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A Short Review on Enhancing Structural Resilience with Tuned Liquid Dampers: Seismic and Wind Vibration Control in Buildings

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ABSTRACT

This study examines how well-suited tuned liquid dampers (TLDs) are for reducing wind and seismic-induced structural vibrations, especially in tall buildings. The sloshing of liquid is used by TLDs, passive control devices, to absorb and disperse energy. The study assesses a number of design characteristics, including liquid depth, mass ratio, and tuning ratio. The research investigates the behaviour of TLDs under seismic excitations in various structural configurations using numerical calculations and experimental investigations. Along with highlighting the benefits of utilizing TLDs—like their low maintenance requirements and cost-effectiveness—it also identifies research gaps and suggests optimization tactics for upcoming advancements in TLD technology.

Keywords: Tuned Liquid Dampers, Passive Damping, Vibration Control in Buildings, Structural Vibration, Liquid Sloshing

1. Introduction

Recent developments in seismic design have led to an increased focus on innovative methods for earthquake-resistant structures. Traditional designs, relying on enhanced strength and ductility, are proving insufficient as land values push the trend towards lightweight, high-rise buildings. Consequently, devices that can effectively control structural responses, such as Tuned Liquid Dampers (TLDs), are gaining prominence. TLDs are passive energy-absorbing devices that use the motion of liquid to dissipate energy through sloshing and wave breaking, aligning the fundamental sloshing frequency of the liquid with the natural frequency of the structure. TLDs, when rigidly connected to a structure, can reduce the dynamic response under both wind and seismic loads. Their effectiveness in mitigating structural vibration has been demonstrated in a variety of settings, such as residential and commercial buildings. Unlike conventional approaches that increase stiffness or add significant mass to structures, TLDs offer a more economical solution with minimal maintenance requirements. Research has shown that while TLDs can control the wind response of structures, their application in seismic response control needs more comprehensive study. These papers focuses on assessing the effectiveness of TLDs under seismic excitation, proposing design parameters like tuning ratio (ratio of sloshing frequency to natural frequency), mass ratio, and water depth ratio. By utilizing both actual and artificial ground motions, the paper evaluates the performance of TLDs across different structural configurations. Existing seismic control methods include active and passive systems. Active systems rely on external power sources, posing risks during power outages, as seen in the Kobe earthquake. Passive systems like TLDs, however, do not require external power and offer a fail-safe mechanism, making them highly suitable for developing countries with limited resources. Seismic base isolation, another passive technique, has shown efficacy but comes with limitations in managing base displacements during large earthquakes. TLDs complement these systems by adding damping and improving overall seismic resilience. This study contributes to the understanding of how TLDs can be optimized to enhance the seismic performance of structures, especially tall buildings. The research also reviews applications of TLDs in mitigating wind-induced vibrations in slender structures. Additionally, the study proposes a probabilistic design framework to account for uncertainties in structural properties and ground motions, improving the robustness of TLDs as a vibration control solution. The paper offers valuable insights into the design and application of TLDs in various structural contexts, encompassing seismic isolation, wind response in high-rise buildings, and earthquake protection for existing structures. Through numerical simulations and experimental these researches established guidelines for effective TLD implementation, providing a foundation for future developments in structural control technology.

2. Performance Evaluation and Methodology

Using seismic excitation and earthquake data from the Imperial Valley, the OWT-FB (Overhead Water Tank with Floating Base) technology decreased peak displacement by 30% and RMS displacement by 24%. Numerical investigations utilizing an SDOF model demonstrated that the OWT-FB maintained stable sloshing frequency despite fluctuating water levels, unlike conventional systems. This stability guaranteed efficient damping and vibration control in a variety of tank situations [1] and the Slender Tuned Sloshing Damper (STSD) for controlling seismic vibration was evaluated in the study using MATLAB simulations and mathematical modeling. The STSD demonstrated constant performance with peak reductions of 14.1% to 17.6%

and RMS displacement reductions of 20.3% to 29.6%, despite changes in liquid depth. It may be retrofitted into existing buildings and provides effective damping comparable to traditional TSDs, albeit it is still difficult to sustain effectiveness during changes in liquid depth [2]. In this study examines the effectiveness of flow damping devices (FDDs) combined with TLDs in reducing seismic responses in soft-soil buildings [3] . Using numerical simulations of a SDOF model with roof water tanks, the study accounted for soil-structure interaction (SSI) during events like the Chi-Chi and Northridge earthquakes. Results show that while soil flexibility increases seismic demand and alters building behaviour. TLDs significantly reduce structural responses, especially in flexible base buildings. Where in [4] the study uses a real-time hybrid simulation (RTHS) system to assess (TLDs) in reducing seismic responses of high-rise structures. A water tank served as the physical substructure, with a 2DOF high-rise model simulated in Simulink. TLDs showed up to 15% reduction in displacement and 5% in acceleration, performing better in mitigating displacement during nonlinear responses. Nonlinear responses exhibit poorer mitigation effects than linear responses. While TLDs reduce structural energy consumption without negative effects, their effectiveness in nonlinear conditions is limited. This study explores the design and performance of isolated tuned liquid dampers (ITLDs) in MDOF structures. ITLDs, featuring a dual-mode design, effectively mitigate seismic vibrations by controlling multiple modes, reducing floor displacements and accelerations. Numerical simulations and parametric analysis optimized key parameters. Hysteretic curves confirmed improved damping and isolation, enhancing seismic resilience [5]. The analysis highlights that the mass ratio of the TLD to the structure is a key factor in its efficiency [6]. The Suspended Particle-Tuned Liquid Damper (SPTLD) outperformed the traditional Tuned Liquid Damper (TLD) in shaking table tests, reducing RMS values by 75.9% and peak acceleration by 67.4% under seismic excitations [7]. The investigation proved that tuned liquid dampers, or TLDs, are an efficient way to lessen wind turbine vibrations. Three TLDs with a 12% mass ratio achieved reductions of up to 71.45%, whereas a single TLD with a 4% mass ratio decreased lateral deformations by as much as 12.5%. The fatigue life of the turbine was also increased by up to 36% using this design. The study validated results with a scaled 5 MW wind turbine model using ANSYS Fluent for fluid-structure coupling analysis [8]. The sloped TLD design achieves higher damping efficiency with less liquid volume, making it suitable for space-constrained structures [9].

Retaining Walls Using a Compliant-Tuned Liquid Damper (*CTLD)s* effectively reduce displacement (13.95%–50.04%) and acceleration (13.51%–53.21%) of retaining walls during seismic events, mitigating earthquake-induced forces. Using an SDOF model and finite element analysis (FEA), the study optimized CTLD performance by tuning the frequency (1.00) and damping ratio (0.05) [10]. Sloshing liquid dampers (SLDs) effectively reduce vibrations and minimize force in MDOF structures, especially during earthquakes. Multiple dampers are often needed for floor acceleration control, with tuning ratios differing between SDOF and MDOF structures [11]. In seismic tests, the high frequency-TLD exhibits a 42.2% RMS displacement reduction and a maximum decrease of 27.6%. The frequency band of 5.5–6 Hz is where optimal performance is observed [12]. Damping ratios computed by applying the logarithmic degradation technique. Sloshing frequency was assessed in this case using impulse tests and SAP2000 model ling. They investigated different baffle orientations and water depths in 464 tests. where the peak vibration control happened right before the baffle closed completely. Analytical forecasts and experimental frequencies were nearly identical [13]. A nonlinear model based on shallow water wave theory was validated using RTHT. Using the Runga-Kutta-Gill approach, simulated difference equations are solved. Seismic vibrations in elevated water tanks are successfully reduced by TLD. The nonlinear model and the experimental data are strongly aligned. Significant reductions in response are caused by higher mass ratios, and performance is affected by tuning ratios [14]. A new mathematical model was developed to simulate liquid sloshing behavior and evaluate flow- damping. devices using Lagrange's equations. Experimental studies verified the model's accuracy, focusing on the first sloshing mode with wire-mesh screens. The optimal damping ratio for TLDs with these devices was found to be around 0.05 [15]. This research assesses the effectiveness of viscous, viscoelastic, and tuned mass dampers (TMDs) in controlling seismic responses in vertically uneven buildings. Dampers were found to reduce maximum displacements by 35% to 50%, depending on the type and degree of irregularity. Using SAP 2000-17 software and the response spectrum method, G+12 buildings with irregularities from 0% to 75% were analyzed. Pseudo-static analysis showed the impact of dampers in minimizing top-story displacements, with various configurations tested for optimal placement [47]. The study shows that Tuned Liquid Dampers effectively reduce seismic vibrations in low-rise reinforced concrete buildings. Shake table tests revealed that a denser sugar-water solution (1.3 gm/cc) outperformed normal water, increasing the damping effect and reducing residual sloshing. The best results were achieved with a liquid depth ratio of 0.2 to 0.4. Different tank shapes and excitation frequencies also influenced TLD performance and sloshing forces [16]. The Modified Tuned Liquid Damper (MTLD) outperforms traditional TLDs in reducing structural displacements and accelerations, particularly under sinusoidal loading, with less than 10% error between simulations and experiments. MTLD is optimized for wind loading, though it offers marginal improvements over TLD for seismic events. TLD remains effective at reducing displacements but becomes less efficient as damping ratios increase [17] The structure-fluid dynamics of deep liquid storage tanks (DLTs) mounted on rooftops are assessed numerically using ANSYS Workbench. The structural components are analyzed using Finite Element Analysis (FEA) and the fluid dynamics are analyzed using the Finite Volume Method (FVM). Turbulence is handled by the usual k-epsilon model, while RANS equations are solved using the Volume of Fluid (VOF) method. DLTs effectively reduce peak roof displacements, with reductions of 16.98% in the X-direction and 24.29% in the Z-direction, and peak accelerations, by 10.36% and 15.47%, respectively, according to a coupled CFD-FEA dynamic study [18]. According to the study, the Modified Tuned Liquid Damper (MTLD) with a submerged pendulum works better at decreasing vibrations over a range of natural frequencies than the conventional TLD (CTLD). Specifically, on the third floor, the MTLD reduced displacement responses by 1.9 times greater than the CTLD. These results were confirmed by shake table testing on a three-story steel building and were backed by SAP2000 numerical simulations [19]. A theoretical model based on Housner's centralized mass model led to a solution for liquid motion velocity and a formula for total equivalent damping. Experiments and SAP2000 analysis showed DNS-TLD outperforms regular TLD by increasing efficiency with less water through enhanced sloshing and a sloped-bottom design. DNS-TLD's effectiveness in seismic control, especially for high-rise structures, is validated by both numerical and experimental results. It combines the benefits of DNTLD and STLD for superior energy dissipation and closely approximates ideal damping [20]. This research evaluates the performance of Tuned Liquid Dampers (TLDs) in controlling lateral displacement in single- and multi-story buildings, optimized using various liquids. Experiments and simulations show that liquid properties like viscosity and density significantly impact TLD effectiveness, especially in multi-story structures. Using the Adaptive Harmony Search (AHS) algorithm and FEMA seismic records, liquids such as seawater, acetone, and mercury were analyzed, with higher viscosity and density liquids proving more effective. Optimized TLDs demonstrated enhanced seismic control, particularly in 10- and 40-story buildings [21]. The study shows that Multiple Tuned Liquid Dampers (MTLDs) outperform traditional TLDs by providing better damping and performance across a broader frequency range, especially at low excitation levels. Using mechanical and nonlinear multimodal models, the study found that MTLDs are more robust, with each tank tuned to a unique frequency. While increasing the number of tanks reduces the damping ratio, MTLDs enhance structural control at minimal cost [22]. The study shows that Multiple Tuned Liquid Dampers (MTLDs) outperform single TLDs (STLDs) in reducing small-amplitude vibrations and are less affected by tuning errors. Experiments confirmed MTLDs' broader frequency response and better damping. While both systems perform similarly at large amplitudes due to nonlinear damping, MTLDs remain more efficient at lower amplitudes. MTLDs are practical, cost-effective, and improve vibration control in real-world applications [23]. The Tuned Liquid Column Damper (TLCD) effectively reduces structural vibrations, with higher mass ratios improving performance. Increasing the TLCD/SSP mass ratio from 1% to 3% decreases displacement by 43.77% to 78.32%, though an optimal mass ratio of 1.5% prevents detuning. Experimental and simulation studies, using a six-degree-of-freedom platform, confirmed the accuracy of the model, showing that acceleration damping improved by up to 77.88%. However, frequency shifts occurred with higher mass ratios, emphasizing the need for optimal tuning [24]. The spring-connected Liquid Column Damper (LCD) effectively controls seismic vibrations in short-period structures. Numerical studies using stochastic equivalent linearization and transfer function formulation showed optimal performance by calculating the equivalent viscous damping ratio. Both frequency-domain random vibration and deterministic time-domain studies confirmed the system's effectiveness. Time history analysis further validated the LCD’s ability to control vibrations efficiently [25].

METHOD	**PDR %**	**RMS PD %**	**AR %**
OWT-FB	30	24.00	NaN
STSD	NaN	29.60	NaN
TLD+RTHS	15	NaN	5
SPTLD	NaN	75.90	67.40
TLD in Wind Turbines	71.45	NaN	NaN
CTLD	50.04	NaN	53.21
SLDs	NaN	42.20	NaN
High-Frequency TLD	27.60	NaN	NaN
DLTs	24.29	NaN	15.47
TLCD	78.32	NaN	77.88

Table 1: Performance Metrics of Seismic Technologies

PDR- Peak Displacement Reduction, **RMS PD** – RMS Peak Displacement, **AR**- Acceleration Reduction

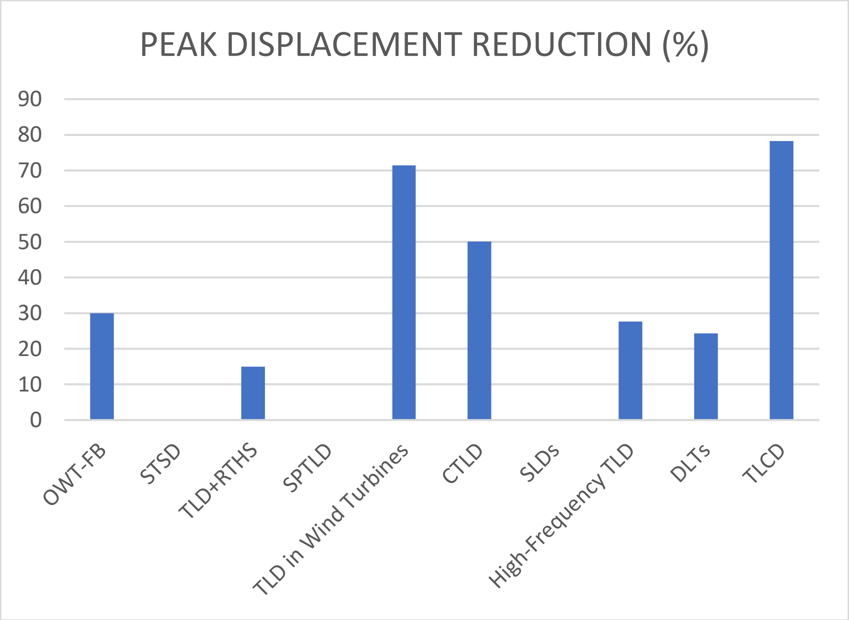

Fig.1 Comparison of Methodologies Based on Peak Displacement Reduction

3. Application of TLD

Structure vibration can be effectively reduced with the use of tuned liquid dampers (TLDs), particularly during seismic activity. For controlling high-frequency vibrations that traditional dampers could have trouble with, the HF-TLD (High-Frequency Tuned Liquid Damper) is quite helpful. This damper improves the liquid's sloshing effect and its ability to maintain structures during dynamic loads, such as earthquakes, by including springs and a floating ceiling. The usefulness of HF-TLDs in actual seismic scenarios has been demonstrated by experimental research and analytical models. This is especially true in earthquake-prone areas where preserving structure integrity is essential. The dual functionality of TLDs is a major advantage. They can be added to buildings' already-existing water tanks to allow them to function as vibration control devices in addition to storing water. Because of this, they are an affordable option, especially in developing or earthquake-prone areas where it could be too costly to install sophisticated dampening systems. Compared to more complicated systems like Tuned Mass Dampers (TMDs), the TLD is an appealing option because of its straightforward construction, minimal maintenance requirements, and ability to be adapted into existing buildings without requiring major structural alterations. By adding a floating roof to the conventional TLD design, the TLD-FR (Tuned Liquid Damper with Floating Roof) improves its flexibility to changing excitation frequencies. This feature improves the damper's ability to manage structural responses, which makes it perfect for high-rise buildings and airport towers, which are frequently excitations like wind or seismic pressures. An extra degree of control is provided by Multi-Tuned Liquid Dampers (MTLDs), particularly in constructions with various dominant mode shapes, like tall or asymmetrical buildings. MTLDs can be fine-tuned to counteract complicated vibrational behaviour, especially those produced by wind or earthquakes, by varying the fluid depth in each tank. Towers and high-rise buildings can benefit from flexible vibration control because to the space-efficient nature of MTLD systems, which can be installed into both new and existing structures. Another noteworthy development in TLD technology is the ITLD (Integrated Tuned Liquid Damper) system, which is intended to regulate several vibration modes in buildings. ITLDs can considerably lessen dynamic reactions to seismic occurrences by carefully arranging these dampers on various floors, such as the sixth and sixteenth floors of a high-rise building. Because of this, they are especially helpful in areas that are prone to earthquakes, as they can increase a structure's durability and safety. To sum up, tension beam dampers (TLDs), such as the HF-TLD, TLD-FR, MTLD, and ITLD, offer a practical and affordable way to reduce structural vibrations during seismic activity. For engineers wishing to improve building safety without going over budget, they are a viable option because they may be integrated into already-existing water tanks or building components. These dampers are flexible, low-maintenance, and adaptive, providing notable advances in vibration control across a range of engineering applications, whether they are utilized in towers, tall buildings, or bridges. Their significance in contemporary seismic design and retrofitting procedures is highlighted by their capacity to improve structural performance in vibrations caused by wind and earthquakes exposed to single-frequency excitations like wind or seismic pressures. 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4. Research gaps

Studies on Tuned Liquid Dampers (TLDs) have identified a number of gaps in the literature that need to be filled. While most studies focus on flexible, high-rise models, there is a dearth of research on TLDs for low- to medium-rise building and short-period structures. Significant difficulties arise when tuning TLDs for short-period structures, and the work that has already been done does not adequately address TLD performance in a variety of seismic scenarios or tank sizes and forms. With few investigations on the impacts of varying fluid depths, excitation spectra, and soil conditions, nonlinear energy dissipation mechanisms in TLDs are still not well understood. Liquid damping may be underestimated by theoretical models, and there are differences in the estimates for tiny excitation amplitudes. Furthermore, the influence of narrow TLD tanks on sloshing frequency and damping efficacy is not completely taken into consideration. The durability and long-term performance of TLDs in a range of environmental circumstances have not been thoroughly investigated, and the difficulties associated with maintenance are not fully understood. Sparse experimental validations and real-world applications accompany the paucity of large-scale TLD testing. Additional study is required to examine different liquid characteristics and their effect on TLD effectiveness, as well as to validate numerical models against a variety of seismic records. Furthermore, not enough research has been done on smart materials, TLD configuration optimization, and magnetic field applications. A thorough comparison between TLDs and other energy dissipation techniques is hampered by the paucity of research on sophisticated damping technologies. Multiple-frequency tuning, fluid depth change, and TLD design for non-harmonic excitations need more investigation. There is a lack of cost-effectiveness, long-term performance, and maintenance statistics; further study is required to examine real-world implementation issues. Ultimately, further effort is needed to improve TLDs under various excitation scenarios and to strengthen the experimental support for suggested architectures.

5. Conclusion

The report emphasizes how well different tuned liquid damper (TLD) systems can reduce structural vibrations, especially in high-frequency structures and seismically vulnerable places. A noteworthy invention is the High-Frequency Tuned Liquid Damper (HF-TLD), designed specifically for low-height constructions and utilizing a helical spring to provide a natural vibration frequency of 3 Hz. Finding the ideal mass ratio is crucial since experimental data demonstrate that HF-TLD can minimize structural displacements by 20%. However, increasing its mass does not necessarily result in better performance. It

has also been demonstrated that traditional TLDs can reduce vibrations, particularly when set to the natural frequency of the structure. Depending on the water level and tuning frequency, rectangular TLDs are found to work better than square ones, and sloshing motion greatly reduces structural response. By focusing on several natural frequencies, improving energy dissipation, and demonstrating benefits in both seismic and wind-induced scenarios—particularly for tall buildings—Multi-Tuned Liquid Dampers (MTLDs) offer an even more effective alternative. Moreover, inexpensive TLDs can be created from water tanks, which are frequently employed in structures; the ideal mass for a tank is between two and three quarters of the structure's total weight. It is advised that future studies investigate long-term performance, novel materials, and cutting-edge designs to boost TLD systems' effectiveness in a range of environmental circumstances.

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