Seismic resistance for high-rise buildings using water tanks considering the liquid - tank wall interaction

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Abstract

In recent years, considerable attentions have been paid to research for the development of structural control devices, particularly focusing on the mitigation of wind and seismic's effects. The use of water tanks at roof as resistant solutions, which are known as Tuned Liquid Dampers (TLD), for high-rise buildings is considered in this paper. In the literature, TLD has shown significant advantages and can be one of excellent methods to control high-rise building's vibration. Liquid storage tank is designed to achieve its natural frequency same as that of the building. As a result, the resonant phenomenon will occur and contribute to the building's balance.

Besides using TLD to analyze the seismic resistance for high-rise buildings, this paper is also considered the interaction between the liquid and tank wall for with/without using water tank at roof as seismic resistance devices. Results showed that the maximum displacements at the top of buildings can be decreased from 50% to 80% and internal stresses are also reduced meaningfully.

Keywords: Tuned Liquid Dampers, sloshing, dynamic control, finite element method, liquid-structure interaction.

Introduction

In general, TLD is a tank with a part of liquid inside relied on liquid sloshing to dissipate vibration energy (Figure 1, 2). In fact, the liquid is employed to provide all of the necessary characteristics of a secondary system. Meanwhile, its gravity provides the required restoring mechanism. Therefore, the secondary system has characteristic periods that can be tuned for optimal performance, in the same way as a tuned mass damper (TMD). TLD is a passive mechanical damper and has been used in marine for centuries, and in the 20th it was applied in aerospace. The advantages of TLD are low cost, easy install & maintenance and the most advantage is that it can apply for almost kind of structure including existing building or tower.

A liquid storage tank on a fixed offshore platform was first used as a TLD to suppress the wind-induced vibration of the platform structure by Vandiver et al. (1979) [17], and was shown to be effective. Yozo Fujino (1989) [7] was one of the first researching TLD's wind resistance with full scale testing. Sun LM (1992) [8] analyzed TLD's capacity under wind and earthquake by theory and compared with experiment but in his research, the amplitude of liquid sloshing is not large. Bui Thanh Tam (1997) [2], showed that TLD can reduced 60% of the vibration of structure by using finite element method (FEM). Dorothy Reed (1998) [15] published his research about TLD under very large liquid sloshing's amplitude and Jin Kyu Yu (1999) [5][6] modeled TLD as an equivalent TMD with non-linear stiffness and damping.

In mechanical, civil and aerospace engineering, fluid-structure interactions with a moving free surface can have significant influence on the dynamic behavior of the structure and needs to be properly taken into account. Large amounts of work deal with linearization on the free surface, or other simplifications because of the complexity of the problem. However, for fluid-structure interactions including large scale sloshing motion of the fluid and large displacement motion of the structure, advanced theory and numerical methods are required [5] [6]. In recent years, advances have been made in this respect. In some circumstances, especially when the deformations of the container are small compared to its displacements, it is reasonable to simplify the structure as a rigid container supported by a system consisting of elastic springs and dashpots. Typical situations include TLD to passively suppress vibrations of high-rise buildings or towers of cable-suspension bridges, and liquid-loaded vehicle systems. In these fluid structure interaction problems involving large-amplitude sloshing, the nonlinear characters caused by the free surface motion and the dynamic boundary conditions need to be considered. The nonlinearity can also be inherited from the dynamics of the structure.

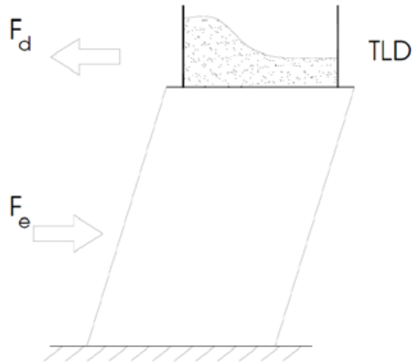


Figure 1. Mechanism of building with TLD

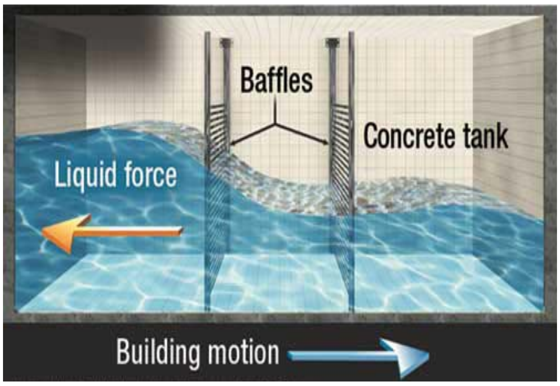


Figure 2. Inside a liquid tank as TLD

All of previous TLD's design assumed that the tank's wall or TLD is rigid to ignore tank's flexibility in that the complicate at the liquid-tank interface. In fact, there are many tank's failures (Figure 3, 4) because of this assumption so that it is attracted researchers and engineers in the last few years (Praveen K. Malhotra *et al*. (2000)[5]; M. Gradinscak (2009)[10] to study. Andersson (2001)[16] first investigated the possibility of using container flexibility for control of liquid sloshing. Recently, M. Gradinscak (2009)[10] presented that flexible container partially filled with water, as the sloshing absorber, and it can be advantages over a rigid container for effective control. However, in this study the building is modeled as a single degree of freedom, and the mass ratio of TLD over structure is 10% (this ratio is too much to practically apply especially in high rise building).

Figure 3. Sloshing damage to upper shell of tank (courtesy of UC Berkeley)

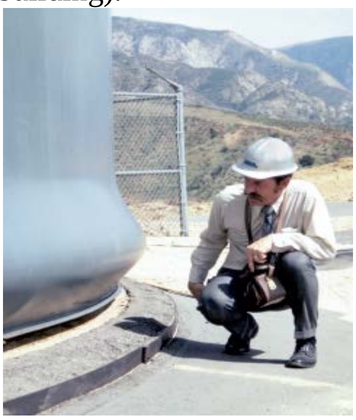


Figure 4. Elephant-foot buckling of a tank wall (courtesy of UC Berkeley)

The work in this paper is to analyze building under harmonic load and earthquake with and without TLD. Addition, the effects of flexible tank's wall is considered throught several main parameters in container such as natural frequency of liquid sloshing, shear forces, moments in tanks wall or in building for instance column's moments, top displacements. In this work, **Ansys** V.11 is used to model the hold structure and investigate the thick of tank wall to describe the relation of the rigid and flexible tank.

The liquid-tank's wall interaction in TLD

The TLD is designed to have the same natural frequencies with structure and achieved the resonant phenomenon. One side helps to promote maximum ability of the damper but the other side it changes the TLD's dynamic properties through the liquid-tank's wall interaction. The main problem in studying of the liquid-structure interaction is solving the boundary condition at tank's wall. The equations described this condition is re-written by Biswal (2003)[18] as:

$$\begin{bmatrix} [M_s] & [0] \\ \rho_f[S] & [M_f] \end{bmatrix} \begin{Bmatrix} \ddot{d} \\ \ddot{p} \end{Bmatrix} + \begin{bmatrix} [K_s] & -[S]^T \\ [0] & [K_f] \end{bmatrix} \begin{Bmatrix} d \\ p \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{1}$$

with:

- M_s, M_f are mass matrices of structure and liquid
- K_s, K_f are stiffness matrices and liquid
- $\ddot{d}, d$ are acceleration and deformation of the structural boundary
- p is the liquid hydro-dynamic pressure.

Equation (1) leads to a non-standard, unsymetric eigenvalue. It is more difficult to find the eigenvalue for large size matrices. Many studies were presented to deal with this problem, and **Ansys** V.11 can be used to model liquid, container and main structure. The natural frequencies, amplitude of liquid sloshing are selected to emphasize the importance of the interaction. The tank's wall, columns and beams were modeled by using "*Beam3*" element, liquid by "*Fluid 79*" element. The liquid–container interaction was achieved by coupling the displacements of the liquid and container walls in the normal direction to the container walls.

The effect of tank's wall to natural frequency

Four types of containers with different thickness of tank's wall, *t*, from thin to thick are analyzed to find the natural frequencies and then compared with Housner's formulation (1967)[1] for rigid container. The containers are $T0.59\times0.03$ (container's width is 0.59m, height of liquid is 0.03m), $T1.00\times0.10$, $T3.00\times0.20$, $T6.00\times0.50$. The natural frequency of tank [5]:

$$f = \frac{1}{2\pi}\sqrt{\frac{\pi g}{2a}\tanh\left(\frac{\pi h_f}{2a}\right)} \tag{2}$$

The relation between flexible tank and rigid tank can be set up though ψ by Duc Tuong et al (2010)[1] as the flexibility parameter which is depended on thickness of tank wall, height and modulus of liquid:

$$\psi = E\times\frac{t_{\text{tank}}^3}{h_{\text{liquid}}^3} \tag{3}$$

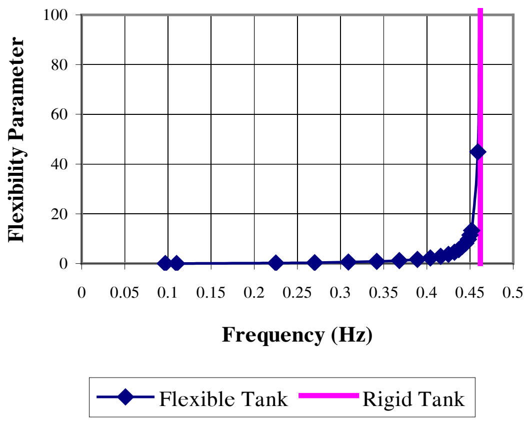


Figure 5. Frequency of $T0.59\times0.03$

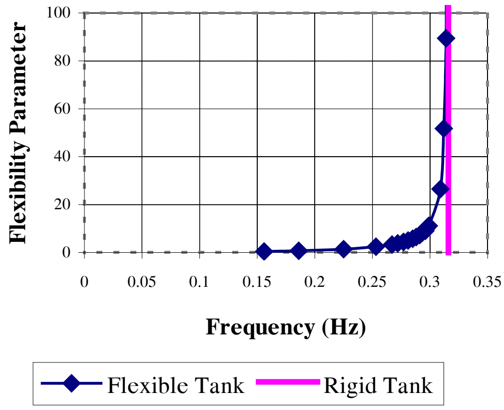


Figure 6. Frequency of $T1.00\times0.10$

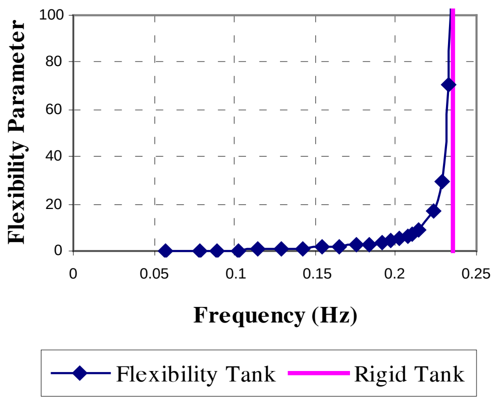


Figure 7. Frequency of $T0.59\times0.03$

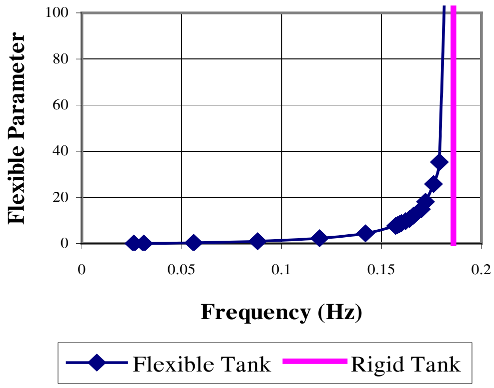


Figure 8. Frequency of $T1.00\times0.10$

Figure 5, 6, 7, 8 showed that the container is rigid if ψ is more than *100* otherwise it is flexible. And easily see that the thicker tank's wall, the higher frequency of TLD.

The effect of tank's wall to sloshing amplitude

To see clearly the effect of the liquid–tank's wall interaction, a numerical example is considered. A rectangular concrete container has the sections $6.0m\times1.0m\times0.5m\times t$, in length, height, liquid height and wall's thickness, and is applied harmonic load $x = A_o \sin\omega t$ with $A_o = 5(mm)$. The properties of concrete are: $\rho = 2400kg/m^3$, $E = 2.65e10(kN/m^2)$, $\upsilon = 0.2$. The mass of the structure was 28.941kN. From (2), $f_{\tan k}^{rigid} = 0.18582(Hz)$ and in **Ansys** V.11 $f_{\tan k}^{rigid} = 0.18250(Hz)$. Based on the flexibility parameter ψ [1], this container is rigid when $\psi \geq 100 \Leftrightarrow t \geq 1.78mm$.

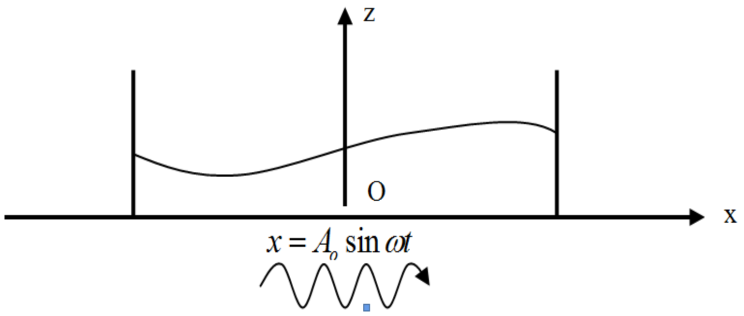


Figure 9. Container $T6.0m\times1.0m\times0.5m\times t$

Under harmonic loading $x = A_o \sin \omega t$ with $A_o = 5(mm)$ and $f = 0.25Hz$. The sloshing can be expressed as Figure 10 and 11, it is clear to see that when t is rigid or near rigid $(\psi \geq 100)$, sloshing amplitude is merely the same (Figure 10) and the amplitude in flexible container is much more than in rigid one (Figure 11).

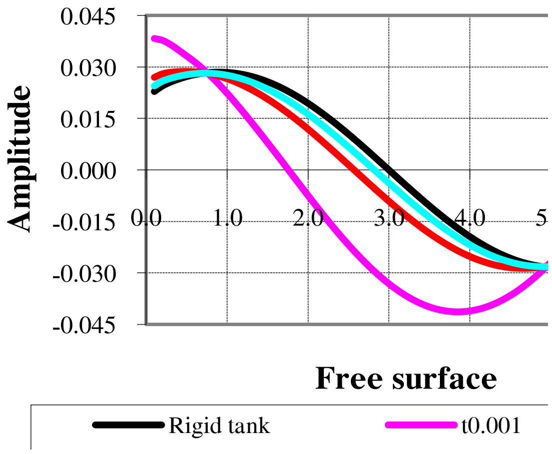


Figure 10. Sloshing amplitude in near rigid container

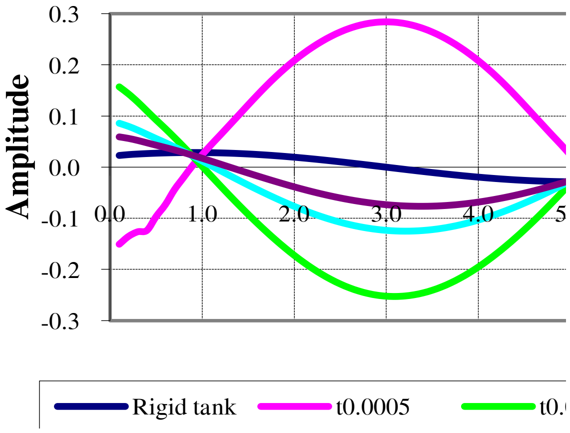


Figure 11. Sloshing amplitude in flexible container

Come to conclusion, the liquid-tank's wall interaction is important in container design because of two reasons: (1) the interaction leads to change the dynamic properties of tank and the natural frequencies of container can adjust easily by increasing or reducing the tank wall's thickness; (2) under the same load, sloshing amplitude in flexible tank is higher in rigid tank. This implied flexible tank is carried more load than in the rigid one so that when design TLD the flexibility should be checked by parameter ψ to protect the stability of container. Because of the rigid tank wall assumption, there are a lot of failure containers especially with the dynamic loads.

Numerical Example in Designing TLD Considering Liquid-Tank's Wall Interaction

Two examples are analyzed to investigate the seismic resistance of TLD for high-rise building. The first one presents the main point in designing damper and the second shows the TLD's capacity and emphasize the importance of liquid-container interaction.

Example 1

Design TLD for a steel building 70m in height under harmonic and seismic load, El-Centro earthquake data is used to analyze the seismic resistance of the building in **Ansys** V.11 and Newmark's method is used to predict sloshing and top building's deformation. Building has 14 storeys with each storey 5m in height and one span 3m in length. All of beams and columns section are the same and the tank is $T0.6m \times 0.8m$ with $E_{steel} = 2.1 \times 10^{11} N/m^2$, $\rho_{steel} = 7800 kg/m^3$, $\upsilon = 0.3$. Mass of structure is $P_{building} = 6685000N = 6685kN$.

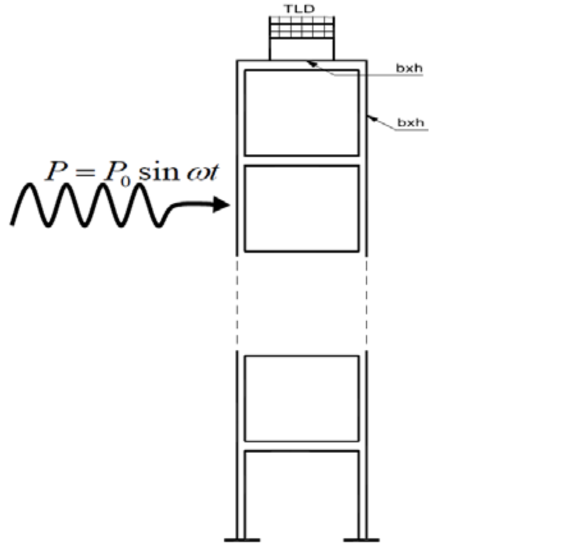


Figure 12. 14-storeys building with TLD

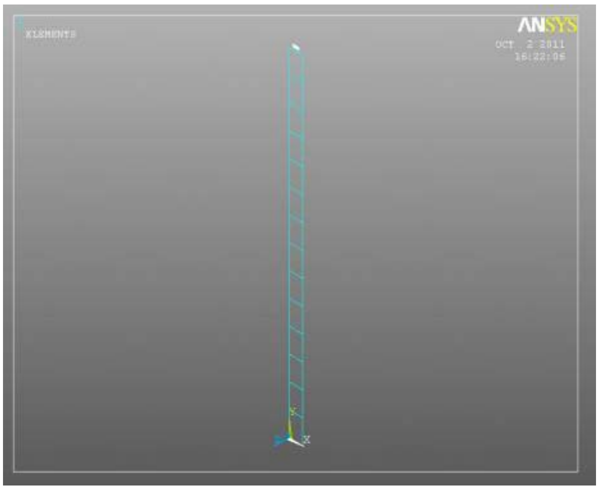


Figure 13. 14-storeys building in Ansys

The TLD is designed based on Sun LM's guides (1992) [8], that is: $f_{TLD} \approx f_{structure}$ and $P_{TLD} \approx \frac{1}{100} P_{structure} = 6685N$. And two conditions can be described as:

$$\begin{cases} P_{TLD} = \gamma \times g \times b_t \times h_f = 9810 \times b_t \times h_f = 6650 \\ f_{TLD} = \frac{1}{2\pi} \sqrt{\frac{\pi g}{b_t} \tanh\left(\frac{\pi h_f}{b_t}\right)} \approx f_s = 0.70873 \end{cases} \tag{4}$$

Where b_t and h_f are tank's width and liquid height. The liquid in TLD is water with $E_{water} = 2.2 \times 10^9 N/m^2$, $\rho_{water} = 1000 kg/m^3$, $\upsilon = 0.5$. Withdraw from(4), we have $b_t \approx 1.2m, h_f = 0.5m$. Then the natural frequency of TLD followed (2) is $f_{TLD} = 0.749Hz$, the building is under harmonic load $P = P_0 \sin \omega t = 1000 \sin \omega t (N)$ with frequencies of load from $0 \rightarrow 1.2Hz$ and El-Centro earthquake. Figure (14) and (15) shows the response of structure with and without TLD.

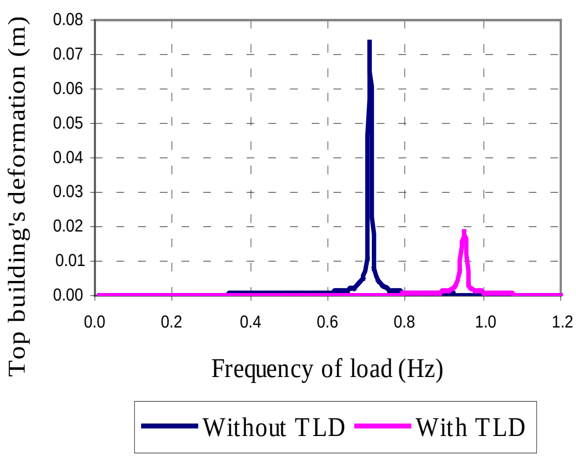


Figure 14. Structure under harmonic load

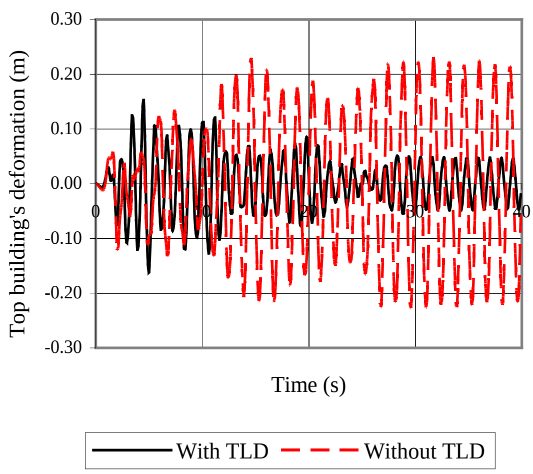


Figure 15. Structure under El-Centro

In Figure (14) the top building's deformation reduces 4 times when using TLD and the resonant occurs at frequency $f = 0.94Hz$. Figure (15) shows that the building's vibration reduced 80% under seismic load if TLD is used. Beside, the moments in the left column of the structure with TLD are less than without TLD 25%.

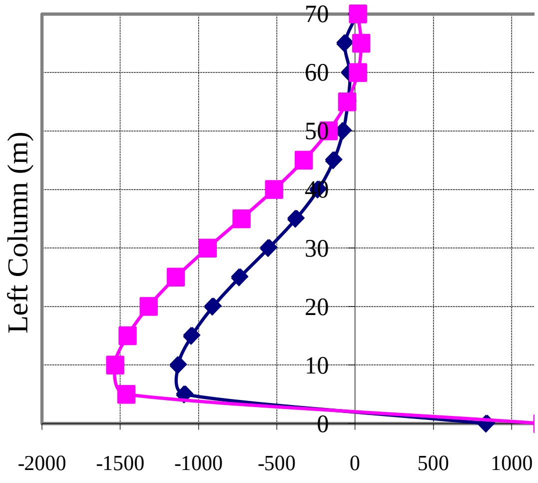


Figure 16. Moments in left column of the building

Example 2

An eight storeys steel building has one span 3.0m in length and each storey is 3.0m in height with $E_{steel} = 2.1\times10^{11} N/m^2$, $\rho_{steel} = 7800 kg/m^3$, $\upsilon = 0.3$. Mass of structure is $P_{building} = 881762.8N \approx 881.763kN$. Figure 17 showed the natural frequency of structure $f_1^{building} = 0.29(Hz)$. The transient analysis is carried out to find the response vibration of the building with the frequencies of load from $0 \rightarrow 1(Hz)$ and Figure 18 illustrated the maximum response vibration of the structure without TLD is 1.8m at $f = 0.29(Hz)$.

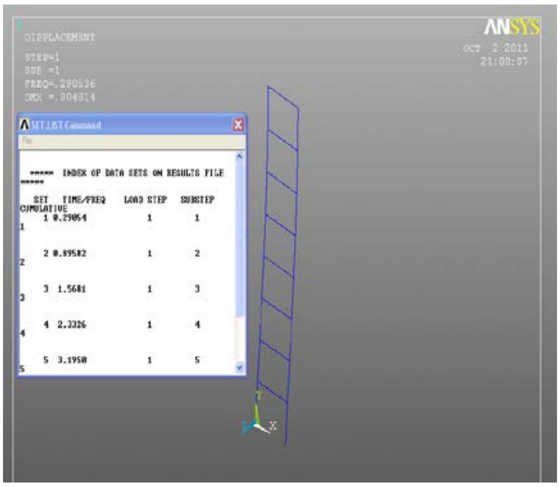


Figure 17. 8-storeys building's frequency in Ansys

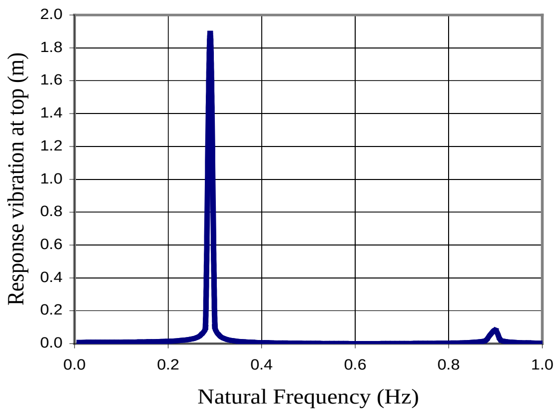


Figure 18. Response vibration of building without TLD

The TLD is designed by the same progress with Example 1 in **Ansys** V.11 to suppress the vibration and its section is $L_{TLD} \times h_{liquid} = 2.0m \times 0.2m$, $f_{TLD}^{rigid} = 0.277(Hz) \approx 0.95 f_{building}$ and $P_{TLD} = P_{tank} + P_{water} = 10079N \approx 1.13\% P_{building}$. The thickness t of container is changed from thin to thick to investigate the effective of liquid–tank's wall interactions. The thickness t of container is separated in two types which are rigid and flexible. Figure 19 described the response vibration of building with rigid TLD that means $\psi \geq 100$ is reduced 50% and the resonance was occurred at $f = 0.29(Hz)$, the same with the natural frequency of the building. But in the Figure 20, the resonance was occurred uncontrollably and at the undefined value. Thus, the flexibility of TLD must be checked when designed.

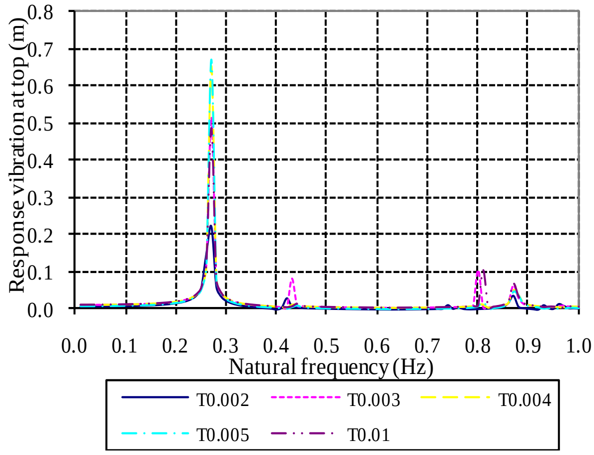


Figure 19. Top displacement with rigid TLD

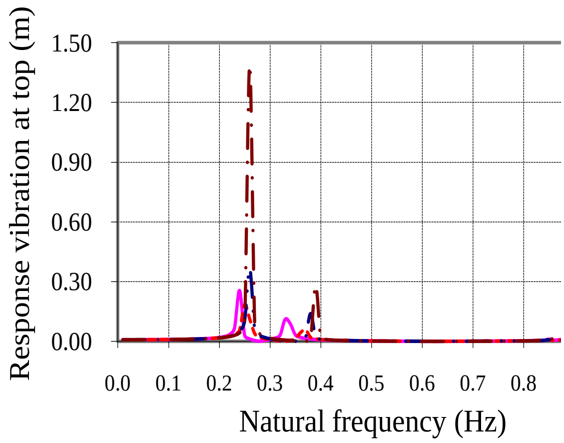


Figure 20. Top displacement with flexible TLD

To continue this part, the seismic resistance of TLD is analyzed. El-Centro and Newmark is used as data and tool to track liquid sloshing and displacements of building. When occurred earthquake, TLD is activated and the liquid sloshing is oscillated as shown in Figure 21, and contributes to reduce 67% the vibration of building as shown in Figure 22. However, with the different container's thickness, there were various top deformations as illustrated in Figure 23.

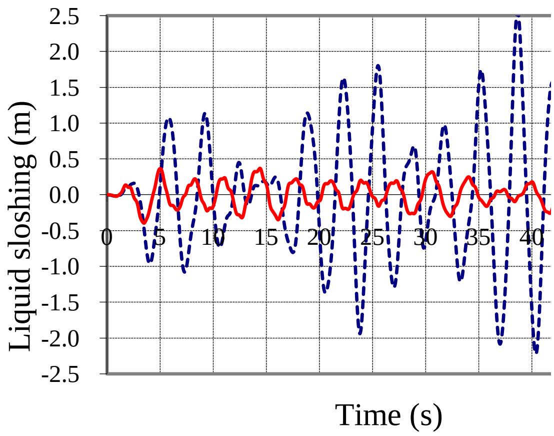


Figure 21. Sloshing at top building

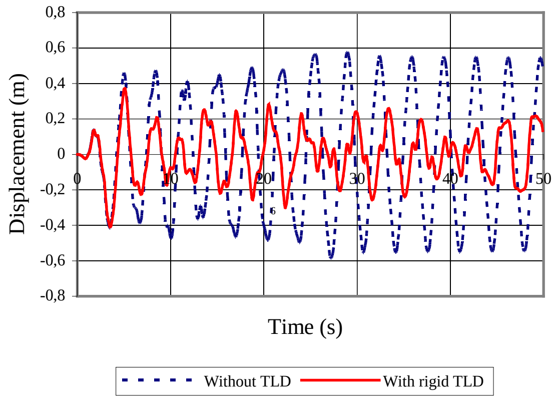


Figure 22. Top building with & without TLD

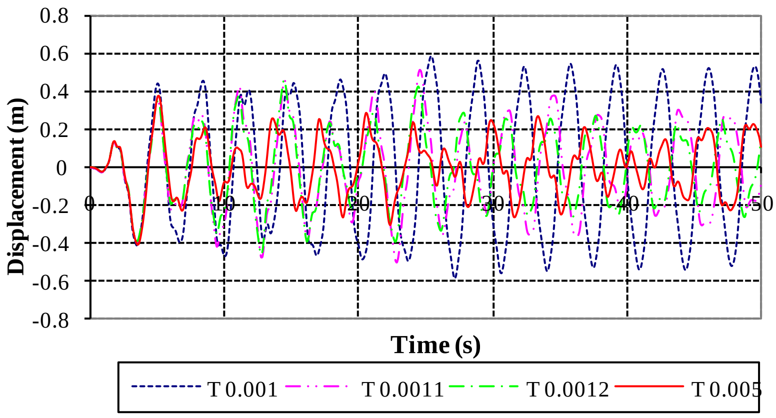
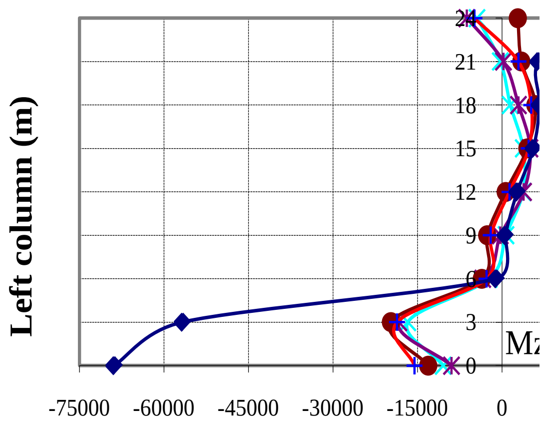


Figure 23. Top building with flexible TLD

To see more clearly the seismic resistance capacity of the damper, the moments in column of the building are illustrated in the Figure 24 and 25 in cases with and without TLD. That figure showed TLD can reduced from 50 to 75% moment in column (good agreement with Sun and Fujino's experiment in 1989 [7]).



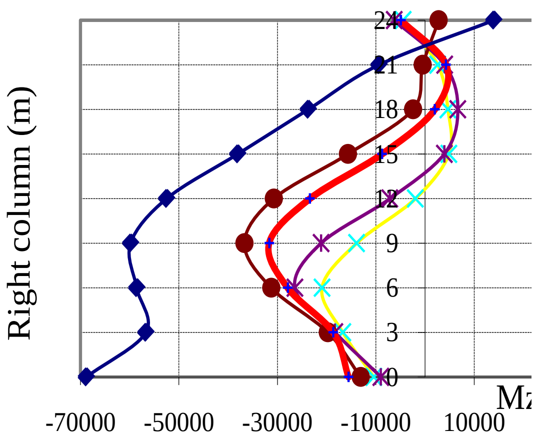


Figure 24. Moment in left column of building **Figure 25. Moment in left column of building**

Conclusions

The seismic resistance capacity of TLD is enough good if the ratio of TLD over the suppressed modal mass of the structure is 1-3%. With 1-3%, the TLD's weight does not significant affect the dynamic characteristics of the structure. Then, the vibration at the top of the building is reduced from 67% to 75% based on TLD. This leads to the moment in columns also reduced meaningfully up to 80% (good agreement with Fujino's results (1988) [13]).
When TLD is activated, there is no different of the building's internal forces between rigid and flexible tank's wall as showed in Figure 24 and 25. So the recommendation is that TLD should be designed to have a rigid wall to avoid the tank's deformation because of the interaction.

Using TLD to seismic resistance will re-distribute the internal forces so that the maximum moment may be not appear at the column base at Figure 16 and 25.
The interaction at liquid-tank's wall is very important so that it must be considered carefully. The interaction can change the dynamic properties of container wall then the water tank could not be TLD. Otherwise, one can use the flexibility to control the natural frequency of the tank [10].

The TLD can be designed easily as in example 1 by adjust the size of tank and height of liquid. It also can be applied for almost structure.

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