A typical above ground pipeline

2.2. Earthquake loading

Only the transverse earthquake loading is considered in the study. The ground motion is represented by a stationary stochastic process with a power spectral density (PSD) of the form proposed by Kanai (1957) and Tajimi (1960)

$$S(\omega) = \frac{\omega_g^4 + 4\xi_g^2\omega_g^2\omega^2}{(\omega_g^2 - \omega^2)^2 + 4\xi_g^2\omega_g^2\omega^2}\Gamma \tag{1}$$

where ω_g and ξ_g are characteristic ground frequency and damping ratio respectively, and they are selected as $\omega_g = 12$ rad/s and $\xi_g = 0.6$. Γ is a scaling factor depending on the ground motion intensity and $\Gamma = 0.0202$ m^2/s^3 is used, which corresponds to a ground motion time history with duration 20 s and PGA=0.3g based on the standard random vibration method (Der Kiureghian 1985). To investigate the seismic response of the pipeline in the time domain, the acceleration time history compatible with the PSD function is simulated based on the spectral representation method (Bi and Hao 2012). The cut off frequency is set as 25 Hz and the sampling frequency is 100 Hz. Fig. 5 shows the simulated acceleration time history and Fig. 6 compares the PSDs of the simulated time history and the given model (Eq. (1)). Good matches can be observed.

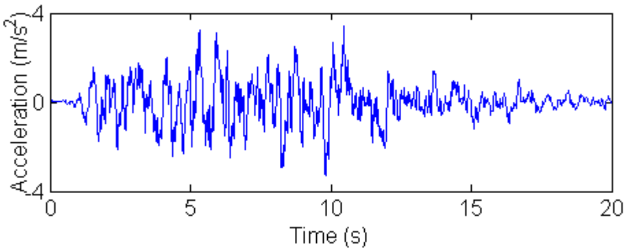

Fig. 5. Simulated acceleration time history

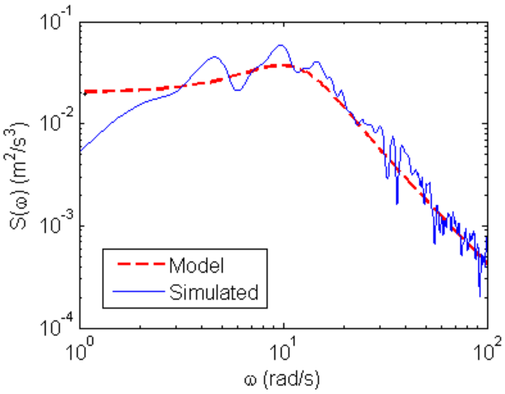

Fig. 6. Comparison of the PSDs between the simulated time history and the model

3. ANALYTICAL MODEL AND OPTIMIZED CORE MATERIAL PARAMETERS

A SP subjected to transverse earthquake loading can be simplified as a TMD system shown in Fig. 1 as discussed above. The stiffness (k_S) and the damping (c_S) of the main system are related to the characteristics of the external pipe and the support conditions. The determination of the main system is discussed in Section 3.1. The corresponding values for the tuned system can be estimated based on the main system and seismic excitation according to the optimal design method, which is discussed in Section 3.2. It should be noted that only the mass of the internal pipe is considered in the present study, the stiffness and damping are not considered because the internal pipe is assumed to be significantly stiffer and have less damping than the core material that would be used to connect the external and internal pipes. The optimal parameters for the core material may be slightly different if the stiffness and damping of the internal pipe are considered.

3.1. Parameters for the main system

Since it is impossible to model the whole length of a pipeline system and the distance between two supports is assumed to be 40 m as mentioned in Section 2.1, a one-span external pipeline model of 40 m span length is established in this study. The mass of the external pipe is m_S=7.10x10^3 kg. The constraints from adjacent spans on the one span model are simulated by installing rotational springs at each end of the model. The rotational spring stiffness is determined through a convergence study, namely updating the rotational spring stiffness value until the calculated displacement responses at the one-span pipeline are similar to those obtained from the multi-span (nine spans in this study) model and a value of 2x10^7 Nm/rad is finally selected. Fig. 7 shows the transverse displacement time histories at middle span of the one-span and nine-span models when they are subjected to the simulated time history in Fig. 5 by using the commercial software ANSYS. It can be seen that they almost coincide with each other. The one-span model is thus adopted to estimate the parameters for the main system. The fundamental vibration frequency of the one-span model can be calculated by carrying out an eigen value analysis, which is $\omega_s = 10.61$ rad/s. The stiffness is thus k_S=8.01x10^5 N/m and damping is c_S=7.54x10^3 Ns/m by assuming a 5% critical damping ratio.

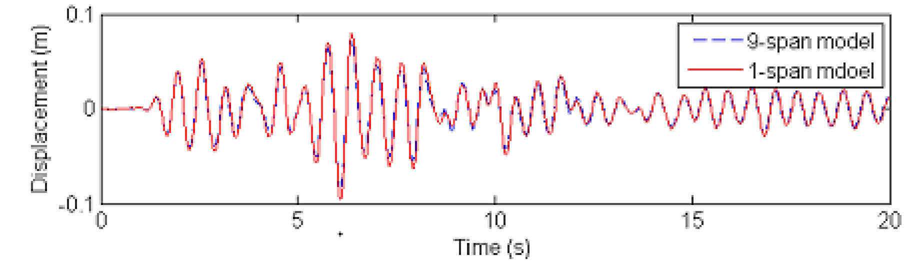

Fig. 7. Comparison of the transverse displacements at middle span of the nine-span and one-span pipe models subjected to the simulated ground motion

3.2. Parameters for the TMD system

To effectively mitigate seismic induced vibration, the core material should be optimally designed. Many methods are available for the optimal design. The method proposed by Hoang et al. (2008) is adopted in the present study. The optimized values can be expressed as follows when the frequency ratio $1 < \lambda = \omega_g/\omega_s < 3$

$$\gamma^{opt} = \frac{\sqrt{1-\lambda\mu/6}}{1+u} - \frac{0.7\xi_s}{1-\mu/2} \tag{2}$$

$$\xi_T^{opt} = \sqrt{\frac{\mu(1-\mu/4)}{4(1+\mu)(1-\mu/2)}} + 0.25\mu\xi_s \tag{3}$$

In the present study, ω_s=10.61 rad/s and ω_g = 12 rad/s as discussed above, thus λ =1.13. $\mu = m_T/m_S$ is the mass ratio and it is 0.78 based on the cross section of the SP given in Section 2.1. ξ_s is the damping ratio of the main system, which is assumed to be 5%. The optimal tunning frequency $\gamma = \omega_T/\omega_S$ and damping ratio ξ_T are thus 0.4624 and 0.3894 respectively. The stiffness and damping provided by the core material should then be 1.33x10^5 N/m and 2.11x10^4 Ns/m respectively for optimized vibration reduction. All the parameters for the simplified TMD system thus are determined, and the seismic responses of this simple system to the transverse seismic excitation can be calculated.

4. EFFECTIVESS OF USING SANDWICH PIPE FOR PIPELINE VIBRATION CONTROL

To study the effectiveness of using SP to mitigate seismic induced vibration of above ground pipelines, a traditional SP with cement-based core is also calculated. In this case, the internal pipe, external pipe and core will oscillate together. To save the modelling effort, steel pipes and cement core are smeared together with equivalent Young's modulus and equivalent density, and the analysis is also carried out by using ANSYS (2009). Figs. 8 and 9 show the transverse displacement time history of the internal and external pipes at the middle span of the pipeline with cement-based core and optimized core.

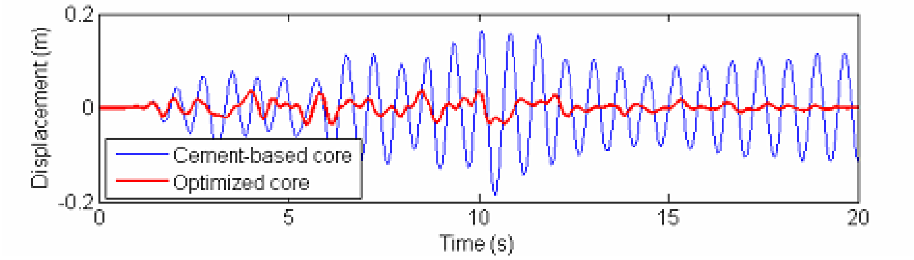

Fig. 8. Transverse displacement time histories of external pipe at the middle span of the pipeline with cement-based core and optimized core material

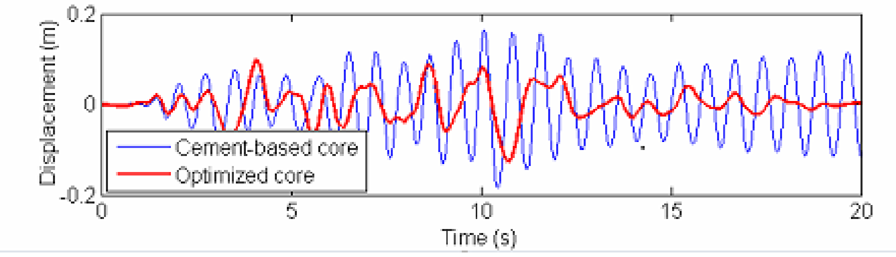

Fig. 9. Transverse displacement time histories of internal pipe at the middle span of the pipelines with cement-based core and optimized core material

It can be seen that with the optimized core, the maximum transverse displacements of external and internal pipes are 0.036 and 0.126 m respectively, while for the traditional cement-based core, the displacements are both 0.185 m. A SP with optimized core material can significantly suppress seismic induced vibration of the pipeline.

It should be noted that the above results are based on the simplified TMD model, detailed 3D finite element models and experimental studies are needed to verify the concept.

5. CONCLUSIONS

This paper advocates the concept of using SP to mitigate seismic induced vibration of above ground pipelines. The simplification of a SP to a TMD system is discussed in detail. A numerical analysis is carried out to illustrate its effectiveness. Numerical results show that a SP with optimized core material can significantly suppress seismic induced vibration of above ground pipelines. It may have great application potential in onshore and offshore pipeline systems to control vibrations induced by different sources.

ACKNOWLEDGEMENT

The first author acknowledges the partial financial support from the ARC DECRA project DE150100195.

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