The vibration reduction performance of Tuned Liquid Damper on high-rise buildings with three-dimensional numerical simulation

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Abstract. The vibration reduction effect of high-position fire-fighting water tanks on the roof of office buildings in State Grid Corporation of China is discussed in this article. A three-dimensional tuned liquid damper (TLD for short)-structure model was established based on Coupled Euler-Lagrange algorithm to compare the calculated results under unidirectional and bidirectional seismic waves. Meanwhile, a 10-storey frame structure with asymmetric plane was selected to study the controlling performance of TLD on torsional response. Top displacement and aseismic ratio are taken as the key parameters to verify the availability, and the results show that the displacement response of TLD-structure has the character of linear-superposition geometrically, and the response gets the maximum when the seismic characteristic period tends to its natural period. The position with smaller structural stiffness should be taken as the primary controlling part, and reduction effect is better in the direction with strong displacement-response. TLDs have positive effects on controlling the structural torsional response and the aseismic ratio could reach 30% or more.

1. Introduction
Most office buildings in State Grid Corporation of China are high-rise structures with the feature of dense-population and multi-storey, thus the fire security and earthquake resistance should be highly emphasized to reduce the loss. The commonly-used fire-fighting facilities are large water-tanks installed on the top-level, which have negative effects on structural seismic performance for the reason that the stored water greatly aggravates the dead-weight of structural system. To change the negative factors into positive ones, the water-storage-tanks are designed to TLD (short for Tuned Liquid Damper) that could be used as passive controllers to improve the aseismic safety of building structures. The optimization scheme of TLD has been deeply studied and widely used in recent years due to the advantage of easy installation and multiple applications. A liquid nonlinear-sloshing test was applied on the vibration response of Jinshan Mansion in Zhuhai and the results indicated that the TLD had a positive effect on slowing down the wind-induced acceleration[1]. The water-tanks on the top-floor could be transformed to TLD device by modifying the design parameters, and the conclusions showed that the reduction ratio reached 35% effectively[2]. Meanwhile, the damping force of rectangular TLD was theoretically deduced based on the assumptions that the liquid was non-viscous and sloshed within a narrow range[3]. The controlling performance of TLD on seismic response was discussed based on lumped-mass method, the research findings demonstrated that the device had remarkable...
effects after the earthquake running 6-7 seconds[^4]. In summary, model experiments are usually limited to high-investment and physical environment although the testing phenomena could be checked directly. Numerical simulation methods could overcome the aforementioned shortcomings, however, the existing methodology for calculating the interaction between TLD and structures mainly concentrated on two-dimensional areas which referring to multiple hypotheses.

In this article, a three-dimensional TLD-structure coupling model is established based on ABAQUS finite-element software to study the controlling effect. The research findings provide the basis for practical application.

2. Mathemetic model

2.1. Parameter definition

The Coupled Euler-Lagrange algorithm is a methodology describing the interaction between flowing liquid and FEM meshes, which could be applied to the simulation of TLD-structure under seismic excitation. The upgrading version ABAQUS supports the plug-in program concerning the aforementioned algorithm, and the liquid-solid coupling model could be easily established by defining the material properties, boundary conditions, stress loads in ABAQUS/Explicit module. The defined parameters are specified as follows:

(1) Material properties

The flowing water was set as Eulerian domain while the fire-fighting tanks were deformable Lagrangian medium respectively. Eulerian domain was required to be three times larger than cistern size to ensure that the boundary covered the splashing area of water. Besides, an Eulerian reference was defined to figure out the initial position of water. The physical parameters related to the state equation were listed in Table.1

![Table 1. Material Properties](image)

(2) Element types

The reduced integrated shell element S4R with six DOFs was selected to simulate the tank boundaries, which could settle the difficult nonlinear problems effectively. Otherwise, the solid element EC3D8R was used to calculate the reference and Eulerian domain, to relieve the problem of smaller deflection and overhardening element characteristics.

(3) Mesh division

The quantities and quality of finite elements have a direct relationship with the computational efficiency and precision, that is to say well-balancing these two factors is beneficial to acquiring available research data. Based on the finite element software ABAQUS, the tank boundaries were segmented using the free mesh method, and the Eulerian domain with reference was cut using the the structured mesh method respectively. After repeated trial-calculation to guarantee the arithmetic convergence and data accuracy, the meshing size of tanks was assigned to 0.10, the Eulerian domain
and the reference were 0.03 and 0.07 respectively, as shown in Figure 1.

![Figure 1. Mesh division of individual element](image)

(4) Fluid-solid coupling model

A predefined field between Eulerian domain and reference was established based on “Volume Fraction Tool”, and the reference was defined as water material property to identify the initial position. “General contact”, which could automatically simulate the interaction between Lagrangian elements and free-flowing liquid in Eulerian domain, was used to set up the fluid-solid coupling. Therein, the contact character was ruled as “Rough” to simulate the non-slip condition between the water and the tanks. The tuned-liquid-damper system was installed on the top-level of main structure with “Tie” constraint property.

(5) Boundary condition

Fully-constraint was applied to the structural foundation in initial-step, and then the DOFs in earthquake direction were released to input the seismic acceleration recordings. Vibration reduction analysis on TLD-structure system was conducted in subsequent steps.

2.2. Seismic response analysis

Compared with response spectrum method that commonly used, the time-dependent seismic response of TLD-structure system was easily calculated through dynamic time-history method, which simultaneously took vibration frequency, amplitude, duration and natural frequency into consideration. Besides, the maximum of top-displacement, velocity, acceleration, internal force and deformation in every moment were obtained with high-precision.

In this article, the TLD-structure fluid-solid coupling models are classified into two types: models uninstalled TLD device and ones equipped with TLD device. To clarify, the positive effects of fluid sloshing on structural vibration reduction was considered in the “TLD-structure” models.

2.3. Seismic waves selection

According to the Code for seismic design of buildings[5], three primary factors should be taken into account when selecting seismic waves: (1) Spectral characteristics-Adjusting the seismic spectrum to ensure the major section within the characteristic period of proposed field, and there exists some similarities between the selected seismic waves and possible ground motion to forecast the damage degree; (2) Peak ground acceleration-Scaling up and down the peak acceleration of selected recordings in accordance with seismic intensity. The modified acceleration should be equivalent to specified peak level[5] in numerical values; (3) Seismic duration-The running time should be 5~10 times longer than the natural period of structures, and cover the peak ground acceleration of selected earthquakes.

Based on the principles above, two seismic recordings and one artificial earthquake wave were recommended for time-history analysis, relevant parameters were listed in Table 2.

| Seismic waves | Characteristic period(s) | Peak acceleration (cm/s²) | Scaling factor | Duration (s) |
|---------------|--------------------------|---------------------------|----------------|--------------|
| El-Centro     | 0.56                     | 341.72                    | 0.21           | 7.0          |
3. Vibration reduction analysis on TLD-structure system

Considering the fact that the earthquake excitation was usually multi-directional, the unidirectional horizontal seismic recordings and the bidirectional horizontal seismic recordings were applied on the TLD-structure system separately. The calculating results were compared and analysed to study the controlling performance of TLD.

3.1. Analytical object

Existing scientific papers reveal that the two horizontal components of seismic waves are different, they should be modified at a ratio of 1:0.85 when carrying out three dimensional analysis [5]. A ten-storey RC frame-shear wall structure was selected as the research example, as shown in Figure 2, and its first three mode-shapes were listed in Table 3 [6-9].

![Figure 2. Finite element model of structure](image)

| Mode shape | Characteristic Period (s) | Effective mass coefficient in X-direction (%) | Effective mass coefficient in Y-direction (%) | Effective mass coefficient in Z-direction (%) |
|------------|--------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| 1          | 0.804                    | 69.56                                       | 0.05                                        | 0.35                                        |
| 2          | 0.696                    | 0.12                                        | 63.28                                       | 8.50                                        |
| 3          | 0.560                    | 0.14                                        | 6.46                                        | 72.83                                       |

3.2. Results and analysis

The selected seismic recordings-El-Centro, Taft, Shanghai artificial wave-were applied on the TLD-structure system in unidirectional mode and bidirectional mode respectively. [10-12] As a result, the largest top-displacement for each working condition was summarized in Table 4.

|                  | Unidirectional mode (cm) | Bidirectional mode (cm) |
|------------------|--------------------------|-------------------------|
| El-Centro-X      | 7.83                     | 7.82                    |
| El-Centro-Y      | 6.54                     | 5.56                    |
| Taft-X           | 6.55                     | 6.55                    |
| Taft-Y           | 5.47                     | 4.65                    |
| Shanghai-X       | 2.17                     | 2.17                    |
| Shanghai-Y       | 1.81                     | 1.52                    |
As known in Table 4, the seismic responses in X-direction were almost identical under both unidirectional waves and bidirectional waves. However, in the Y-direction, the numerical values corresponding to bidirectional mode were 0.85 times smaller than those for unidirectional mode, since the bidirectional seismic recordings were imposed at a suggested ratio of 1:0.85. The analysis above leads to conclusions that the displacement responses of TLD-structure have the character of linear-superposition geometrically, and the effects of orthogonal seismic components on structural seismic performance are non-interfering. Meanwhile, the TLD-structure systems with regular and symmetrical plane exhibit a plane-decomposability when subjected to bidirectional seismic waves, it comforms to the assumption that the resisting force in a certain direction only carries the earthquake excitation in self-direction. The displacement-response under El-Centro seismic wave was remarkably stronger than those under Taft seismic wave and Shanghai artificial wave, for the reason that the characteristic period of El-Centro was closer to the structural natural period. It can be concluded that the structural seismic response gets the maximum when the seismic characteristic period tends to its natural period.

Aseismic ratios corresponding to the three selected seismic recordings are also listed in Table 5. It is shown that the values in X-direction was slightly larger than those in Y-direction under the bidirectional seismic waves, that is to say the reduction effect was better in the direction with strong displacement-response. Therefore, the position with smaller structural stiffness should be taken as the primary controlling part when equipping the TLD device.

Table 5. Aseismic ratio for selected seismic recordings

|          | El-Centro | Taft   | Shanghai |
|----------|-----------|--------|----------|
| X-direction | 18.63    | 18.04  | 14.37    |
| Y-direction | 18.04    | 14.15  | 10.62    |
| Aseismic ratio(%) |          |        |          |

Note: Aseismic ratio is defined as the ratio of decreased top-displacement with TLD to structural top-displacement without TLD.

4. Research on controlling torsional response

In practical engineering, a significant number of building structures exist irregular and asymmetric planes, and the shearing force of vertical components raises drastically due to the torsional response caused by the weight eccentricity and stiffness eccentricity\(^{[13,14]}\). The situation above tends to cause fracture failure, on account of the poor energy-dissipating capacity and low ductility. Hence, the controlling effect of TLD on the torsional response of asymmetric structures is tentatively studied in this section.

4.1. Numerical calculation model

A 10-storey RC frame structure with asymmetrical plane was selected as the analyzing example, and two installation schemes of TLD device were compared to study the seismic performance. As shown in Figure 3, a combined TLD device was equipped at the center of top-floor in one design, and two separated TLDs were located at the edges in another design.

![Figure 3. Installation schemes of TLD device](image-url)
4.2. Results and analysis

The ratio of elastic horizontal displacement $P_1/P_2$ was listed in Table 6. It was shown that the ratio was generally larger than 1.5 in the structure without TLD device, which was classified as irregular torsion. The numerical values decreased to about 1.0 when equipped with TLD, and the aseismic ratios reached 30% or more. Besides, the ratio in Scheme-A was larger than that in Scheme-B, indicating that the vibration reduction effect of TLD located at the edge of structural plane is better than that located at the center.

Table 6. Ratio of elastic horizontal displacement

| Position | Without TLD | With TLD | Aseismic ratio(%) |
|----------|-------------|----------|-------------------|
| Scheme -A | 1.641       | 1.022    | 37.69             |
| Scheme -B | 1.641       | 1.011    | 38.37             |

5. Conclusion

In this paper, a numerical simulation of three-dimensional fluid-solid coupling model 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 displacement response of TLD-structures has the character of linear-superposition geometrically, and those with regular and symmetrical plane exhibit a plane-decomposability when subjected to bidirectional seismic waves. The structural seismic response gets the maximum when the seismic characteristic period tends to its natural period;

(2) The reduction effect is better in the direction with strong displacement response, and the position with smaller structural stiffness should be taken as the primary controlling part;

(3) The TLDs have positive effects on controlling the structural torsional response, and the aseismic ratio could reach 30% or more. The vibration reduction effect of TLD equipped at the edge of structural plane is better than that located at the center.

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