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Application of Tuned Liquid Dampers for the Efficient Structural Design of Slender Tall Buildings


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David Lee
David Lee has over 29 years of experience in managing feasibility studies and design and construction supervision for a wide range of buildings and structural projects including high-rise buildings, basements, foundations, and associated geotechnical works. Recent notable projects included Resort Worlds at Sentosa (Singapore), Etihad Towers (Abu Dhabi), Shanghai IFC and Wharf Wheelock Plaza (Shanghai), and Grand Lisboa (Macau). David has a special interest in wind engineering for tall buildings. He has been involved in some of the slender tall buildings constructed in Hong Kong, including The Summit, Harbourfront Landmark and York Place.

Martin Ng
Martin Ng was involved in a variety of specialized research and consultancy projects, including a health monitoring project for the Tsing Ma Bridge and a vibration control study for the Stonecutters Bridge, both in Hong Kong. During his PhD study he researched and developed seismic control systems for buildings. Since he joined AECOM, he has consulted on building monitoring projects and has worked on the design of auxiliary damping devices for Hong Kong and overseas projects.

> "Tall, slender buildings on restricted sites present structural engineers with dynamic problems that are difficult to resolve… This performance-based design approach permits investigating separate structural systems and the design of the corresponding optimal parameters to achieve adequate static and dynamic building responses for an efficient structure."

The design of tall buildings has undergone a constant evolution during the past decade. Advancements in material, structural systems, analysis, and construction techniques have allowed for the design of lighter and more slender structures. However, this evolution leads to tall buildings being increasingly prone to potential motion problems under wind and earthquake loading. This is particularly true in Hong Kong, where land which is suitable for development is scarce (see Figure 1). In addition, the combination of high wind loads and slender high-rise buildings means that controlling the motion in these buildings can be a critical factor in the design.

This paper summarizes the experiences gained in a residential project on efficient design for building motion reduction using tuned liquid dampers. The potential advantages in terms of performance and cost of using an auxiliary damping system over the conventional method are discussed. Also, an outline of the design procedures for a tuned liquid damper is given. The improved performance of the building and recommendations for future designs are highlighted.

Wind and Building Motion

Wind has a major effect on the lateral loads of a tall building in Hong Kong because of its location in a typhoon-active region. The very first step for efficient structural design is to research the most accurate wind load prediction and the associated structural responses. A static response could be assessed based on the loads suggested in the wind code. However, load estimation related to wind directional effect and the local topography of the site is not comprehensive. When the building is more slender than typical tall buildings, it becomes more dynamically sensitive. For example, cross-wind in the form of vortex shedding can harmonize with the building's natural periods and will be more critical compared to along-wind. The wind code normally contains limited information related to loading due to cross-wind and wind tunnel testing, as those results will be valuable in terms of supplementing this knowledge gap.

The conventional method of preventing excessive wind induced motion is to increase the stiffness of the building. This reduces the amplitude of motion and the likeliness of resonance. As the stiffness of the building increases, so does its natural frequency, and therefore the chance of a close match between building frequency and dominant frequency of wind can be prevented. However, in a very slender building project, the penalty for increasing the stiffness could mean an

Figure 1. Typical urban area in Hong Kong

increase in material costs and the loss of usable floor area required for accommodating larger stiffening elements.

Tuned Liquid Damper

This paper assesses a design alternative of using an auxiliary damping system, which is a much more efficient way of counteracting tall building motion. A Tuned Liquid Damper (TLD) is the considered type of damping system as it offers benefits of a low initial cost and minimal maintenance over time. The damper is tuned to the natural frequency of the building so that it provides counteracting inertia force in the out-of-phase motion with the building and leads to dissipation of the building vibration and reduction in motion. The effectiveness in building acceleration reduction (being directly related to occupant comfort), between the conventional method and the design alternative is compared. Design procedures for a slender building with a TLD are also outlined and an overview of the experience gained for future designs is given.

A Hong Kong Case study

The considered case study project involves the structural design of a new 39-story residential and commercial building named York Place at Wanchai, Hong Kong. The 152-meter (499-foot) tall building is a reinforced concrete framed residential tower standing on a three-level podium (see Figure 2). Confined in a tight site area of approximately 27 × 27 meters (89 x 89 feet), the development is surrounded by existing buildings, busy traffic and crowded retail outlets. A shallow base width of just 13 meters (43 feet) led to an extremely high slenderness ratio of 1:12, making the structure potentially sensitive to dynamic wind load

Performance-Based Design

From the design experiences in various building projects, it has been observed that there is a discrepancy between the structural parameters and the corresponding optimal values for satisfactory static and dynamic performance. To assure that a slender structure could be designed to handle static and dynamic responses in an efficient way, a performance-based design approach is devised through which separate structural systems and their optimal parameters are designed. The proposed procedures followed a rigorous process of preliminary analysis, wind tunnel studies, analytical design of the TLD, field measurements of the as-built structure, and experimental evaluation for the structure-TLD system (see Figure 3).

Step 1: Structural optimization with analytical building model

An analytical building model was created using ETABS Building Analysis and Design Software (see Figure 4). The structural parameters of element layout, size and material grade in the analytical model were evaluated in sensitivity analysis to identify their most efficient deployment for providing sufficient lateral stiffness within the building layout (see Figure 5). In this stage, the wind load derived from wind code was considered. Review of the structural system will be carried out in next design stage when more comprehensive loading information from wind tunnel studies is available. The updates normally involve the fine tuning of element sizes because the wind load suggested in the wind code is usually conservative.

Step 2: Wind tunnel testing

Wind tunnel testing included wind characteristics and building responses influenced by

Figure 2. York Place under construction and completed

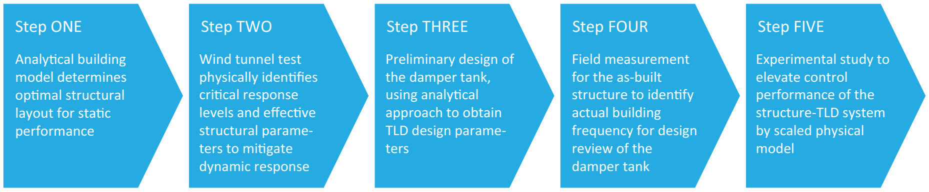


Figure 3. Design procedures for tall slender buildings with tuned liquid damper

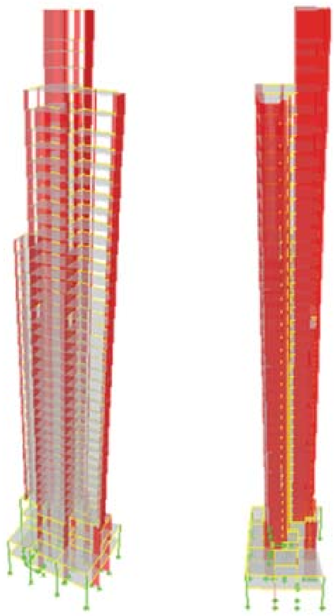


Figure 4. Analytical building model

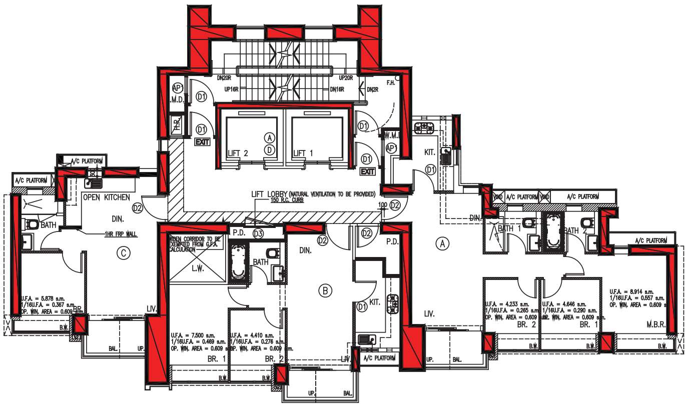


Figure 5. Structural layout of typical floor

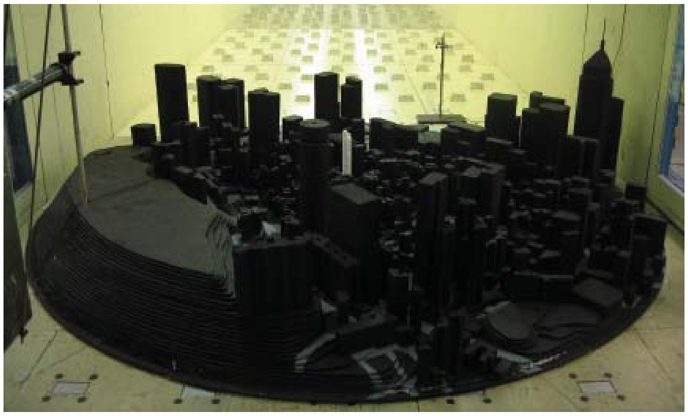


Figure 6. Scale model of building and surroundings

surrounding topographical features (see Figure 6), building form and its dynamic characteristics to provide a physical evaluation of wind load and wind-induced acceleration of the building. The testing was conducted at the CLP Power Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology (HKUST). A 1:400 rigid scale model of the building was tested in the wind tunnel following the High-Frequency-Base-Balance technique. Existing and planned surrounding buildings and topographical features within a radius of 500 meters (1,640 feet) were included in the tests. The building model included all significant surface features, such as balconies and windows. The approaching wind was calibrated to simulate wind flow from a topographical study, which was also carried out with a 1:2000 scale topographical model.

To evaluate serviceable performance on occupant comfort, accelerations at the 43rd floor were assessed, being the highest habitable floor of the building. The accelerations were determined on the assumption that the damping thresholds of the structure are 0.8% for first and second modes (sway in x-direction and y-direction) and 1.5% for third mode (rotational). The results indicated that the peak building accelerations in both swaying directions exceeded the permitted maximum value of 0.15 m/s^2 (6 inch/s^2) for a ten-year return period.

Sensitivity analysis on evaluation of structural parameters for acceleration alleviation was carried out. Both approaches of modifying structural frequency and structural damping of the building were considered for this project. Effectiveness of these approaches was assessed and reviewed on a theoretical basis. From the wind tunnel test, acceleration of the building is estimated as follows:

$$\sigma_{\ddot{x}} = \omega^2 \sigma_x \qquad (1)$$

$\sigma_{\ddot{x}}$ and σ_x denotes the standard deviation modal acceleration and displacement of the building, respectively; $\omega = 2\pi f_s$ and f_s is the natural frequency of the structure. The standard deviation modal displacement is calculated from the power spectral density of the measured modal force $S_p(f)$, combining with the mechanical admittance function $|H(f)|^2$ which represents the dynamic properties of the building.

$$\sigma_x = \frac{1}{k}\left(\int_0^{\infty} |H(f)|^2 S_p(f)\,df\right)^{1/2} \qquad (2)$$

$$|H(f)|^2 = \frac{1}{\left[1-\left(\frac{f}{f_s}\right)^2\right]^2 + \left(\frac{2\zeta f}{f_s}\right)^2} \qquad (3)$$

Since the building acceleration is a function of natural frequency (i.e., structural stiffness) and damping ratio of the structure, the mentioned approaches are viable to control building acceleration but their effectiveness is of concern. For the approach of amending structural stiffness, standard deviation of displacement in dynamic parts is possible to be reduced when the stiffness is properly tuned, such that the structural frequency f_s at peak value of $|H(f)|^2$ is distant from that of $S_p(f)$ the peak. Nevertheless, the reduction is likely to be cancelled out by the term of ω^2 when the increment of its frequency is the case. In contrast, increasing the damping ratio ζ of the structure, which also reduces the $|H(f)|^2$, can guarantee the reduction of displacement, and thus the acceleration, because the structural frequency f_s is not altered in this approach and the acceleration is unaffected by the term of ω^2.

A range of structural frequencies and damping ratios were studied to verify interpretation of the two considered approaches. The

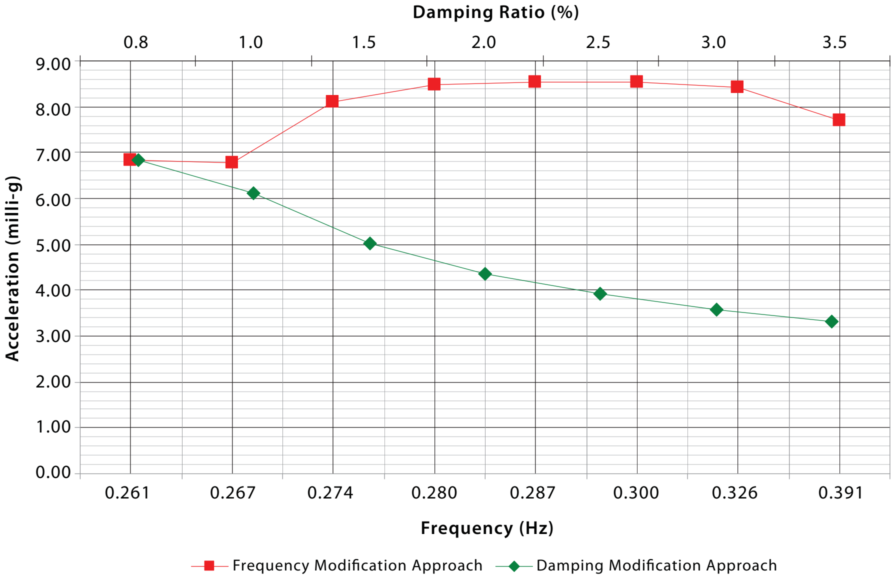


Figure 7. Effect of frequency and damping ratio modification on building acceleration

...thin

> “One of the key things about skyscrapers is in terms of the skyline at least, they can be really tall if they're thin.”
>
> *Paul Goldberger, architecture critics for The New Yorker, on NY skyline. From interview by Richard Hake, WNYC, August 20, 2010.*

corresponding building accelerations in y-direction are illustrated in Figure 7. Based on the structural frequency in the optimal layout designed to static criteria, frequency ranges of 2.5 to 50% were considered and it is seen that a higher level of acceleration resulted instead. On the other hand, difficulty in achieving a large percentage of frequency tuning was noted. Without amending the structural system but upgrading the concrete grade, wall thickness, and lintel beam depth of the analytical model, only 5–10% of the frequency increment could be reached. By increasing the damping ratio from values of 1 to 3.5%, a gradual decrease of acceleration was noted. Based on the results of the sensitivity study, it is persuasive to consider provision of auxiliary damping system as a comparatively certain and effective scheme for mitigation of building acceleration.

Step 3: Preliminary design of the damper tank

TLD was the selected auxiliary damping system in the case study project. TLD is basically a water tank as a secondary mass attached to the main structure with its sloshing fluid frequency tuned to the natural frequency of the structure. Since the damping capacity of TLD could be effectively adjusted in a controllable manner, it therefore increases damping capability of the primary structure and improves the dynamic performance (see Figure 8). The application potential of TLD for the vibration control of building structures was studied in the late 1980's (Fujino et al. 1988). The success of the TLD system in reducing wind-excited structural vibrations has been well established in the support of numerous analytical and experimental studies over the last three decades (Chaiseri et al. 1989). The application of the TLD system in prototype structures and full-scale field measurements for the performance were also recorded in Japan (Tamura et al. 1995).

The effectiveness of a TLD is very much dependent on its optimal properties, which include tuning frequency, mass ratio and damping ratio. The sloshing frequency of the TLD is comparatively easy to achieve by the design of tank dimensions and water depth. However, the inherent damping of the sloshing fluid, without assistance of additional energy dissipating devices, is usually considerably lower than the required value for optimal performance of the TLD. There have been a number of studies demonstrating the effectiveness of installing baffle screens inside the tank to enhance the effectiveness of damping (Kaneko and Ishikawa 1999). Analytical models for simulation of the response behavior and evaluation of performance of TLDs equipped with baffle screens has been thoroughly discussed and verified with experimental studies by Tait et al. (2005) and Tait (2008). This was the theoretical model adopted for preliminary design of the proposed TLD.

The design equations were applied to design a double-deck TLD placed on the roof of the building to suppress the building acceleration in x-direction and y-direction sway motions, which are respectively first and second modes of the structure (see Figure 9). Analytical building frequencies were first considered in this design stage. The first and second fundamental modes were estimated to be 0.24 Hz and 0.26 Hz, respectively. The internal dimensions (length × breadth) of the damper tanks for both decks are 8.45 meters × 5.43 meters (27.7 feet x 17.8 feet) and water depths in the upper and lower TLD are 1.92 meters (6.3 feet) and 0.87 meter (2.9 feet) respectively. A 1.5% of mass ratio was provided for the tanks in the adopted sizes. To attain the target for effective damping as evaluated in the wind

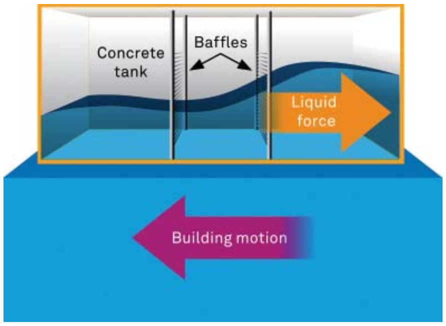


Figure 8. Working principle of a damper tank

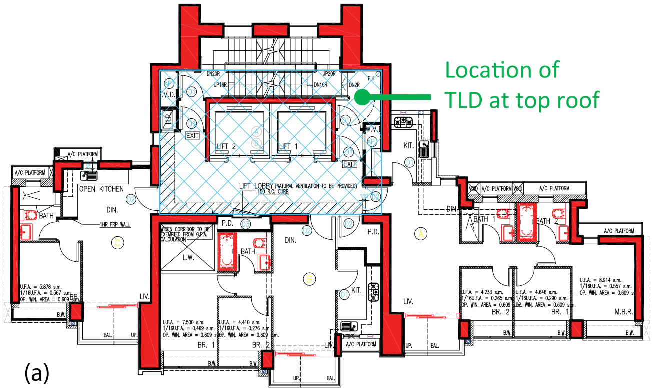


Figure 9a. Arrangement of damper tank – plan

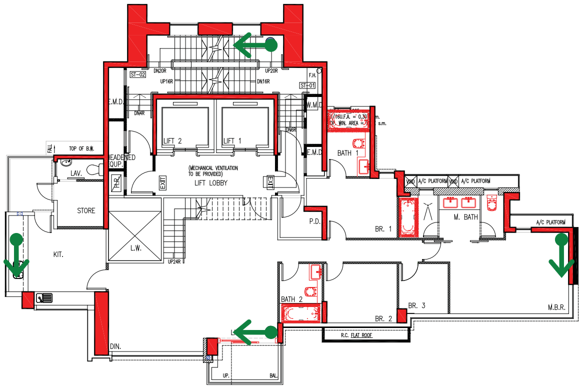


Figure 10. Accelerometers deployment layout

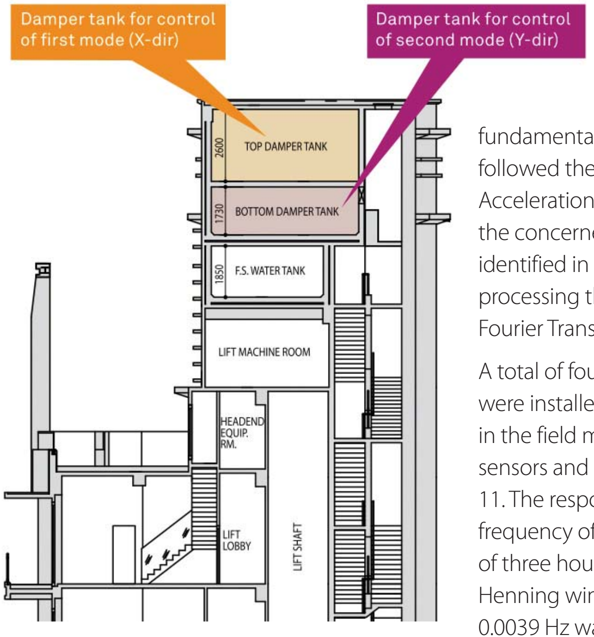


Figure 9b. Arrangement of damper tank – elevation

tunnel testing, pairs of baffle screens with a solidity ratio of 40% were deployed in each TLD. The pairs of baffle screens were placed in the middle of the TLD 85 centimeters (33.5 inches) and 1.1 meters (3.6 feet) apart for the upper and lower TLD, respectively.

Step 4: Field measurement in an as-built structure

The effectiveness of TLD is depending upon the match tuning of the sloshing frequency to the building frequency. Field measurements of the as-built structure were therefore carried out to identify the physical values for design review of damper tanks before they were constructed. Identification of the first three fundamental frequencies of the building has followed the ambient vibration approach. Acceleration time histories were measured and the concerned structural frequencies were identified in the frequency domain by processing the recorded signals with Fast Fourier Transform (FFT).

A total of four unidirectional accelerometers were installed at the top floor of the building in the field measurement. Arrangement of the sensors and setup are shown in Figures 10 and 11. The response signals were sampled at a frequency of 20 Hz and recorded for a duration of three hours. Spectral analysis with a Henning window in a frequency resolution of 0.0039 Hz was employed. The field measurement results showed that the frequencies of sway modes (first and second mode) were in fair agreement with the analytical estimations, whereas the deviation in the frequency of rotational mode (third mode) was relatively larger.

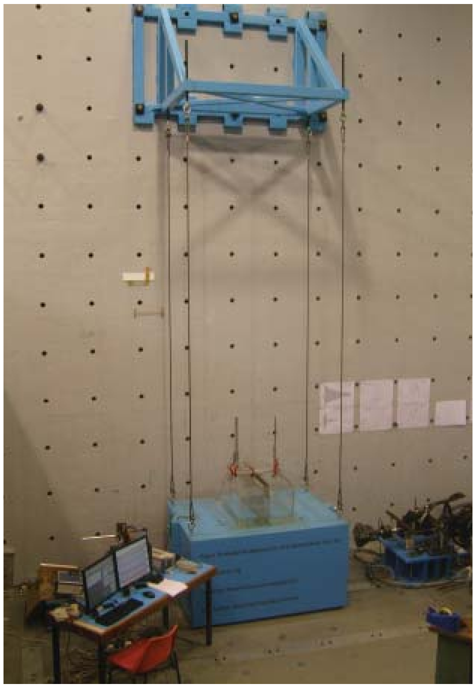
In general, the analytical model will underestimate the stiffness of the building, and thus the natural frequencies, because the non-structural elements were essentially not considered. For a better estimation of the building frequencies in the preliminary design of the damper tank in terms of size for layout planning, a higher value of Young's modulus of concrete was considered in a separate model. It was reviewed that this method is fairly satisfactory to attain a closer estimation for building frequencies in the sway modes, but it is not as effective for the rotational mode. Perhaps the major reason is that rotational frequency is more influenced by the perimeter wall or façade and the modeling excluded these elements. Nevertheless, no damper tanks were designed for the rotational mode and the design of damper tanks for the sway modes will not be affected.

Step 5: Experimental evaluation of structure-TLD system

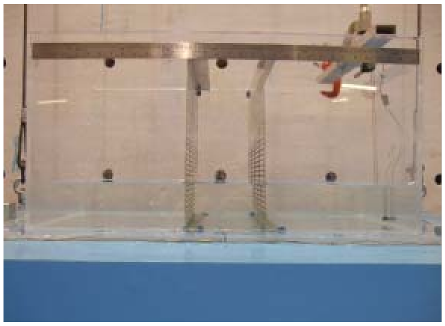
Water motion in the TLD is nonlinear and its damping performance is motion-amplitude dependent. As a result of the nonsymmetrical structural layout of the studied building, sway motions of the building are coupled and this effect was not considered in the theoretical model. For a more precise assessment of the physical performance of the proposed structure-TLD system, experimental evaluation with a 1:10 scale model was performed.

The laboratory-scale study was conducted at the Hong Kong Polytechnic University (PolyU). The experimentally replicated structure-TLD system was designed as a suspended system, which is comprised of a rigid mass to simulate the modal mass of the building, along with a TLD with baffle screens, an actuator to input external excitation, an accelerometer to measure responses of the structure under excitation, and an acquisition system to display, record and analyze the input and output signals from the system. The structure-TLD system, with different settings of water depth and screen locations was vibrated to a resonance state with sinusoidal excitation to

Figure 11. Uni-directional accelerometer and acquisition



Structure-TLD system



Damper tank

Baffle screen

Figure 12. Setup for experimental evaluation of TLD

the design levels of acceleration, over a range of frequencies to identify the control performance and effective damping of the system. An example of the arrangement of the damping screens in the TLD is shown in Figure 12.

The tests for the first and second mode control were carried out separately. For the first mode motion (x-direction), investigation showed that the acceleration level of the test structure was optimally suppressed at a water level of 19.5 centimeters (7.7 inches) or 1.95 meters (6.4 feet) at full scale, with a pair of baffle screens placed 8.5 centimeters (3.3 inches) apart or 85 centimeters (33.5 inches) at full scale. The tested values were in close agreement with the analytical design. Steady-state acceleration of the structure at different excitation frequencies of external force is highlighted in Figure 13.

These studies demonstrated that the accelerations of the primary structure could be significantly reduced compared to a no-damper structure when TLD is optimized for water level and baffle screen location. Baffle screens are crucial components to enhance water damping and to achieve more robust performance of TLD compared to providing no screens. In this design setting, the effective damping of the system was enhanced to 3.0%. The design setting for optimal acceleration reduction of the second mode (y-direction) is a water level of 8.8 centimeters (3.5 inches) or 88 centimeters (34.6 inches) at full scale with baffle screens 11 centimeters (4.3 inches) apart, or 1.1 meters (3.6 feet) at full scale. A close agreement with analytical design was similarly noted and the effective damping ratio was increased to 4.6%.

The influence on control performance of TLD in a coupled building motion was investigated by changing orientation of TLD to the building motion. The results, as shown in Figure 14, indicate that the performance of TLD is only slightly affected for the largest testing angle of 24 degree. A similar observation was noted in the second mode study. The insensitive behavior of the control and robust performance of TLD to the coupled building motion is an encouraging result, because an unsymmetrical layout is typical in residential buildings.

Choice of Auxiliary Damping Devices

There are two main streams of passive auxiliary damping devices: Tuned Mass Dampers (TMD) and Tuned Liquid Damper (TLD), which are generally considered in building applications for wind and seismic vibration control. Sydney Tower, Washington National Airport Tower, Higashimyama Sky Tower and Taipei 101 are application examples of TMD. Employment of TLD can be seen in Shi Yokohama Prince Hotel, Nagasaki Airport Tower, Comcast Center, etc. In Hong Kong, there are a few applications of TLD in residential buildings, such as The Summit and The Harbourfront Landmark. It should be noted that the heights of these buildings are 220 meters (722 feet) to 235 meters (771 feet) respectively. Amongst the application records of passive auxiliary damping devices, TMD system has demonstrated its identical competence for vibration control in wind and seismic events, whereas TLD was mostly employed for enhancing vibration resistance of buildings against wind. Since the structural design in Hong Kong is mostly dominated by the forces of the wind, TLD is considered to be a better choice economically to implement and maintain. This is due to the comparatively simple system of TLD compared to the sophisticated mechanical parts of TMD. If there is a constraint in the installation space, TMD is perhaps more desirable because TLD has limitations on the changing density of the system mass for water. However, a higher density of material could be engaged in TMD to make the device more compact.

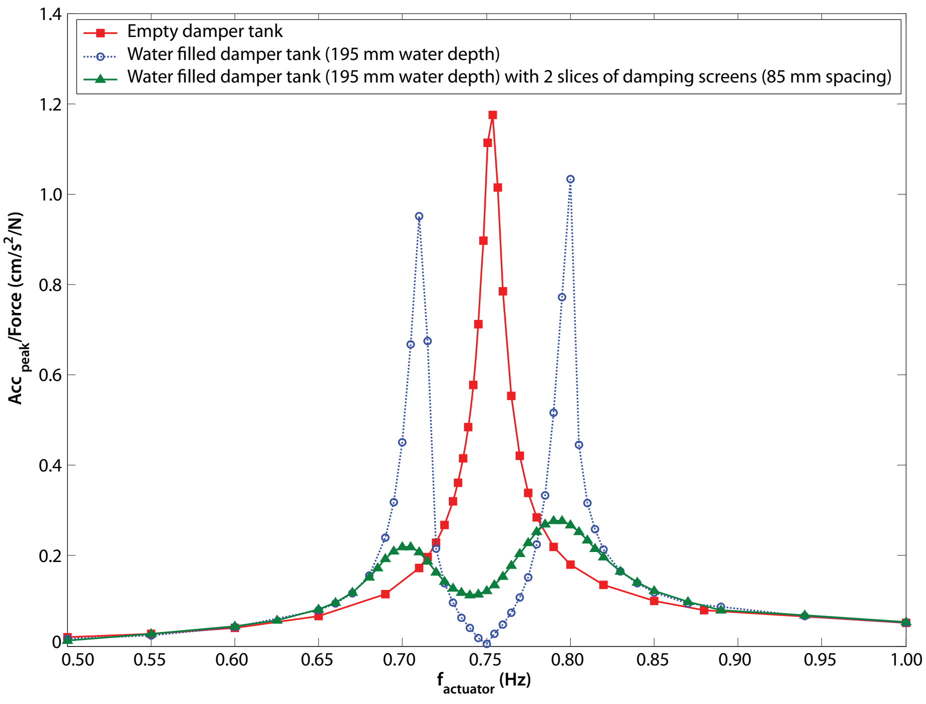


Figure 13. Building acceleration (x-direction) in different control cases

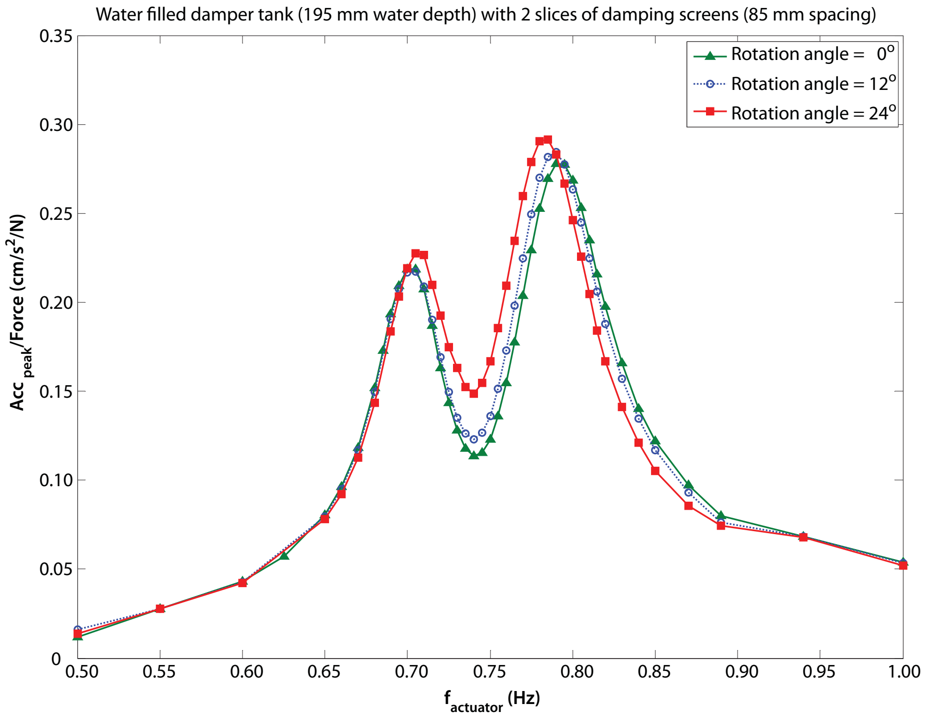


Figure 14. Building acceleration (x-direction) at different orientations of TLD

Summary

Tall, slender buildings on restricted sites present structural engineers with dynamic problems that are difficult to resolve economically and effectively through a conventional design approach. A performance-based design approach permits investigating separate structural systems and the design of the corresponding optimal parameters to achieve adequate static and dynamic building responses for an efficient structure. The example project has demonstrated that tuned liquid dampers have a great potential to enhance the dynamic performance of tall, slender structures, enabling creative architecture, optimizing usable floor space and material use, and resolving the problem of occupant comfort. ■

Acknowledgements

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