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Investigating the Influence of Rooftop Swimming Pool Depth as a Tuned Liquid Damper on Seismic Building Deflection Using Response Spectrum Analysis

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ABSTRACT

Tuned Liquid Damper (TLD) is a control system used to reduce structural vibrations in buildings or other structures (Hochrainer & Ziegler, 2006). One innovative use of this control system is a rooftop swimming pool (JIN et al., 2023). Research on utilizing pools as TLDs has been conducted, but no study has specifically focused on selecting the optimal depth of a rectangular rooftop swimming pool in irregular buildings. This study aims to analyze the influence of the selection of rooftop swimming pool depth on an irregular building structure's deflection. The analysis was conducted using ETABS, with the object being a 10-story hotel building with 2 basements. The existing swimming pool, measuring 16.25 x 4.85 meters and located on the rooftop, was analyzed with 3 different depth variations. The swimming pool was modeled using a spring mass model as a dynamic load according to ACI 350.3-2020. The analysis was carried out using the response spectrum method with parameters based on the building's location. The analytical findings reveal that the swimming pool depth can influence its performance as a tuned liquid damper (TLD) in an uneven building construction. The research revealed that model 3 had the least maximum displacement, with a reduction of 2.72% in the x-direction and 3.27% in the y-direction. It can be inferred that in the examined building, a swimming pool with a depth of 2 meters (model 3) is more successful at decreasing displacement, particularly in the y-direction.

Keywords: tuned liquid damper; pool; mass ratio; depth ratio; structural deflection.

INTRODUCTION

Tuned Liquid Damper (TLD) is a control system used to reduce structural vibrations in buildings or other structures (Hochrainer & Ziegler, 2006)(Pabarja et al., 2019). This damper consists of a container filled with liquid tuned to the natural frequency of the structure, effectively dissipating energy and reducing oscillation (Bauer, 1984). This technology has proven effective in mitigating the impacts of wind, earthquakes, and other external forces on buildings (Zahrai et al., 2012). When the structure vibrates, the liquid moves back and forth, dissipating energy and reducing the amplitude of vibrations (Modi & Munshi, 1998).

One innovative application of TLD is the use of rooftop swimming pools (JIN et al., 2023). Utilizing swimming pools as TLDs demonstrates the flexibility and effectiveness of pools in ensuring the safety and resilience of structures in various environments (Ruiz et al., 2016). The water in the pool acts as a mass that responds to dynamic loads, effectively dampening vibrations and reducing displacements in the building (Hosseini & Beskhyroun, 2023a). An additional benefit of using swimming pools as TLDs is not only structural stability but also an attractive facility for building occupants (Ali & Moon, 2007). Thus, planning a swimming pool as a TLD represents an innovative way to integrate technology into structural design to enhance safety and aesthetics.

Several parameters must be considered when designing a swimming pool as a TLD (Tuned Liquid Damper). These parameters include pool size (Bhujel et al., 2022), pool shape (Deng & Tait, 2009), water volume (Ocak et al., 2023), pool depth (Love & Tait, 2013), and its position in the building (Shejul, 2017). Additionally, the pool's oscillation frequency in response to the building's movements must be carefully calculated to ensure optimal damping effects (K. & Ahsan, 2000). By considering these factors, engineers can optimize the design of swimming pools as TLDs to maximize their effectiveness in reducing vibrations and enhancing structural stability (Nanda, 2010).

This study will discuss the influence of swimming pool depth on the effectiveness of the pool as a TLD. The depth of the swimming pool can significantly affect its ability to dampen vibrations within the building. Previous research indicates that deeper pools can be more effective at damping vibrations because they have more water mass to absorb and dissipate energy (Love & Tait, 2013). However, depth must be carefully balanced with other parameters to ensure optimal TLD performance. By analyzing the relationship between swimming pool depth and its effectiveness as a tuned liquid damper, designers can make informed decisions to enhance the safety and aesthetics of the structure.

Several studies on TLDs indicate that swimming pool depth impacts the seismic performance of buildings (Mahesh & Murali Krishna, 2021). However, there has yet to be a study specifically focusing on the selection of optimal rooftop swimming pool depth in irregularly shaped buildings with rectangular pools. This presents a novelty in this research, where an analysis of varying depths of rectangular rooftop swimming pools applied to an irregular building will be conducted. By studying the relationship between the depth of rectangular swimming pools and the seismic performance of irregular buildings, it is hoped that readers can gain a better understanding of how to optimize swimming pool design as TLDs for multi-story buildings. This research may lead to improvements in the safety and resilience of buildings in earthquake-prone areas.

INTRODUCTION

Research Tools and Data

In this study, the analysis is conducted on an existing building with a rooftop swimming pool, where the building has technical and material data as shown in Table 1. The specifications of the examined rooftop swimming pool are detailed in Table 2.

Table 1. Technical data of the building

Spesifications	Detail
Location	Yogyakarta
Bulding Type	Reinforced concrete structure
Fungtion	Hotel
Soil Type	Medium (SD)
Number of Floors	B-2 & G+10
Building Height	39.6 meters
Structural System	Dual system
Concrete	Fc’ 35 Mpa (for columns)
	Fc 25 Mpa (for other elements)
Reinforcement	BJTP fy 240 Mpa, BJTU fy 400 MPa

Table 2. Pool data

Parameters	Value and unit
Lenght (L)	16.25 m
Width (B)	4.85 m
Depth (H_L)	1.5 m
Wall Thickness (t)	250 mm

Structural Modeling

The structural modeling and analysis of the building are conducted in three dimensions using the ETABS program. The modeling of the building used can be seen in Figure 1.

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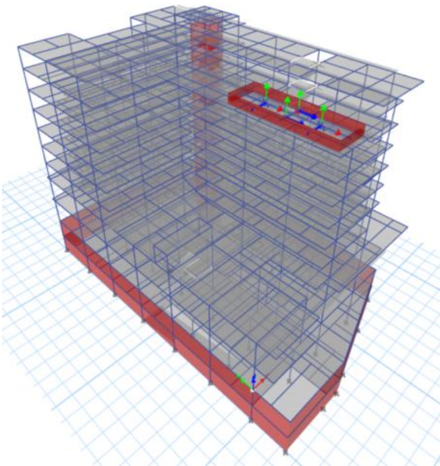

Figure 1. Structural modeling on ETABS

Structural Loading

The structural loading in this study is carried out by referring to the regulations and standards for load planning applicable in Indonesia. The references or standards used in this study include:

1. SN1 1727-2020 about Minimum Design Loads and Related Criteria for Buildings and Other Structures
2. SNI 2847-2019 about Requirements for Structural Concrete for Buildings
3. SNI 1726-2019 about Procedure for Earthquake Resistance Planning for Building Structures and Non-Building Structures
4. ACI 350.3-20 about Requirements for Seismic Analysis and Design of Liquid-Containing Concrete Structures

Analysis Method

The analysis method used in this study is the response spectrum analysis. This method was chosen because it is the simplest method permitted in (SNI 1726, 2019) for analyzing irregular building structures.

The earthquake acceleration parameters used were obtained from the 2021 Design Response Spectrum data from the Directorate General of Cipta Karya, Ministry of Public Works and Housing (PUPR), corresponding to the coordinates of the location in Yogyakarta City and the soil class SD (Medium Soil). The earthquake acceleration parameters and other earthquake parameters can be seen in Table 3, while the response spectrum graph is presented in Figure 2.

Table 3. Earthquake acceleration parameters and other earthquake parameters.

Acceleration parameters	Value and unit	Earthquake parameters	Value
S_S	1.1259 g	KDS	D
S_1	0.5094 g	Ie	1
T_L	6 s	R	7
T_0	0.15 s	C_d	5.5
T_S	0.77 s	Ω_0	2.5
S_{DS}	0.79 s	Ct	0.0048
S_{D1}	0.61 g	x	0.75

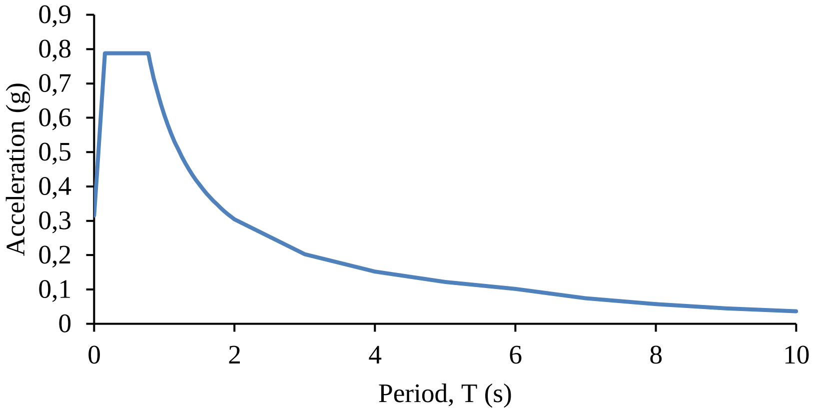

Figure 2. Response Spectrum Graph

Swimming Pool Analysis as a TLD

The analysis of the swimming pool as a TLD is carried out by modeling the swimming pool with dynamic water loads using a spring-mass model with an additional mass and specific stiffness calculated according to the equations based on the ACI 350.3-20 regulations. (ACI 350.3, 2020) explains that for rectangular tanks, the equations that can be used for fluid-structure interaction are as follows:

$$\frac{M_i}{M_L} = \frac{\tan[0.866\ (L/H_L)]}{0.866\ (L/H_L)} \tag{1}$$

$$\frac{M_c}{M_L} = 0.264(L/H_L)\tan[3.16(H_L/L)] \tag{2}$$

$$\text{Untuk } L/H_L < 1.333,\ \ h_i/H_L = 0.5 - 0.09375(L/H_L) \tag{3}$$

$$\text{Untuk } L/H_L \geq 1.333,\ \ h_i/H_L = 0.375 \tag{4}$$

$$h_c/H_L = 1 - \left[\frac{\cosh[3.16(H_L/L)] - 1}{[3.16(H_L/L)]\,.\sinh[3.16(H_L/L)]}\right] \tag{5}$$

$$T = \left(\frac{2\pi}{\lambda}\right)\sqrt{L} \tag{6}$$

$$\lambda = \sqrt{3.16g\,.\tanh[3.16(H_L/L)]} \tag{7}$$

where, h_i = height of the resultant impulsive hydrodynamic pressure, h_c height of the resultant convective pressure, H_L = water depth in the tank, L = length of the tank, M_L = total mass of water, M_i = impulsive mass, and M_c = convective mass.

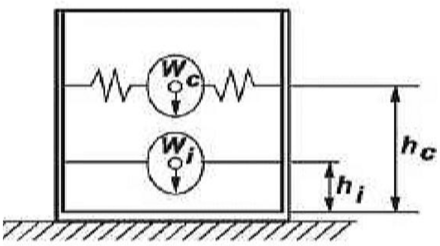

Figure 3. Distribution of water mass as a dynamic load (ACI 350.3, 2020)

The stiffness value for the convective spring is given by the following equation (Bhujel, Bhatt, & Pradhan, 2022)

$$K_c = 0.833[W_L/H_L]\,.\,tan^2[3.16(H_L/L)] \tag{8}$$

where, $W_L = M_L.g$

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Research Parameters

The building being studied will be modeled by varying the depth of the swimming pool, where the dimensions and position of the swimming pool are matched with the existing conditions, and the swimming pool is assumed to be in a full condition. The variations of the model being analyzed have several parameters as listed in **Table 4**.

Table 4. Variations and parameters of the analyzed model

Parameters	Model 1	Model 2	Model 3
L (m)	16.25	16.25	16.25
B (m)	4.85	4.85	4.85
H_L (m)	**1**	**1.5**	**2**
V_L (m^3)	78.81	118.22	137.92
M_L (kg)	78812.50	118218.75	137921.88
H_i (mm)	375	562.50	750
H_c (mm)	501.57	755.27	1012.42
M_i (kg)	18756	41908.92	72840.14
M_c (kg)	64932.12034	95917.75	125244.96
Kc/2 (kN/m)	11.88	25.92	44.19
T_{TLD} (s)	10.38	8.54	7.47
f_{TLD} (Hz)	0.10	0.12	0.13

Flow Diagram

The flow diagram for this research can be seen in **Figure 4.**

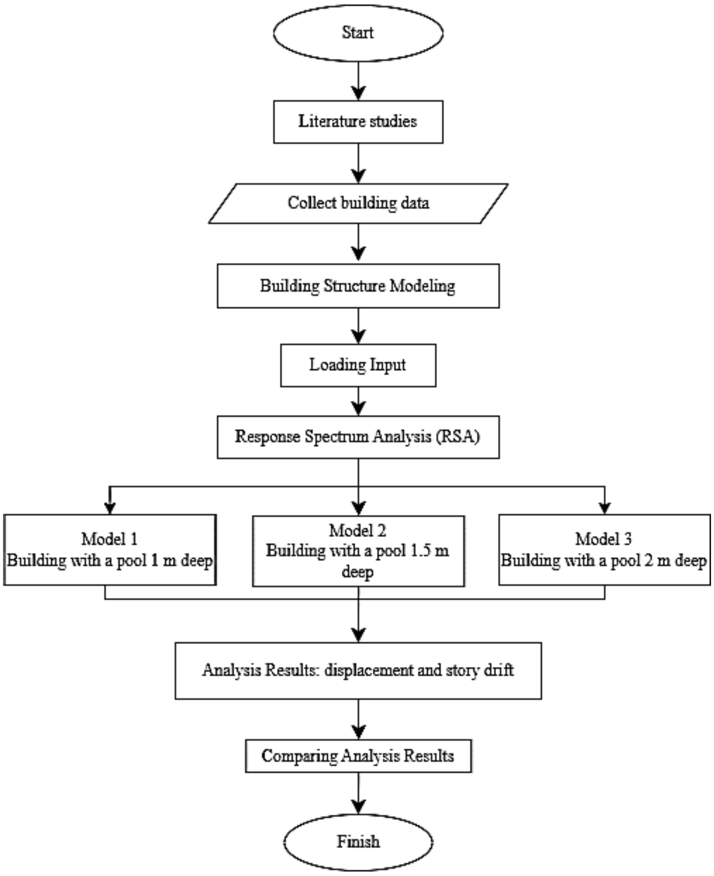

Figure 4. Research flow diagram

RESULTS AND DISCUSSION

From the analysis results, the maximum elastic displacement (δe) maksimum tiap lantai dari masing-masing model sebagaimana yang terlihat pada Tabel 5. for each floor of each model is obtained as shown in Table 5. This result is then multiplied by the amplification factor of C_d/I_e to obtain the inelastic displacement value (δi) as regulated in SNI 1726-2019. The values of C_d dan I_e are previously known to be 5.5 dan 1, respectively, making the amplification factor ($f_{x,y}$) equal to 5.5. The inelastic displacement (δi) for each model can be seen in Table 6.

Table 5. Elastic displacement for each floor of each model

Story	Elastic Displacement X (mm)			Elastic Displacement Y (mm)		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
11	62.90	63.70	68.09	59.24	58.01	52.39
10	57.45	58.56	64.95	56.37	55.35	49.55
9	51.58	52.31	60.33	51.75	51.16	45.03
8	45.97	45.74	53.86	45.85	45.60	39.58
7	39.22	38.92	46.00	38.89	38.81	33.53
6	31.71	31.22	37.13	31.12	31.06	27.02
5	24.13	23.41	28.12	23.23	23.14	20.42
4	17.31	17.15	20.18	15.62	15.50	13.95
3	7.81	7.46	8.93	6.38	6.31	5.81
2	2.26	2.01	2.17	1.19	1.19	1.15
1	0.62	0.55	0.60	0.13	0.15	0.13
0	0.00	0.00	0.00	0.00	0.00	0.00

Table 5. Inelastic displacement for each floor of each model

Story	Inelastic Displacement X (mm)			Inelastic Displacement Y (mm)		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
11	345.95	350.32	374.50	325.81	319.03	288.15
10	315.99	322.07	357.24	310.05	304.41	272.50
9	283.70	287.69	331.82	284.65	281.36	247.64
8	252.81	251.59	296.23	252.18	250.81	217.68
7	215.69	214.07	252.97	213.88	213.44	184.43
6	174.39	171.69	204.23	171.17	170.83	148.62
5	132.69	128.75	154.65	127.77	127.25	112.32
4	95.21	94.34	110.96	85.89	85.26	76.72
3	42.94	41.05	49.09	35.08	34.69	31.97
2	12.45	11.03	11.95	6.54	6.53	6.31
1	3.42	3.01	3.32	0.72	0.84	0.74
0	0.00	0.00	0.00	0.00	0.00	0.00

From Tables 5 and 6, it can be seen that the maximum displacement value for each model occurs at the roof floor (story 11). This maximum displacement occurs at the same nodal point for each model, specifically nodal 29 for displacement in the x direction and nodal 21 for displacement in the y direction (see Figure 5). This nodal point will be considered in this research to determine the effect of swimming pool depth on the deflection of the building structure. The comparison results can be seen in the graph in Figure 6.

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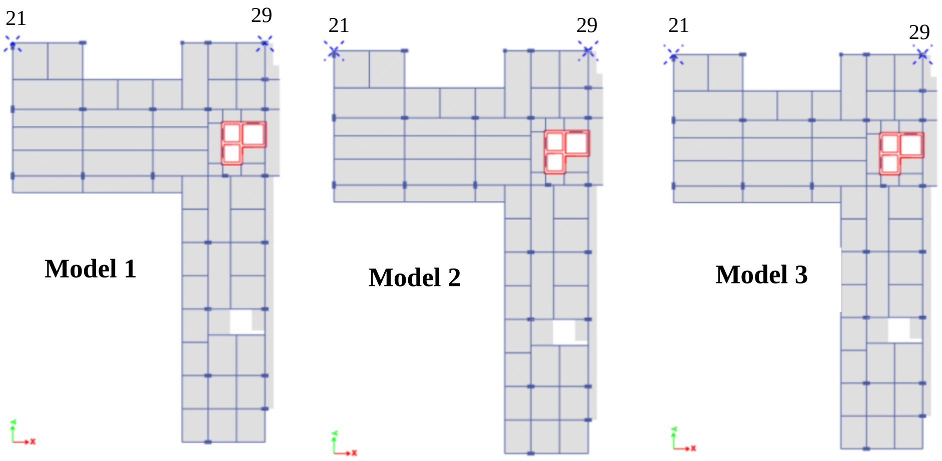

Figure 5. Location of nodal points where maximum displacement occurs

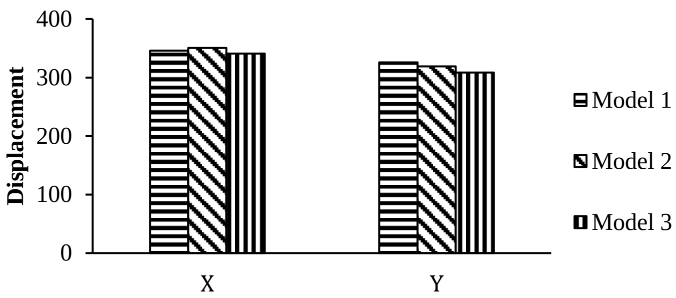

Figure 6. Graph comparing maximum displacement

Next, the story drift (Δ) is calculated as the difference in displacement between each floor, where the values are limited by the drift limit (Δ_{max}) as regulated in SNI 1726-2019. The drift limit for the building being studied is calculated using the equation 0.02h/ρ, where h is the floor height and ρ is the redundancy factor with a value of 1.3 (for buildings with irregularities). The results of the story drift (Δ) for each model and the drift limit (Δ_{max}) can be seen in Table 7, and their comparisons can be seen in the graphs in Figures 7 and 8.

Table 7. Story drift (Δ) and drift limit (Δ_{max})

Story	h (mm)	Drift X (mm)			Drift Y (mm)			Limit (mm)
		Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	
11	3200	29.96	28.25	17.26	15.76	14.62	15.65	21.54
10	3300	32.29	34.38	25.42	25.40	23.05	24.85	49.23
9	3200	30.89	36.11	35.59	32.47	30.55	29.96	50.77
8	3200	37.12	37.52	43.26	38.29	37.37	33.25	49.23
7	3200	41.29	42.37	48.75	42.72	42.61	35.82	49.23
6	3200	41.70	42.94	49.58	43.40	43.58	36.29	49.23
5	3200	37.49	34.41	43.69	41.88	41.99	35.60	49.23
4	4500	52.26	53.28	61.88	50.80	50.57	44.75	49.23
3	4500	30.50	30.02	37.14	28.55	28.15	25.65	69.23
2	3500	9.03	8.01	8.64	5.82	5.70	5.58	69.23
1	3200	3.42	3.01	3.32	0.72	0.84	0.74	53.85
0	0	0.00	0.00	0.00	0.00	0.00	0.00	49.23

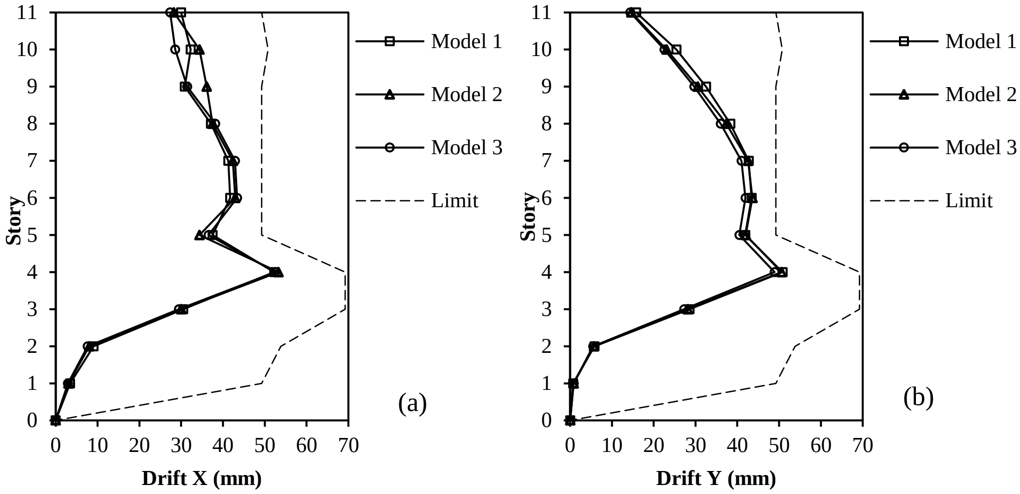

Figure 7. Graph comparing story drift (a) X Direction (b) Y Direction

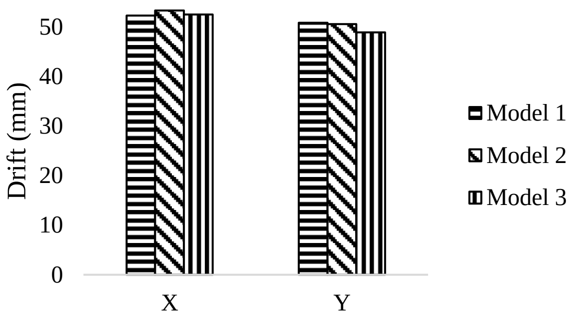

Figure 8. Graph comparing maximum drift (story 4)

One important factor in analyzing the effect of depth on its effectiveness as a TLD is the mass ratio and the depth ratio of the swimming pool. The mass ratio and depth ratio for each model can be seen in **Table 9**.

Table 8. Mass and depth ratio for each model

TLDs Parameters	Model 1	Model 2	Model 3
Depth Ratio in the X Direction (H_L/B)	20.619%	30.93%	41.24%
Depth Ratio in the Y Direction (H_L/L)	6.154%	9.23%	12.31%
Mass Ratio	0.47%	0.71%	0.94%

CONCLUSION

The comparison results of maximum displacement (Figure 6) and story drift (Figure 7) indicate that the differences in displacement among the models are relatively small, meaning the influence of the swimming pool as a TLD is quite minimal for the building under study. This is due to the mass ratio of the swimming pool being quite small, at < 1% (Table 8). Based on the depth ratio, Love dan Tait (2013) explain that TLDs are generally designed with a depth ratio between 5% and 25%. For medium depth, the effective depth ratio is above 15%. Pandey et al., (2022) state in their research that the maximum allowable depth ratio for TLDs is 30%, as a high depth ratio may reduce the performance of nonlinear sloshing. According to this theory, Model 3 will be more effective in reducing displacement occurring in the Y direction because it has a depth ratio in the Y direction close to 15% and in the Y direction > 30%. This aligns with the analysis results obtained in this research. From the results shown in Figure 6, it can be seen that Model 3 is more effective because

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it has the smallest displacement, with a reduction of 2.72% in the X direction and a reduction of 3.27% in the Y direction. Referring to the maximum drift (Figure 8), the smallest drift in the X direction occurs in Model 1 with a reduction of 1.92%, while in the Y direction, the smallest drift occurs in Model 3 with a reduction of 3.28%. These percentages indicate that for the building in question, a swimming pool with a depth of 2m (Model 3) is more effective in reducing displacement, particularly in the Y direction. Although in Model 3, the mass ratio in the X direction > 30%, this does not lead to a significant increase in drift. It can be concluded that the selection of swimming pool depth can influence its effectiveness as a tuned liquid damper (TLD) in an irregular building. This depends on the mass ratio and depth ratio of the swimming pool. These ratios are closely related; as the pool depth increases, the mass ratio also increases. However, in TLD planning, there are specific limits regarding the optimal mass and depth ratios, making it necessary to choose appropriate dimensions to achieve the desired mass and depth ratios. For future research, changes in the dimensions of the swimming pool can be made to observe the effects of dimension and depth changes with the same mass on the effectiveness of the pool as a TLD. Time history analysis is also recommended to examine the impact of this TLD on buildings during actual earthquakes.

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