

# Optimization of Swimming Pools as Tuned Liquid Dampers for Vibration Control and Seismic Resilience in High-Rise Buildings

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Received August 14, 2025; Revised December 5, 2025; Accepted January 15, 2026

## Cite This Paper in the Following Citation Styles

(a): [1] Mayur M. S., Arun Kumar S. R., Abhilash Kumar K. A., Kiran K. Shetty, "Optimization of Swimming Pools as Tuned Liquid Dampers for Vibration Control and Seismic Resilience in High-Rise Buildings," *Civil Engineering and Architecture*, Vol. 14, No. 1, pp. 583 - 592, 2026. DOI: 10.13189/cea.2026.140139.

(b): Mayur M. S., Arun Kumar S. R., Abhilash Kumar K. A., Kiran K. Shetty (2026). *Optimization of Swimming Pools as Tuned Liquid Dampers for Vibration Control and Seismic Resilience in High-Rise Buildings*. *Civil Engineering and Architecture*, 14(1), 583 - 592. DOI: 10.13189/cea.2026.140139.

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**Abstract** Minimizing the seismic-induced dynamic response of high-rise buildings is crucial to prevent excessive lateral movements, high storey drifts, and occupant discomfort. Due to the low inherent damping problem in tall buildings, new vibration control strategies have been implemented in modern tall buildings, and the Tuned Liquid Damper (TLD) has been proven very effective. A swimming pool has a special opportunity to be utilized in recreational and structural ways when it is designed as a TLD in contemporary high-rise construction. Performance of such a system largely depends on placement and water depth, which have to be optimized to maximize the damping efficiency. The present paper focuses on the seismic performance enhancement of a 32-storey mixed-use high-rise building in Bengaluru, India, by incorporating a swimming pool as a functional TLD. With the difference in pool location (edge pool and center pool) and depth (1.2 m and 1.5 m), five structural models were created and analyzed using structural analysis software, with response spectrum analysis (RSA) according to IS 1893:2016. The original model was the most susceptible as it had the highest time period, displacement, and drift with no pool. By adding an edge-positioned pool, lateral displacements were reduced by as much as 44% and storey drifts by up to 32%, but centrally located pools also enhanced performance, albeit to a lesser extent. In all the set-ups, the maximum lateral

deflection was between 126 -210 mm, which was within the allowable limits. The results point out that the positioning and sufficient depth of a swimming pool used as a TLD can significantly improve seismic resilience with a twofold usage. This new technology is a cost-efficient, aesthetically unified and structurally advantageous way of enhancing the dynamic stability of tall buildings.

**Keywords** Tuned Liquid Damper (TLD), Flat Slabs, Swimming Pool, Response Spectrum Analysis, Time Period, Stiffness, Damping

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## 1. Introduction

The tall buildings in seismic areas are quite different, and the safety of these buildings is highly affected by the ability of the building to handle the dynamic loads [1]. Tuned Liquid Dampers (TLDs) have become more significant in recent decades, being an inexpensive and dual-functional means of controlling vibrations. Based on the idea of neutralizing the motion of buildings by the sloshing effect of water, they rely on the sloshing movement of water to dissipate destructive seismic energy into safe fluid motion. They are particularly attractive in

modern high-rise construction, because they can be incorporated into building features such as swimming pools, and offer both practical features and a structural shield.

The flat slab system, as present in the building in this research, does not have deep beams, a fact that permits open floor plans and less depth. Nevertheless, this type of design also increases the flexibility of the structure and allows it to be affected by larger lateral movements during an earthquake. The effects of earthquakes on such structures are due to ground shaking related to fault rupture, transmission of seismic waves through the various layers of soil and resonance between the natural frequency of buildings and the frequency of ground shaking. These effects may be compounded in soft-soil locations or in high-rise clusters within the city limits, substantially affecting the serviceability of the building in question even though the building may be structurally safe.

Traditionally, structural engineers have used a number of different types of dampers to manage vibrations: Tuned Mass Dampers (TMDs) with solid mass [2], viscous dampers which use the resistance of fluid [3], friction dampers [4] and base isolation [5] systems that isolate the building and isolate it against ground motion. Although these systems are effective, most of them need some structural changes or special spaces that cannot be used in any other way. In comparison, TLDs exploit the inherent characteristics of water to offer damping without introducing big, concentrated masses and occupying additional space. They also possess the advantage that they are easy to tune by varying water depth and container size [6].

The territory selected for the proposed research is a moderate seismic zone, however, the history of earthquakes has proved that moderate earthquakes may also lead to disturbances, including an uncomfortable state of occupants because of swinging, cracks in partition walls, facade, and service failures of the most critical facilities. The tall buildings are present in those regions which frequently must deal with the dual problem of safety and the public trust in their stability.

Several researchers have, over the years, looked at the potential of liquid damping systems to enhance a building's performance [7]. It has also been established through experimental and analytical investigations that rooftop water tanks, when tuned appropriately, are capable of minimizing displacements by 15-45 percent in various seismic conditions. As an example, some projects have demonstrated how water depth can be increased to produce greater damping, and how the best locations, e.g., orienting the tank so that its centre of mass coincides with that of the building, can reduce torsional forces [8]. The present study has used these insights to formulate the modeling strategy [9, 10]. In this paper, a mixed-use building made up of a flat slab with 32 stories will be examined with and without swimming pools as TLDs. Five models are being used:

Model 1 (no pool), Model 2 (edge pool, 1.2 m depth), Model 3 (edge pool, 1.5 m depth), Model 4 (center pool, 1.2 m depth) and Model 5 (center pool, 1.5 m depth). The aim is to find out the effect of depth and location on the efficiency of vibration control when subjected to a seismic load.

According to IS 1893:2016, the seismic analysis is done using the Response Spectrum Method (RSM) [7]. It is an approach to assessing the building performance by integrating the modal responses with respect to a prescribed spectrum of ground motion and provides a trade-off between approximations and computational cost.

The swimming pools are also modelled as equivalent spring-mass systems to illustrate the effect of water sloshing [11].

According to the results of other studies of this type, it is possible to note that edge placement can result in a higher level of reduction in sway in a single direction, and central placement can result in more even damping in both X and Y planes [7, 12]. The deeper the pool, the better it works in general because of the greater mass and sloshing inertia [13]. The current study is based on these observations, in which the authors seek to provide practical recommendations on how to incorporate TLDs into the design of high-rise buildings without making them lose their functionality (in terms of utility) and aesthetics.

This system ensures structural safety while maintaining architectural functionality, without requiring any additional dedicated damping equipment [14]. The findings of this study will be of great importance for understanding how the pool depth, length and location can be maximized to offer maximum vibration suppression and at the same time offer maximum usable space. The results specifically apply to flat slabs, which, because of their flexible structure, are more prone to lateral movements in case of seismic activity. The study also adds value to sustainable construction since it reuses the existing building element into a multi-functional feature, saves material, and increases the comfort of occupants. The results of this project could be used as a guideline for engineers and architects who want to use multi-functional damping systems in the design of high-rises, particularly in seismic-prone areas where cost-effectiveness, space utilization and structural integrity are also paramount. The current study contributes to Sustainable Development Goals (SDGs) 9,11 and 12.

## 2. Materials and Methods

### 2.1. Design of Model

The case study is dedicated to the mixed-use high-rise of 32 storeys and the total height of 167.05 m that is situated in Bengaluru, India. The building combines various functions, such as office spaces, hotel facilities, a

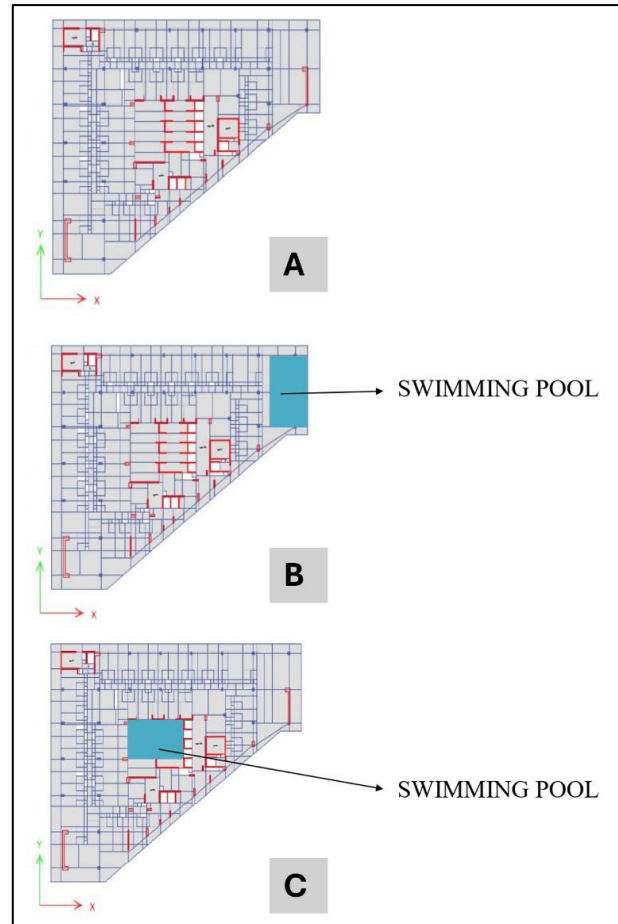
swimming pool on the roof of the building, as well as basement parking with the focus on the usability and earthquake resilience. The structural design has four basements (B1-B4) intended to be used as parking and service utilities and meets the IS 875 (part 2) [15] specifications regarding vehicular live loads, ramp gradients and ventilation. The building has office spaces running between the ground floor and the 24th floor that are served by a flat slab system that allows office spaces to have open floor plans with the appropriate load-bearing capacity, deflection control and punching shear strength.

Levels 25 through 30 contain a luxury hotel where guests can stay, hold banquets and play. The swimming pool is placed strategically on the 25th floor to act both as an amenity and a functional Tuned Liquid Damper (TLD) to reduce structural vibrations caused by both wind and earthquakes. It is at this stage that the system of structure changes to shear walls instead of the flat slabs, which guarantees additional lateral stiffness and loading resistance. The 10th, 19th, 24th, and 30th floors have service floors to allow mechanical, electrical and plumbing (MEP) installations.

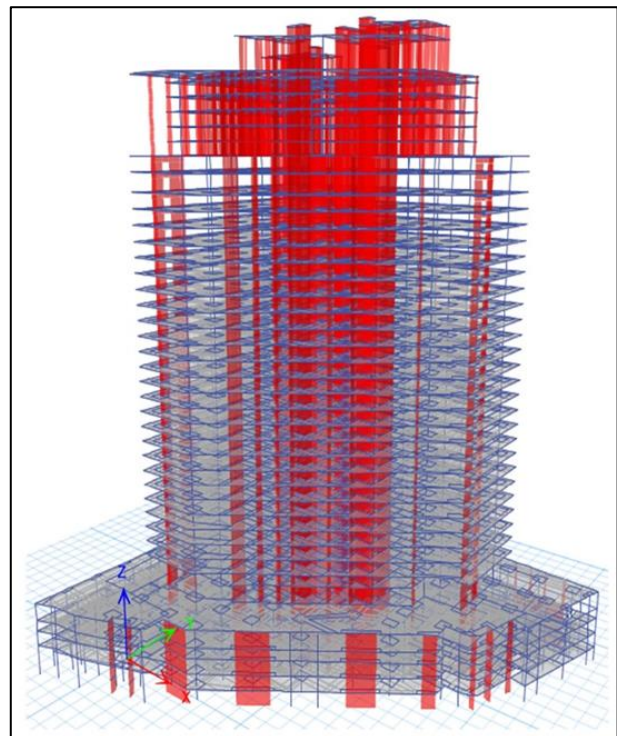
The lateral load-resisting system is in the form of flat slabs up to the 25th floor to achieve efficiency in terms of gravity loads and shear walls above to introduce enhanced seismic and wind performance. The design is achieved in accordance with the provisions of IS 1893:2016 seismic, the zone in Bengaluru, and IS 875 (Part 3) [16] wind loads. The structural Analysis software uses Response Spectrum Analysis (RSA) to perform seismic performance analysis, where the swimming pool is included as a functional TLD whose addition improves the damping properties. In evaluating the study, the researchers consider structural details, shown in Table 1. The plan section of the various cases is shown in Figure 1 and the 3D view of the building is shown in Figure 2.

**Table 1.** Details of building plan and properties of material

No. of Storey	4B+G+32
Slab thickness	150 mm
Thickness of wall	300 mm
Lift Core walls	300 mm
Height of the building	167.05 m
Grade of Concrete for column & shear wall	M40
Grade of Concrete for beams & slabs	M35
Grade of steel	Fe550
Dimension of pool	10.84m X 20.875m
Thickness of swimming pool slab	250mm



**Figure 1.** Plan section of a) No Pool b) Pool at Edge c) Pool at Center



**Figure 2.** 3D view of edge placement of swimming pool

As per IS 16700:2017 code [17], P-Delta effects must be considered for buildings exceeding 45 m in height. The considered structure, with a height of 167.05 m, satisfies this criterion. Hence, P-Delta analysis was incorporated to assess structural stability and nonlinear seismic response. To simulate second-order effects accurately, the scale factors recommended in the code were implemented. A scale factor of 1.2 was applied to dead load, floor finish, super dead load, service load, and wall load, representing their full contribution to gravity effects. For lateral loads such as EQX and EQY, a higher factor of 1.5 was used to reflect their amplified influence under nonlinear conditions. Live loads (LL) were assigned a reduced scale factor of 0.5, accounting for partial occupancy during seismic events.

Property modifiers are prescribed in IS1893 part 1 (2016) code [19], IS 16700 (2017) code [17] and IS:875 (Part 1) (1987) [18]. They contribute to the correctness and safety of structural designs by changing attributes like stiffness, strength, and ductility to account for real-world conditions. Modifiers of 0.25 for slabs, 0.35 for beams, and 0.7 for both columns and walls are considered for the analysis of all five models.

## 2.2. Design of Response Spectrum Analysis

Response spectrum analysis is a method used to estimate a structure's response to brief and transient dynamic events, such as shocks and earthquakes. Analyzing the precise temporal history of these loads is challenging due to their unpredictability. Since these events have short durations, they cannot be considered as stationary processes. The response spectrum method utilizes a specific type of mode superposition, requiring an input to define the extent to which an event of this nature can excite a mode with a particular natural frequency [12]. Although this approach can be determined manually, it is complex, as the manually calculated base shear often differs from the base shear predicted by the program. The structure, located in Seismic Zone II with medium soil conditions, incorporates a lateral load-resisting system consisting of ductile RC structural walls, a conventional RC moment-resisting frame, and a semi-rigid diaphragm. The seismic performance of the structural models developed was thoroughly assessed through Response Spectrum Analysis (RSA) of the developed models as per IS 1893:2016 [19].

The reason behind the choice of this analytical method is that it provides a more realistic and accurate representation of the seismic behavior of a building in comparison to the static analysis, since it uses the contribution of the many modes of vibration instead of paying attention to the fundamental one. When the distribution of mass and stiffness in the structure is realistically included, RSA reproduces the highly nonlinear nature of structural response to seismic excitation. This analysis identifies the basic time period, a

decisive parameter that determines the natural frequency of the building and its tendency to resonate. Moreover, RSA can also give an idea on storey displacements and inter-storey drifts, and thus floors that are of critical importance in terms of lateral movement, which might lead to structural inadequacy or discomfort to occupants. As opposed to simplified methods, RSA considers the time-varying interaction of seismic forces with the dynamic property of the structure, and both the magnitude and distribution of responses are considered at all levels. Table 2 provides the factors considered for the response spectrum analysis. It is therefore ideally applicable to high-rise buildings whose mass or stiffness distribution is irregular, e.g., the flat slab type in this case study, whose seismic performance is affected by the architectural configuration, material types, and the provision of energy-dissipating systems like Tuned Liquid Dampers (TLDs).

**Table 2.** Presents the response spectrum factors considered, following the guidelines of IS 1893 Part 1 (2016) code

Parameters	Values
Zone	II
Soil Type	II
Seismic zone factor	0.1
Response reduction factor	3
Importance factor	1.2

The unusual plan structure that was used in the 32-story mixed-use high-rise building in this study was done intentionally to represent the architectural and functional complexity that is characteristic of urban development today. The structure exhibits different slab configurations between the office and hotel levels, transition between the flat slabs and shear walls above the 25th floor, the existence of a swimming pool that forms a Tuned Liquid Damper (TLD) at various locations, among others, which combine to create an irregular plan and non-uniform distribution of stiffness. When this irregularity occurs, the center of mass (CM) and the center of rigidity (CR) are not aligned, thus giving torsional effects and imbalanced seismic responses when excited laterally. These effects may enhance story drift and offset in areas that are flexural in nature, such as flat slabs. The study provides the interaction of the added sloshing mass with the irregular geometry of the building by placing the TLD at different locations, such as edge and center, to redistribute the dynamic forces and overcome torsional vibrations. The findings indicate that positioning and depth of the pool can have a significant effect on the seismic response, which proves that, in the case of geometrically irregular structures, though, the use of a strategically positioned TLD can cause an increase in performance, drift reduction, and improvement in occupant comfort with minimal structural changes.

### 2.3. Design of TLD

To model the TLD accurately, it is essential to consider the sloshing mass ( $m$ ), which represents the portion of the total water mass that actively participates in sloshing [7]. This is typically a fraction ( $\alpha$ ) of the total water mass in the pool, where  $\alpha$  ranges between 0.1 and 0.25 for shallow tanks. The natural frequency ( $f$ ) of this sloshing mass should be closely tuned to the first mode frequency of the building ( $f \approx f_s$ ) to maximize damping efficiency. This frequency is given by  $f=1/t$ , where  $t$  is the fundamental period of the building.

The sloshing system is modelled as an equivalent single-degree-of-freedom (SDOF) system in structural analysis software. The stiffness ( $k$ ) of the sloshing system is calculated using the expression  $k=m(2\pi f)^2$ , which represents the restoring force due to gravity. Additionally, damping ( $c$ ) is incorporated to account for energy dissipation due to internal fluid friction and wall interaction, defined by  $c=2\zeta\sqrt{KM}$  that is the damping ratio, typically taken between 5% and 10%.

By designing the pool with appropriate dimensions, mass ratio, and positioning (often near the top of the building), the sloshing water can effectively reduce dynamic responses and contribute significantly to the building's seismic and wind resilience.

Table 3 provides input values for TMD (Tuned Liquid Damper) analysis as well as link property modifiers characterized as  $U1(x\text{-axis})$  and  $U2(y\text{-axis})$ .

**Table 3.** Properties of TLD

	DEPTH OF SWIMMING POOL m	1.2	1.5
1	TOTAL MASS OF SWIMMING POOL KN	2768.95	3329.78
2	PERCENTAGE OF SLOSHING CONSIDERED ( $\alpha$ )	15%	15%
3	WEIGHT OF SLOSHING KN	415.343	499.46
4	STIFFNESS ( $k$ ) KN/m	2089.463	2514.996
5	DAMPING ( $c$ ) KNs/m	93.158	112.078

## 3. Results and Discussion

This section presents the outcomes of the seismic performance evaluation of all the five models. Response Spectrum Analysis was used to compute natural time periods, storey displacement, inter-storey drift, and base shear insights into the efficiency of each case in controlling.

### 3.1. Time Period Evaluation Using Response Spectrum Analysis

Response Spectrum Analysis is used to determine the

time period of a structure as it accurately captures its dynamic behaviour during earthquakes by considering its actual stiffness, mass distribution, and damping [20].

The comparison of the time period of all five structures in Figure 3 depicts the time duration in seconds of all the five structural models, which indicates the impact of swimming pools that are employed as Tuned Liquid Dampers (TLDs) on the dynamic response of a high-rise building. Model 1, with a time period of 8.913 seconds, is the base case in which no swimming pool or TLD is present and the most flexible and least stiff model, which is the most vulnerable to dynamic loads such as wind or seismic loads. Comparatively, models 2 and 3, which accommodate swimming pools in edge locations at varying depths of 1.2 m and 1.5 m respectively, show markedly decreased time durations of 6.744 seconds and least of 6.565 seconds respectively, which shows the increased stiffness and better control of vibrations. This implies that TLDs located at the edge and more profoundly are very fruitful in quelling building oscillations. Models 4 and 5, with swimming pools located at the centre of the building, and depths of 1.2 m and 1.5 m, respectively, exhibit slightly longer time periods 7.954 and 7.793 seconds, thus demonstrating that edge location is more effective in reducing the vibration than the central one. The findings affirm the fact that inclusion of the TLDs in the form of swimming pools can enhance the dynamic stability of the high-rise building significantly, with central positioning and deeper pools being the most advantageous.

### 3.2. Storey Displacement Evaluation Using Response Spectrum Analysis

Figure 4 indicates the change in storey displacement at various floor levels of a high-rise building in SPEC x load case, all the five models with and without swimming pools as Tuned Liquid Dampers (TLDs). On the vertical axis, the storey levels are displayed starting at the base up to the terrace and on the horizontal axis is the lateral displacement in millimeters. This model without pool (model 1) indicates the maximum displacement at all levels, particularly at the terrace, which is 210.719mm and has high structural flexibility. Conversely, the models that include the swimming pools-as TLDs-experience enlarged decrease in the displacement, confirming the usefulness of water sloshing in the reduction of seismic response. The maximum deflection in other models is 160.776, 152.82, 153.182 and 141.905 respectively. Overall, they accounted for **23.7%**, **27.3%**, **27.3%** and **32.6%** respectively. The displacement trend proves that the incorporation of a swimming pool as a tuned liquid damper can increase seismic resistance tremendously, with central positioning being more effective at 27.3% (1.2m depth) and 32.6% (1.5m depth) absorbing energy and controlling displacement compared to edge positioning.

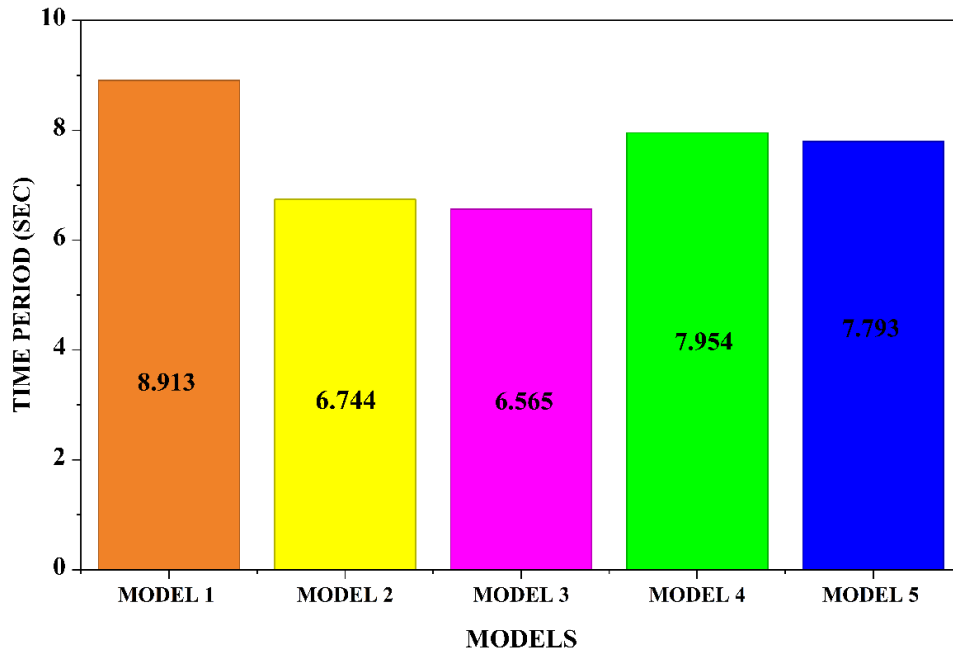


Figure 3. Time period comparison

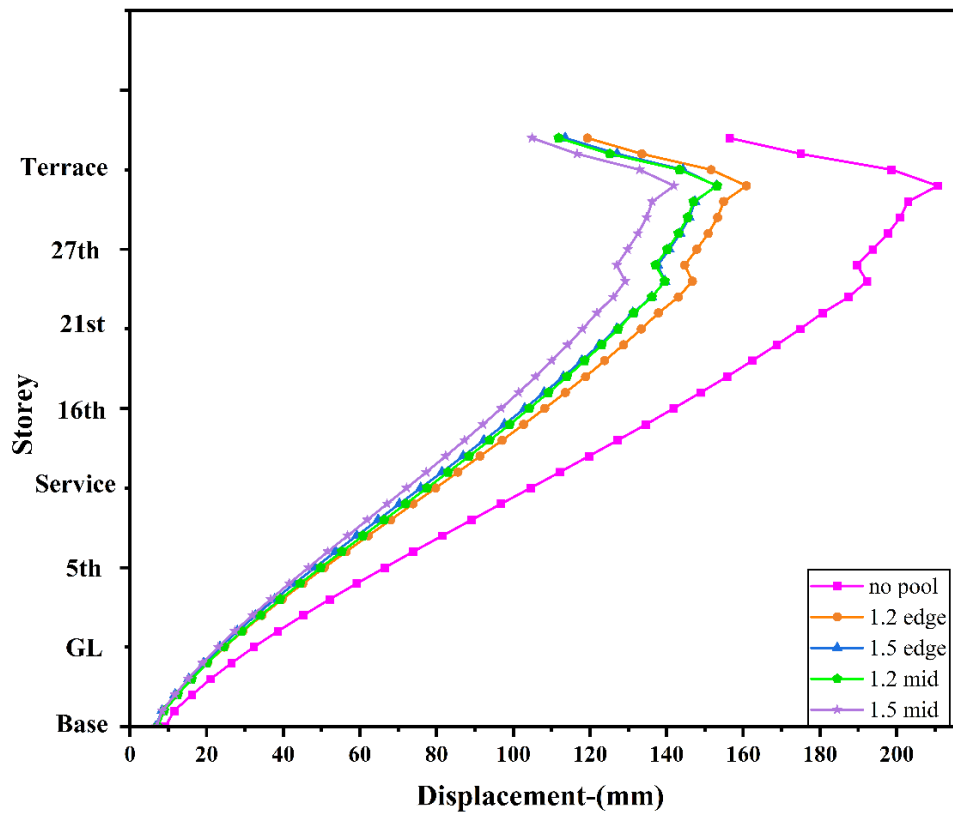


Figure 4. Story v/s Story displacement graph of X-Axis

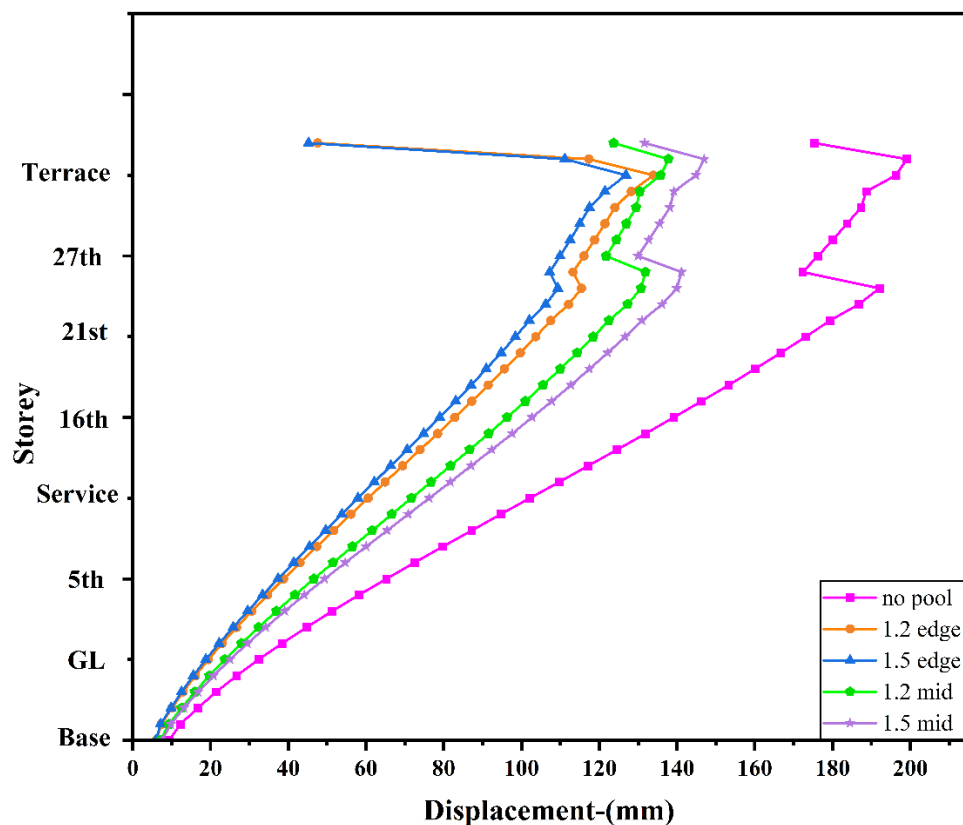


Figure 5. Story v/s Story displacement graph of Y-Axis

Figure 5 indicates the change in storey displacement at various floor levels of a high-rise building in SPEC Y load case, five models with and without swimming pools as Tuned Liquid Dampers (TLDs). On the vertical axis, the storey levels are displayed starting at the BASE up to the LMR TOP and on the horizontal axis is the lateral displacement in mm. This model with the exclusion of the pool (model 1) indicates the maximum displacement of 199.066mm, which has a high displacement. Conversely, the models that include the swimming pools-as TLDs-experience enlarged decrease in the displacement, confirming the usefulness of water sloshing in the reduction of seismic response. Out of the TLD models, the model 3(TLD with 1.5m Depth and on the edge) exhibits the least displacement of 126.838mm. Model 2, model 4 and model 5 even have 133.921mm, 137.785 and 146.974 respectively. Overall, the displacement trend proves that the incorporation of a swimming pool as a tuned liquid damper can increase seismic resistance tremendously, with edge positioning being more effective at **44.2%** in model 2, **36.2%** in model 3, absorbing energy and controlling displacement, compared to central positioning **31.1%** model 4 and **26.17%** in model 5.

### 3.3. Evaluation of Storey Drift Using Time History Analysis

Story Drift is the relative horizontal displacement between two consecutive floors of a building during lateral loading like earthquakes. The storey drift for all five models remains within permissible limits as per IS 1893 [19].

In Model 1, the building lacks a swimming pool and there is therefore no secondary structure to absorb and dissipate the motion leading to the maximum storey drift. By adding a pool at the edge such as in Models 2 and 3, this allows the sloshing water to engage the building movement in one prevailing direction resulting in moderate reductions of 6.02% in 1.2 m depth and 11.04% in 1.5 m depth, with the pool at the latter depth being superior since it has a larger water mass, inertia, and energy absorption capabilities. The situation is much different when the pool is relocated to the Centre, as in Models 4 and 5, where the improvement can be as much as 26.95 percent and 32.23 percent due to the damping effect being symmetrical and thus aligning the sloshing mass to the Centre of mass of the building so that it can counteract vibrations more evenly in both X and Y directions as shown in Figure 6 and Figure 7.

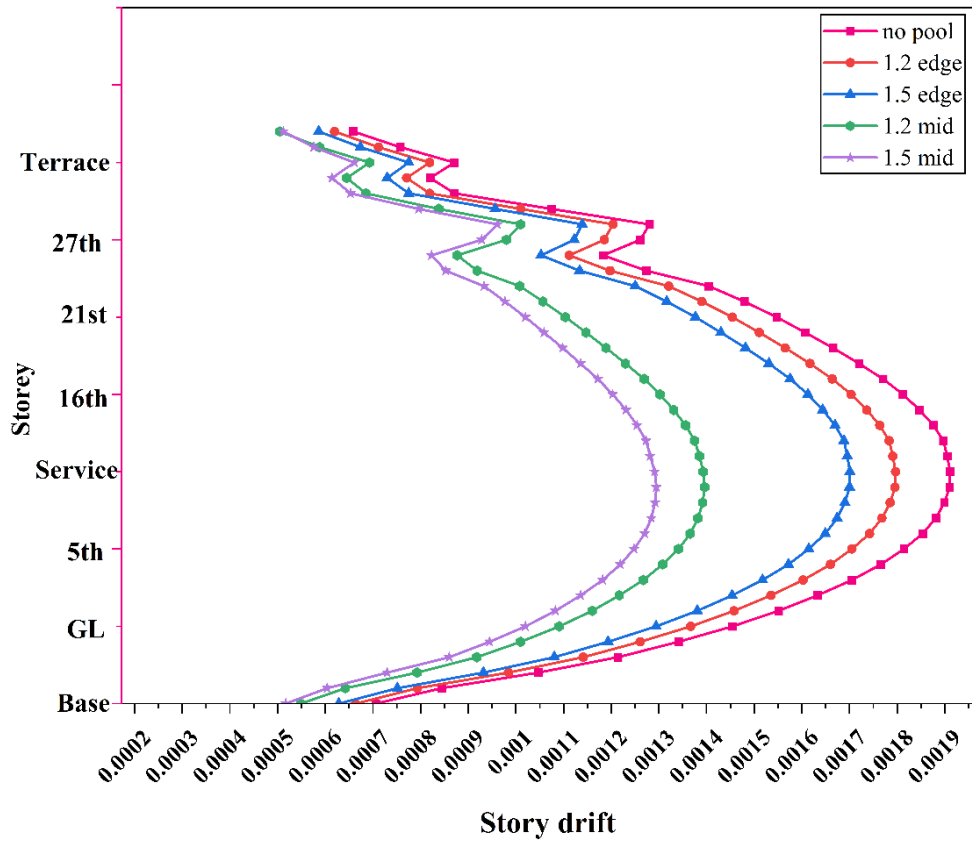


Figure 6. Story v/s Story drift of X-Axis

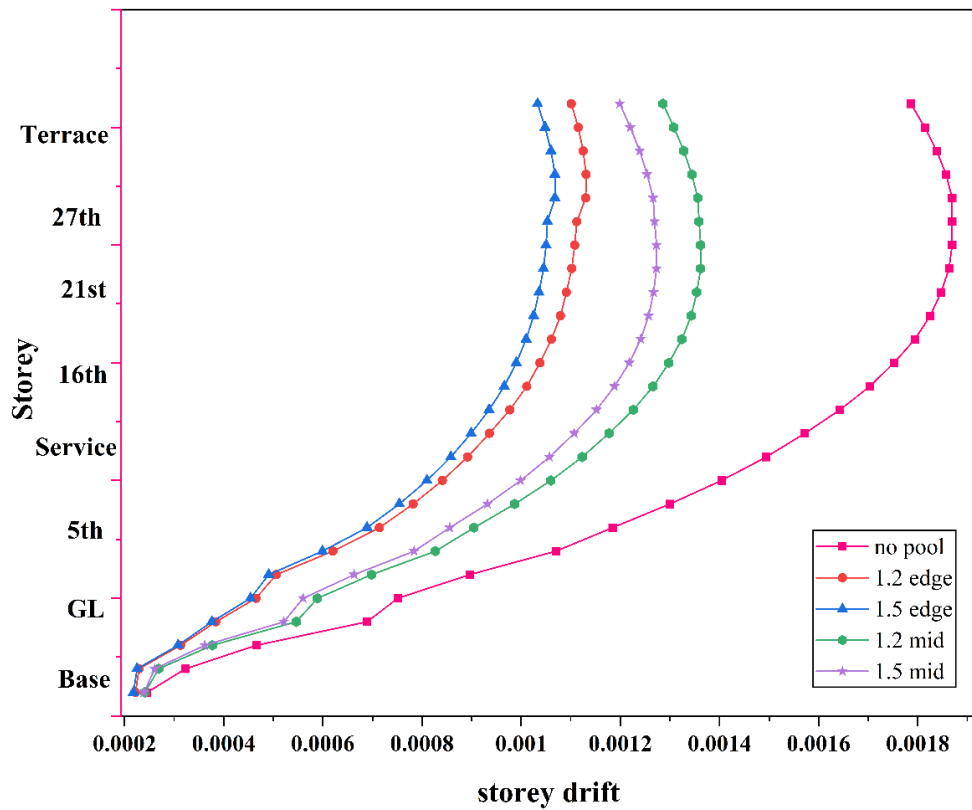


Figure 7. Story v/s Story drift of Y-Axis

Under the baseline, which has no swimming pool (Model 1), the storey drift is maximized in X and Y directions in the building since no other mechanism is provided to absorb or dissipate the motion. The insertion of an edge-located pool in the case of Models 2 and 3 slightly improves the X-axis- 6.02 and 11.04 percent decrease in depths of 1.2 m and 1.5 m, respectively- and dramatically improves the Y-axis-39.49 and 42.86 percent decrease in depths of 1.2 m and 1.5 m, respectively. The deeper pool always beats the shallow one thanks to the greater amount of water mass and the ability to dissipate energy. Moving the pool towards the middle, like in Models 4 and 5, changes the performance trend; on the X-axis, the decreases increase to 26.95 and 32.23 percent, because the symmetrical location enables the sloshing mass to be balanced at the centre of mass of the building to counter vibrations more evenly. The middle of the Y-axis offers a 27.13% and 31.89% cut, but not as domineering as the edge position in that axis.

## 4. Conclusions

Conclusively, the incorporation of a TLD, as a swimming pool, minimizes the time period, displacement of the story, and drift drastically. The depth of the pool is also important, as well as its location in the central position; this location and additional depth result in the best seismic performance, which provides the best resilience of the building under lateral loads.

## Acknowledgements

We are very grateful to Manipal Academy of Higher Education, Manipal and DesignTree Service Consultants Pvt. Ltd. for providing us with all the facilities and resources.

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