Numerical Study on Various Position of Multiple Water Tanks toward Earthquake on High-rise Building

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Abstract. Earthquake can cause many problems to the structures, which lead to building collapse and may takes humans life. One of the effort to reduce the structural response is by introduce the damping system to the buildings where the energy of the system is slowly reduced until the vibration of the system is totally eliminated and the system is brought to rest. Several techniques are available nowadays, however passive control system has advantage in term of cost especially in Malaysia where the earthquake is not the major threat like in Japan but it is good to tune existing water tank to became a passive damper where it is there went situation needed. The objective of the present paper is to analyse the practicality of implementing multiple water tank as passive Multiple Tuned Liquid Damper and finding the best position of water tanks, which would reduce peak response of the structure subjected to seismic forces using SAP2000. 15 multi-storey concrete structure attached with five water tanks with 3 different situation of water tanks location under consideration. In order to study the depth ratio parameter, the water level was varies for each situation such as ¼ tank for all water tanks, half tanks for all water tanks and ¾ tank for all water tanks. The results shows that Position 2 filled with ¾ water has highest significant reduction in term of structural displacement which is 12.6mm compare to other water tanks positions and water level.

Keywords: earthquake, building, water tank, control system

1. Introduction
The breaking and movement of tectonic plate due to sudden energy release inside the earth cause natural disaster known as earthquake. This phenomenon can cause tsunami, rock falls, landslide ground settling and liquefaction. Furthermore, human life and manmade structures will also affected from this event which contains a very powerful energy which leads to destruction. Malaysia is not located at the active seismic region but surrounded by an active seismic bay and can be considered exceptional as it is in a non-earthquake zone as opposed to Indonesia (Sumatra Island) and the Philippines. However, Malaysia will be affected as well if there is any big magnitude earthquake took place 350 km away from the active fault line. During the earthquake on 22 January 2003 originated near Sumatra, it had affected buildings of 1 to 10 storeys high in Penang and Kuala Lumpur, so water tank as a passive Tuned Liquid Damper (TLD) could be considered as a precaution measurement for future unpredicted earthquake [1].

Nowadays, the advance development of light-weight high strength material has cause the trend in construction industry move to skyscrapers and tall buildings. This is due to over high density of
population in the cities in conjunction of land space scarcity that makes tall buildings more economic. These new generation of tall structures is vulnerable to earthquake excitations due to its light-weight, material flexibility and low inherent damping. These factors will increase failure possibility of structural elements. Vibration can be periodic or non-periodic that cause problems to the structures as well as the discomfort to the occupants inside. Vibration control is important for machinery, space shuttle, airplane and ship. With the modernization of engineering design and construction techniques, the vibration mitigation technique has find a way to civil engineering and infrastructure field. In this modern day, the total damping for structures is nearly 5% of the critical [2]. Conventional approach to cater the vibration from horizontal motions especially from earthquake is by strengthening the structural members. Alternatively, isolation systems and supplemental damping systems can be considered.

Isolation systems are installed between the foundation and the base elements of the building to separate the building and the moving ground during earthquake. In order to absorb vibrations from earthquake, this base isolation needs to be designed less amount of lateral stiffness compare to the main structure. Meanwhile, for supplemental damping system, the external device is installed at the top of the building. This supplemental damping system can be categorized into four groups which are active, semi-active, passive and hybrid [3]. Passive systems work without required any external power source that makes this damper system is cost-effective compare to other supplemental damping systems. One of the example of passive damping system is motion-activated damper which absorb structural energy through motion [4]. Tuned mass damper (TMD) and tuned liquid damper (TLD) are examples of this category. The TLD is also known as tuned sloshing damper because it uses water sloshing motion to dissipate energy. Tuned liquid damper is a passive damper which depends on hydrodynamic force to harmonize with natural frequency of the building [5].

TLD is a rigid tank filled with liquid which is typically water is used in practice [6]. TLD shape can be square, rectangular or circular and usually TLD is a water tank placed at the top of building. This is another advantageous of TLD because with proper tuning, the water tank not only use for water storage but it can be used as a passive damper to control and reduce the structural vibration. The sloshing and wave breaking during the seismic excitation is very important criteria to control and reduce the building vibration.

A single water tank as TLD will be placed at the centre of the building so that each center of mass will coincide [7]. In real situation, single tank as TLD cannot contain the necessary liquid mass as a water storage and supplement as well as to achieve the desired structural acceleration reduction so a combination of several water tanks is necessary. This combination of several water tanks known as multiple tuned liquid damper (MTLD) where the sloshing frequencies of each tanks are tuned to a range of the structural frequency [8]. Furthermore, slightly detuned of single TLD can reduce the system efficiency and it is impossible to detuned the TLD frequency during the excitation event since it is passive damper system [9].

Several studied had been conducted to find the practicality of implementing the water storage tank as a passive damper. Shad et al. [10] had conducted experimental and numerical studied for seven structures on one storey single degree of freedom system attached with TLD. In this study, the TLD was actually a single water tank that been divided into three section. The position of this rectangular water tank was maintain at the same location, only the water filled inside these three divided compartment was varying. The highest reduction of structural response reported when all three compartment filled with water. Love & Tait [8] conducted a research to find the performance of structure when installed with one (traditional TLD), two and three water tanks as MTLD that having distributed properties for single degree of freedom structure. It showed that the MTLD had better result compare to single TLD when the tanks have different damping ratio and natural sloshing frequency. Gowda [11] had considered several parameters for TLD-structure and found out that TLD is to be more functional and cost-effective for larger buildings. Tuong et al. [12] concluded that the dynamic response of the 8-story building subjected to harmonic loading with a rigid TLD remarkably reduced compare to the flexible TLD where did not prove to be as efficient as the rigid TLD.
2. Numerical Work

The present work aims to find the best water level with it position at the top of building which give the highest reduction in structure response subjected to seismic load using SAP2000.

2.1. Equation of motion for seismic analysis

The movement of the structure is the response due to the motion of the ground and depends on its mass, rigidity, damping and load or displacement applied. An equation of motion in the system was affected by the earthquake intensity can be written as equation (1) below:

\[ u_t = u + u_g \]  

(1)

where \( u_t \) is single mass total displacement; \( u \) is the relative displacement between mass and ground; and \( u_g \) is the ground motion displacement.

By applying Newton’s law and D’Alembert’s principle of dynamic equilibrium, it can be shown that

\[ f_i + f_D + f_S = 0 \]  

(2)

where \( f_i \) is the single mass inertial force and is due to the acceleration of the mass by \( f_i = m \ddot{u}_t \); \( f_D \) is the damping force on the mass and connected to the velocity across the viscous damper by \( f_D = c \dot{u} \); \( f_S \) is the elastic force applied on the mass and related to the relative displacement between the mass and the ground by \( f_S = ku \), where \( m \) is mass of dynamic system; \( c \) is damping ratio; and \( k \) is the stiffness. Fill in these equations for \( f_i, f_D \) and \( f_S \) into equation (2) gives

\[ m \ddot{u}_t + c \dot{u} = 0 \]  

(3)

Equation (3) is often referred to as the motion equation for the SDOF. New equations can be obtained for a system subject to ground motion by substituting equation (1) into equation (3)

\[ m \ddot{u}_t + c \dot{u} = -m u_g \]  

(4)

The motion equation for the MDOF system is equivalent to the SDOF system. The difference is only the stiffness \( k \), mass \( m \) and damping \( c \) are in matrices form. The aid of software is used to speed up the analysis process for MDOF system.

2.2. Model

15 multi-story concrete structure was considered for this analysis with the aid of analysis software; SAP2000. The structure was design using space frame with fixed at the bottom. The details are given in Table 1.

| Parameter                  | Details            |
|----------------------------|--------------------|
| Building type              | Reinforced Concrete|
| Number of floors           | 15                 |
| Number of bay              | 5 x 3              |
| Bay size (m)               | 4                  |
| Floor height (m)           | 3                  |
| Dimension of column (m)    | 0.45 x 0.45        |
| Dimension of beam (m)      | 0.23 x 0.45        |
| Depth of slab (m)          | 0.15               |
| Concrete strength (N/mm²)  | 35                 |
| Steel reinforcement (N/mm²)| 460                |
During the modelling process, for an optimization of the analysis, the structure was design as lumped mass single degree of freedom spring-mass system. The MTLD placed at the rooftop act as a spring mass system. Figure 1 and figure 2 shows the views of the model in SAP2000.

![Figure 1. X-Y Plane and 3-D View.](image1)

![Figure 2. X-Z Plane and Y-Z Plane View.](image2)

2.3. Time History Loading
The El-Centro 1940 earthquake was consider in the present study in the direction of global-X towards the structure. Time history analysis was conducted in this study for structures without water tank and with water tank that varies in water level. The summary of time history records used for this analysis was obtained from the website of Pacific Earthquake Engineering Research Center (PEER) as shown in Table 2. Time history of El-Centro is considered with acceleration values at 0.01 sec time interval as shows in Figure 3 below. The reason to consider El-Centro 1940 in the analysis is because this time history was widely used in study and research so it is easy to make comparative study for future research.

![Figure 3 Time history El-Centro 1940.](image3)

| Record       | Station/Year | Magnitude | PGA (g) |
|--------------|--------------|-----------|---------|
| Imperial Valley | El-Centro 1940 | 6.9       | 0.32    |

2.4. Tuned Liquid Damper
High-rise building will has several water tanks at the top of it for a water storage. During earthquake occurrence, this huge dead load can be utilize as TLD to absorb extra energy exert to the building. In the present study, a rectangular water tank will performing as tuned liquid damper. Five water tanks had been considered during the study. One water tank will be permanently located at the center of the top building so that the center structure mass and the tank mass will coincide [7].

The water tank dimension plan is summarize in Table 3. The water tank was placed over 1m high columns. The water level consider in this study is; (i) ¼ tank for all tanks, (ii) half tanks for all tanks (iii) ¾ tank for all tanks. The water level was varies in each situation in order to study one of the MTLD parameter that is depth ratio (the ratio of water depth to tank length) which give the optimum structural response reduction. The reason full water level not consider in study is because the mechanism of TLD to fully functioning is through water sloshing so a gap is required inside water tank for water to slosh. For optimization, the fluid inside water tank was assume incompressible. The fluid and MTLD was
simplify by modelled it using special joints with added mass and connected these joint to the structure [13].

Table 3. Details of water tank

| Dimension (m) | Height (m) | Column height (m) | Water (liters) |
|---------------|-----------|-------------------|----------------|
| 4 x 4         | 4         | 1                 | 64000          |

The considered water tanks positions is shown in Figure 4, Figure 5 and Figure 6 below.

Figure 4. Position 1 of water tanks.  
Figure 5. Position 2 of water tanks.  
Figure 6. Position 3 of water tanks.

3. Results and Discussion

The objective of the study is to find the effective position of multiple water tanks in reducing the structural response during earthquake event.

3.1. Roof Displacement

Roof displacement of the structure without water tank, Position 1, Position 2 and Position 3 with varies water level were compared as shown in Figure 4, 5 and 6. The results was summarize in Table 4.

Table 4. Roof Displacements for EL Centro Earthquake Data

| Conditions | Water level | Roof Displacement (mm) |
|------------|-------------|------------------------|
| Position 1 | ¼ tank      | 15.0                   |
|            | Half tank   | 13.6                   |
|            | ¾ tank      | 13.3                   |
| Position 2 | ¼ tank      | 14.6                   |
|            | Half tank   | 14.4                   |
|            | ¾ tank      | 12.6                   |
| Position 3 | ¼ tank      | 14.2                   |
|            | Half tank   | 14.9                   |
|            | ¾ tank      | 13.8                   |
The time history response at the roof level is presented in Table 4. The following conclusion can be made:

- The highest reduction can be seen at Position 2 when it is filled with ¾ tank of water where the roof displacement is 12.6mm.
- Less significant position is Position 1 with water level ¼ tank (15.0mm).
- Base on Figure 7, Position 3 had shown the increase in roof displacement (14.9mm) when the water level is half tank. However the roof displacement reduce once the water level is ¾ tank.

![Figure 7. Comparison roof reduction between Position 1, 2 and 3.](image)

3.2. Base shear

Table 5. Base shear in X-direction summary

|                  | Position 1 Base Shear X (kN) | Position 2 Base Shear X (kN) | Position 3 Base Shear X (kN) |
|------------------|-------------------------------|-------------------------------|-------------------------------|
| ¼ water level    | 414.77                        | 414.14                        | 407.35                        |
| Half tank        | 395.09                        | 393.20                        | 402.75                        |
| ¾ water level    | 373.97                        | 402.75                        | 394.43                        |

![Figure 8. Base Shear in X-direction.](image)

Base shear approximates the maximum predictable lateral force that will happen caused by seismic ground motion at the structure base. Table 5 shows the summary of base shear in X-direction

- Referring to Figure 8, the highest and lowest base shear in X-direction occur at Position 1
• The lowest base shear is 373.97 kN meanwhile the highest is 414.77 kN (both at Position 1).
• For Position 3, the base shear distance is not really big gap compare to Position 1.
• For position 2, the pattern of base shear between all there water condition is different compare to Position 1 and 3, which half tank causes less shear base compare to ¾ tank.

3.3. Acceleration Response
i. It is shows that the ¾ tank of water level has the lower maximum acceleration response regardless MTLD position. Please refer Figure 9.
ii. The highest maximum acceleration response experiences during Position 3 with ¼ tank of water level

| Conditions | Water level | Maximum acceleration response (m/s²) |
|------------|-------------|-------------------------------------|
| Position 1 | ¼ tank      | 0.527                               |
|            | Half tank   | 0.449                               |
|            | ¾ tank      | 0.407                               |
| Position 2 | ¼ tank      | 0.548                               |
|            | Half tank   | 0.467                               |
|            | ¾ tank      | 0.429                               |
| Position 3 | ¼ tank      | 0.568                               |
|            | Half tank   | 0.502                               |
|            | ¾ tank      | 0.447                               |

Figure 9. Graph of maximum acceleration.

4. Conclusion
The analysis results demonstrate that multiple tuned liquid damper (water tanks) can be used to reduce structure response due to earthquake forces. It has several advantages over other damping systems such as; low installation and RMO (Running, Maintenance and Operation) cost and less worried about mechanical problems. TLD natural frequency is controllable by adjusting the water depth and container dimension and TLD is applicable for any directional vibration Based on above study, the following conclusions are drawn:
• Base on the overall results, it can be concluded that Position 2 with ¾ water tank reduce most of the structure displacement.
• This position 2 shows the water tanks located around the center of the building has a better structural response reduction. However, when the water tanks pointed at the center like position
3, the efficiency to reduce the structure roof displacement had reduced when the water level increase. This shows water tanks need to be located at the center of the building but in distributing around it not all together near each other.

- It can be concluded from the outcome that the water tanks can be used in designing passive damper by adjusting the water level. Hence, this MTLD can be considered economical especially in the region such as Malaysia where this water tank has an extra purpose rather than just water storage.

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