The applied research on Tuned Liquid Damper in practical engineering with three-dimensional numerical simulation

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Abstract. The practical application of high-position fire-fighting water tanks on the top-level of office buildings in State Grid Corporation of China is studied in this article. Fluid-solid-coupling mathematic models were established based on ABAQUS finite element analysis software to compare the calculational results in two-dimensional situations and three-dimensional ones. Meanwhile, a 22-storey frame-shear wall structure named Innovation Mansion was selected to discuss the vibration reduction effect of TLD. The results indicate that the fluid-solid-coupling analytical method could reflect the nonlinear character of TLD-structure system precisely, and the aseismic ratios were 2%-5% variation between two-dimensional models and three-dimensional ones. The TLD has positive effects on controlling the structural seismic responses and the aseismic ratios could reach 10% around, besides, the TLD damping force not only offset the increased base-shear arose from its own weight, but also reduced the total base-shear.

1.Introduction

Most office buildings in State Grid Corporation of China are high-rise structures which have the characteristics of multi-storey and dense-population, so the structural seismic performance and the fire protection should be emphasized to reduce economic loss. The fire-fighting water-tanks installed on the top-level are upgraded to TLD(short for Tuned Liquid Damper) to improve the aseismic safety of building structures, and the function has been deeply studied in recent years: The vibration reduction performance of TLD-structure system was investigated through a shaking table test. The results suggested that the vibration reduction effect was prominent when the liquid oscillation frequency tended to structural natural frequency, controlling the first-mode and second-mode vibration response in parallel was superior to merely controlling the seismic response of first-vibration-mode[1]. Seismic recordings were imposed on a one-span, three-storey frame-structure specimens to discuss the application of TLD-structure system, and it was found that the vibration reduction performance had a close connection with the size, number and location of water-tanks[2]. The optimal design parameters of TLD-structure were studied based on model experiments, and the aseismic ratio was satisfying when the liquid weight equalled to 1% structural mass generally[3]. Meanwhile, the reduction performance of TLD on seismic response was discussed based on lumped-mass method, the conclusions demonstrated that the device showed remarkable energy-absorption lagging behind the earthquake running 6-7 seconds[4].

In summary, the vibration reduction phenomena could be observed intuitively through model experiments, but it has some faults such as high investment and particular operating-environment.
Numerical simulation methods could compensate the above-mentioned drawbacks via high-performance electronic computer, besides, the interaction between TLD and structures is more rational in mathematic model. In this article, theoretical bases referring to fluid-solid-coupling analysis is recommended firstly and a comparative analysis is conducted between two-dimensional TLD-structure coupling models and three-dimensional ones to highlight the necessity. Finally, an actual frame-shear wall structure model is established based on ABAQUS finite element software to discuss the engineering application.

2. Theoretical basis

2.1 Vibration reduction principle

The water in fire-fighting tanks sloshed into waves when the main-structures suffered the wind-load and earthquake-load, then the dynamic pressure difference resulted from horizontal wave stimulation together with the inertia force in opposite direction had vibration reduction effects on building structures. The maximal damping force was obtained in the condition that the TLD tank-size was designed in accordance with structural natural frequency[5,6], the working principle of tuned liquid damper was illustrated in formula below:

\[ m\ddot{x} + c\dot{x} + kx = F(t) - F_{TLD} \]  

(1)

\( m \) represents the structural weight; \( c \) represents the damping coefficient; \( k \) represents the stiffness coefficient; \( F(t) \) represents the dynamic inputting load; \( F_{TLD} \) represents the damping force arose from water sloshing.

The damping force \( F_{TLD} \) varied with the liquid oscillation frequency \( f_n \), which calculated from the equation below:

\[ f_n = \frac{1}{2\pi} \sqrt{\frac{g}{2A} \left(2n-1\right)\tan h \left[ \frac{(2n-1)\pi h}{2A} \right]} \]  

(2)

\( h \) represents the liquid depth; \( A \) represents the side length in same direction with inputting load; \( n \) represents the order of liquid oscillation frequency.

2.2 Fluid-solid-coupling analytical method

There exists strong nonlinear oscillations between fluid-medium and solid-medium in TLD device, and the Navier-Stokes equation could properly describe this nonlinear behavior. mixed interpolation method was widely used in solving Navier-Stokes equation, however, the solving process for velocity interpolation function and pressure interpolation function was complicated due to the tedious calculation-procedure and inputting-data. In contrast, the Arbitrary Lagrange-Euler (ALE for short) algorithm was an effective solution that seperately calculating the velocity parameters in explicit scheme and pressure parameters in implicit scheme. The fluid-solid-coupling discrete equation base on Galerkin weighted residual method was deduced as follows[7,8]:

\[ M_{ai}^{n+1}u_{pi}^{n+1} = M_{ai}^{n}u_{ai}^{n} - \Delta t \left[ B_{ai}^{n}u_{pi}^{n} + \frac{1}{\rho} C_{ai}^{n}p_{ai}^{n} + D_{ai}^{n}u_{pi}^{n} - F_{ai}^{n+1} - \dot{E}_{ai}^{n+1} \right] \]  

(3)

\( \alpha, \beta \) represents the node number in one element; \( i \) represents the spatial dimension; \( n \) represents the calculation order; \( \Delta t \) represents the pressure difference; \( M, A, B, C, D, E, F \) represents individual parameter matrices.

3. Comparative analysis

Dynamic time-history method was applied to the finite element numerical model of TLD-structure system, the results calculated from two-dimensional coupling models and three-dimensional ones were compared to discuss the necessity for substituting.
3.1 Calculating case
A fifteen-storey RC frame-structure was selected as the research example, and the size of TLD-tanks was designed as 2m×1m×1.2m (length×width×liquid-depth) to make the liquid oscillation frequency equal to the structural first-mode frequency. The numerical simulation models were established in two-dimensional form and three-dimensional form respectively. Utilizing the model analysis, the structural first three mode-shapes were listed in Table.1[9~11].

| Mode shape | Characteristic Period (s) | Effective mass coefficient in X-direction (%) | Effective mass coefficient in Y-direction (%) | Effective mass coefficient in Z-direction (%) |
|------------|--------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| 1          | 1.418                    | 0.00                                        | 74.62                                       | 0.00                                        |
| 2          | 1.347                    | 78.06                                       | 0.00                                        | 0.00                                        |
| 3          | 1.061                    | 0.00                                        | 0.00                                        | 80.08                                       |

The time-dependent seismic response of TLD-structure system was easily calculated through dynamic time-history method, then the maximum of top-displacement, acceleration, internal force and deformation in every moment were obtained with high-precision. The TLD-structure fluid-solid coupling models were classified into two types: models uninstalled TLD device and ones equipped with TLD device. A positive effects of fluid sloshing on structural vibration reduction was considered in models installed TLD device.

According to the Code for seismic design of buildings[12], three primary factors should be taken into account when selecting seismic waves: spectral characteristics, peak ground acceleration and seismic duration. Drawing on the terms requirement, two seismic recordings and one artificial earthquake wave were selected for time-history analysis, the parameters were listed in Table.2

| Seismic waves | Characteristic period(s) | Peak acceleration (cm/s^2) | Scaling factor | Duration (s) |
|---------------|--------------------------|----------------------------|----------------|--------------|
| El-Centro     | 0.56                     | 341.72                     | 0.21           | 7.0          |
| Taft          | 0.44                     | 175.44                     | 0.39           | 7.0          |
| Shanghai artificial waves | 0.34              | 35.31                     | 1.98           | 7.0          |

Note:1. Scaling factors were corresponding to the seismic fortification intensity of 8 degrees; 2. Seven seconds covering peak acceleration was cut from the selected seismic recordings, to reduce computational cost.

3.2 Results and analysis
The selected seismic recordings-El-Centro, Taft, Shanghai artificial waves-were applied on the numerical models, as a result, the largest top-displacements and aseismic ratios for each working condition were summarized in Table.3.

| Seismic waves | Two-dimension without TLD(m) | Two-dimension with TLD(m) | Aseismic ratio(%) | Three-dimension without TLD(m) | Three-dimension with TLD(m) | Aseismic ratio(%) |
|---------------|-----------------------------|---------------------------|-------------------|-------------------------------|----------------------------|-------------------|
| El-Centro     | 0.043                       | 0.040                     | 5.69              | 0.039                         | 0.038                      | 1.58              |
| Taft          | 0.036                       | 0.034                     | 6.87              | 0.035                         | 0.035                      | 1.73              |
As shown in Table.3, the largest top-displacements and aseismic ratios in three-dimensional numerical simulation model were different from those in two-dimensional model, although the vibration reduction trends were identical. The calculation results indicated that the aseismic ratio, as crucial evaluation indicators, were 2%~5% variation between these two types of models.

The reason for the differences was the calculational assumption regarding to nodal normal vectors on free fluid surfaces: in two-dimensional simulation model, the normal vector was defined as \( n_A = n_{Blab}/(l_{Blab} + l_{Als}) + n_{Clac}/(l_{Blab} + l_{Als}) \) and the schematic diagram was presented as Figure.1(a); in the three-dimensional model, the normal vector was \( n_p = n_{1s1/s} + n_{2s2/s} + n_{3s3/s} + n_{4s4/s} \) and the diagram was shown in Figure.1(b).

![Figure 1. Nodal normal vectors on free surfaces](image1)

(a)Normal vectors in two-dimensional model  (b)Normal vectors in three-dimensional model

Meanwhile, the node vectors located at the border of free fluid surface and tank sidewall had different definition as well: in the two-dimensional model, the contacting effect in slipping boundary was not taken into consideration and the vectors were simply assumed to move upward along the sidewall; on the contrary, the contacting effect was considered in three-dimensional model and the node vectors was controlled by the free surface and the sidewall simultaneously.

Generally speaking, the two-dimensional numerical simulation model has some advantages such as simple model establishment, high calculation speed and low computer-configuration requirement, but the definition of nodal normal vector on free fluid surface has great differences with actual situation\cite{13}. The calculational accuracy could be improved through three-dimensional analysing technique and the nonlinear liquid sloshing achieved in this way.

4. Engineering application

From the perspective of urban development, the high-rise buildings are expected to be the major commercial architectures in central cities. The fire-fighting tanks installed on the top-floor are necessities to improve the fire-safety, however, the increased dead-weight arose from large capacity and high position has negative effects on structural seismic performance. According to the engineering requirements, the tanks at top-level were reformed to TLD device to change the negative factors into positive ones.

4.1 Building instance

A twenty-two-storey frame-shear wall structure named Innovation Mansion in Xi’an was chosen as the analytical example, which located in an aseismic region of 8 degree fortification with 0.20g seismic acceleration and 0.35s characteristic period. The design earthquake group was NO.1 and the site classification was Type 2. Member sections and material parameters were listed in Table.4.
Existing research results indicated that the optimal vibration reduction achieved in the condition that the mass-ratio of TLD to structure was 1%~3% and the frequency ratio was about 1.0\cite{14}. Increasing the liquid mass usually led to the phenomenon that the liquid oscillation frequency deviated the structural natural frequency, and these two parameters were hard to balance. On the whole, the influence arose from liquid-mass increasing was larger than that from frequency-ratio decreasing. Considering the easy-construction and reasonable-cost, the size of TLD equipped on the Innovation Mansion was designed as 12m×12m×7.2m (length×width×liquid-depth) and the finite element model was shown in Figure.2.

![Figure 2. Structural finite element model](image)

### 4.2 Results and analysis

According to the standard regulations and seismic selecting principles, two seismic recordings and one artificial earthquake wave (El-Centro, Taft, Shanghai artificial waves) were applied on the Innovation Mansion numerical models. The top-displacement and base-shear were evaluation parameters to analyse the vibration absorption effect.

1. **Top-displacement**

   Under the three earthquake excitations in X-direction and Y-direction, the structural top-displacement time-history curves with and without TLD devices were shown in Figure.3.
The aseismic ratios under different earthquake excitations were summerized in Table.5.

| Seismic waves            | Aseismic ratios in X-direction | Aseismic ratios in Y-direction |
|--------------------------|--------------------------------|--------------------------------|
| El-Centro                | 19.41%                         | 22.90%                         |
| Taft                     | 13.67%                         | 14.45%                         |
| Shanghai artificial waves| 9.86%                          | 12.09%                         |

As shown in Figure.3 and Table.5, the TLD had positive effects on controlling structural seismic responses in general and the aseismic ratios reached 10% around. The aseismic ratios in Y-direction were slightly larger than those in X-direction for the reason that the seismic responses in Y-direction were greater than X-direction, that is to say the better vibration reduction effects achieved based on the premise that the liquid oscillation amplitude in TLD device was large enough. The calculational results indicated that the aseismic ratios under El-Centro excitation (X:19.41%, Y:22.90%) were obviously larger than those under Taft excitation (X:13.67%, Y:14.45%) and Shanghai-artificial-waves (X:9.86%, Y:12.09%), this is because the predominant period of El-Centro was closer to structural first-mode
natural frequency and the stimulated displacement response was larger.

(2) Base-shear

Under different earthquake excitations, the base-shear in X-direction and Y-direction was obtained from finite element analysis, as shown in Figure.4.

![Base-shear in X-direction](a) Base-shear in X-direction  ![Base-shear in Y-direction](b) Base-shear in Y-direction

Figure 4. Structural base-shear under different earthquake excitations

According to response spectrum theory, the increased structural dead-load usually resulted in base-shear increasing. While the analysis outcomes reflected a phenomenon that the TLD damping force not only offset the increased base-shear arose from its own weight, but also further reduced the total base-shear. Obviously, the building structures tends to be safe after equipping with TLD device.

5. Conclusion

In this paper, a numerical simulation of fluid-solid coupling models is carried out through finite element analysis software ABAQUS. Some significant rules and theoretical achievements are obtained for the practical application of TLD device. The conclusions are summarized as follows:

(1) The fluid-solid-coupling analytical method could reflect the nonlinear character of TLD-structure system precisely, and it is beneficial to establish the interaction between fluid-medium and solid-medium in TLD-structure mathematic model;

(2) The top-displacements and aseismic ratios in three-dimensional numerical model were different from those in two-dimensional model, and the aseismic ratios were 2%~5% variation between these two types of models. The definition on nodal normal vector in two-dimensional model has great differences with actual situation, but the calculational accuracy could be improved through three-dimensional analysing technique.

(3) The TLD has positive effects on structural seismic responses and the aseismic ratios could reach 10% around. The better vibration reduction effects could achieve if the liquid oscillation amplitude in TLD device was large enough. The TLD damping force not only offset the increased base-shear arose from its own weight, but also reduced the total base-shear.

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References

[1] Li H N, Jia Y, Li X G et al. (2000) Study on vibration control using TLDs for multi-mode responses of tall flexible structures. Earthquake engineering and engineering vibration, 20(2):122-128.

[2] Chen Z P, Dong P, Huang L T. (2008) TLD vibrational controlling for seismic response of high-rise building. Journal of Architecture and Civil Engineering, 25(1):122-126.

[3] Zhang M Z, Ding S W, Guo X. (1993) Study on structure control using tuned sloshing damper. Earthquake engineering and engineering vibration, 13(1):40-48.
[4] Xin Y X, Lou M L, Chen G D. (2004) Study on structural control of hybrid energy dissipation. Journal of Tongji University, 32(3):286-290.

[5] Jia Y, Li H N, Li Y C. (1998) Simulation of dynamic liquid pressure for tuned liquid dampe. Earthquake engineering and engineering vibration, 18(3):82-87.

[6] Yue B Z, Liu Y Z, Wang Z L. (2000) Numerical simulation and suppression of three dimension large amplitude liquid sloshing. Journal of Shanghai Jiaotong University, 34(8):1036-1039.

[7] Zhou H, Li J F, Wang T S. (2008) Dynamics simulation of fluid-filled coupling system using the ALE finite element method. Journal of Tsinghua University, 48(11):1837-1840.

[8] Zhu H L, Bai X Z. (2007) Description method and simplified classification rule for fluid-solid interaction problems. Engineering Mechanics, 24(10):92-98.

[9] Song Q H. (2013) Fuel tank sloshing noise simulation based on Abaqus. China High Tech Enterprise, 14:58-59.

[10] Kim Y M, You K P, Cho J E. (2006) The vibration performance of tuned liquid damper and tuned liquid column damper. Journal of Mechanical Science and Technology, 20(6):795-805.

[11] Novo T, Varum H, Rodrigues H et al. (2014) Tuned liquid dampers simulation for earthquake response control of buildings. Bull Earthquake Engineering, 12(2):1007-1024.

[12] Code for seismic design of buildings. China architecture and building press. 2010.

[13] Yue Q J, Zhang L, Liu X H. (2008) Measurement of the supplementary damping force of tuned liquid dampers. China civil engineering journal, 41(6):22-26.

[14] Zhou X Y, Yan W M, Yang R L. (2002) Seismic base isolation, energy dissipation and vibration control of building structures. Journal of Building Structures, 23(2):2-13.