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Water Tanks as Tuned Mass Damper in High Rise Buildings: A Review

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Abstract— Due to rapid urbanization, industrialization, increasing land cost and space limitation, the demand of high rise buildings is increasing. Such high rise buildings are constructed with light weight and high strength materials using advanced construction techniques. This leads the structure to be flexible and lightly damped, which increases the possibility of human discomfort, structural damage and even failure during the earthquake ground motion. A new concept of vibration supressing devices can be implemented to mitigate the response of the structure during dynamic excitation. The existing mass of water tank can be used as tuned mass damper without adversely affecting its functional use with low cost and maintenance. It dissipates energy through liquid sloshing and wave breaking. The fundamental liquid sloshing frequency is tuned to the structure's natural frequency to obtain maximum vibration control. The effectiveness of the tuned liquid damper is governed by the parameters i.e. mass ratio, depth ratio and tuning ratio. This paper investigates the effect of water tank as a tuned mass damper on a high rise building.

Keywords— Tuned mass damper, Earthquake, Vibration control, Fundamental liquid sloshing frequency, Natural frequency, Mass ratio, Depth ratio, Tuning ratio.

I. INTRODUCTION

Over the past few decades, world has witnessed various devastating earthquakes, leading to collapse of buildings and severe structural damages causing enhanced loss of human life. The rapid urbanization, industrialization, space limitation and high land costs have resulted in increasing demand of high rise buildings even in the areas with high earthquake risks. The use of lightweight, high strength materials, and advanced construction techniques have led to tall, flexible and lightly damped structures. The welded connections and light facades used in the modern high rise buildings to serve as exterior walls do not contribute to the strength and stiffness of the structure. As a result, these buildings are highly sensitive to dynamic forces and are prone to human discomfort, structural damage and even failure during extreme earthquake ground motion. Thus, it is essential to search for means to suppress undesirable levels of vibration in tall buildings.

A new concept of design based on vibration control suppresses and reduces the earthquake induced forces. The vibration control devices may be active, passive, semi-active or hybrid. An active control system requires an external source of power to dissipate the vibration energy in the structure. Power failure can be the major problem for an active control system during an earthquake. A passive control system or passive damper is the simplest vibration control device which does not need an external power source. It imparts the opposing control forces in response to the structure's motion. The most common types of passive control system are tuned mass dampers (TMDs), tuned liquid dampers (TLDs) and tuned liquid column dampers (TLCDs).

A TMD is a passive control device which consists of a mass, spring and damper attached to the vibrating system. It reduces the undesirable vibration by simply moving in out of the phase to that of the vibrating system thereby imparting inertial forces in the opposite direction to that of the external forces. Tuned liquid damper is a type of tuned mass damper in which the mass is replaced by the liquid. A TLD is water confined in a tank, usually placed on the top of a structure that reduces the dynamic response of the structure by using the sloshing energy of the water when subjected to excitation. Since water tank is an integral part of any building structure, the large mass imparted by it can be used as a tuned mass damper without adversely affecting its functional use, also it requires low installation cost and requires low maintenance. The fundamental sloshing frequency of the liquid in a tank is tuned to the structure's natural frequency to cause large amount of sloshing and wave breaking. This dissipates large amount of vibration energy. The required sloshing frequency of TLD can be obtained by varying the liquid depth in the tank. The structural response is affected by various TLD parameters i.e. depth ratio, tuning ratio, mass ratio and excitation frequency ratio. The depth ratio is the ration of height of the water in the tank (H) to the length of the tank (L). The tuning ratio is the ratio of fundamental sloshing frequency of the TLD to the natural frequency of the structure. The mass ratio is the ratio of mass of the water to the mass of the structure.

II. LITERATURE REVIEW

Said Elias, et al (2017), investigated the wind response control of tall buildings installed with a single tuned mass damper. The TMD is placed at the location of the larger or largest mode shape amplitude. A 76 storey benchmark building is studied in this paper to compare the performance of TMD installed at the top most floor with TMD installed at different floors/ locations of the building under wind forces. The performance of TMD at each floor is examined by tuning it to the first few modal frequencies. The parameters investigated to compare the effectiveness of the different TMD schemes are placement, tuning frequencies, mass and damping ratios of devices. The building is studied for increasing damping and mass ratio of TMD. It is found that TMD placed at the topmost floor and tuned to the fundamental modal frequency exhibits significantly improved performance than other schemes.

Muhammad Jamil Ahmad, et al (2016), conducted an experimental study to check the suitability of water tank as passive tuned liquid damper for reinforced concrete structure under earthquake loading. Two models of four storey RC frame structure symmetrical in plan and vertical are constructed with a water tank attached monolithically on the top and are tested on uni-axial freedom shaking table. The structure is first modelled and designed in ETABS in order to make it safe. The models are then checked for different levels and quantities of water i.e. 0%, 1%, 2%, 2.5% & 3% of weight of the structure. It was found that the weight of water 2.5 and 2.0% weights of structures gave minimum response acceleration and deflection for Model 1 and Model 2, respectively.

Suraj. N. Khante, et al (2016), conducted research with analytical investigation of feasibility of implementing water tank as passive TMD to improved seismic performance of plan irregular RCC building. The water tank is installed at the terrace level of L-shaped building at three different locations under five conditions i.e. tank empty, 0.25h, 0.5h, 0.75h & full tank. The building response is studied for EL centro 1940 & Bhuj 2001 using SAP2000. The investigation is done for three models with different number of floors. It is found that water tank at top can serve as TMD provided the plan location of water tank; water level and mass ratio are tuned properly. It is also seen that TMD (tank + water) located near the centre of mass and center of rigidity of an irregular building shows maximum response reduction as compared to TMD (tank + water) located away from it.

Supradip Saha, et al (2016), conducted an experimental study on performance of multiple tuned liquid dampers to control the response of structures under dynamic loading. Comparative study is done on the behavior of single tuned mass damper and multiple tuned mass damper with three water tanks. The damper systems are separately mounted over steel structure model and experiments are done considering various excitation frequency ratios varying from 0.5-2.0 and depth ratios varying from 0.05-0.3. It is observed that the response reduction by MTLD is more at lower water depth ratios and effectiveness of STLD is more at higher water depth ratios. It is found that a TLD system can be successfully used to mitigate the response of the structure but MTLD is more effective than STLD only within a small amplitude range and STLD is more effective when the liquid sloshing in TLD is large.

D. Rupesh Kumar, M. Gopal Naik, et al (2015) conducted research on study of effect of water tanks when modelled as tuned mass dampers on dynamic properties of structures. In this study, water tank has been modelled as a lumped mass without considering the sloshing effect on the top and intermediate storey in different numbers. Analysis is done using response spectrum method as per IS 1893 (Part I): 2002. Building models are considered with plan and vertical irregularities with different H/D ratios. The TMD system is modelled with 3% of total weight of the floor. All the models with and without TMDs are analyzed by ETABS and checked for time period, base shear and storey drift. It is found that the buildings modelled with three TMDs using 3-Gauss points at the intermediate storey showed maximum benefits. The performance of the building under earthquake loads are found to be improved with TMD.

G. R. Patil, K. D. Singh (2015), focus their research on the evaluation of sloped bottom tuned liquid damper to reduce the seismic response of tall buildings. Finite element method is used to model a ten storey two bay RC frame of height 35m and the liquid in the TLD. The model is analyzed for the sinusoidal ground motion. MATLAB code is developed to study the response of structure, the coupled fluid-structure interaction and the liquid sloshing in the tank. It is found that with 100%, 94% and 90% tuning, the reduction in response is 64%, 18% and 5% respectively. It is observed that the slope bottom TLD uses less amount of liquid than flat bottom TLD and the efficiency of slope bottom TLD can be improved if it is properly tuned.

Ali Ashasi-Sorkhabi, et al (2014), investigated the use of multiple tuned liquid dampers in vibration control. In this study multiple TLDs are designed to increase the effectiveness of control of vibration instead of designing a single TLD and tuning it to the first mode of vibration of the structure. Analytical solution and numerical simulations of multiple tuned liquid damper systems is presented in this paper.

Multiple shallow water tanks are designed to suppress the vibrations in a multi degree of freedom system and the sloshing properties (i.e. frequency & mass ratios) of TLDs are tuned based on the modal properties (i.e. modal frequencies & effective modal masses) of the MDOF structure. After the analytical findings, numerical simulations are done for both harmonic & earthquake loads. It is found that using MTLDs in MDOF structure and tuning them w.r.t the modal properties of structure results in improved vibration control compared to single TLD.

Emili Bhattacharjee, et al (2013), conducted an investigation on the performance of unidirectional tuned liquid damper (TLD) for changing the dynamic characteristics of a structure and dissipation of vibration energy under harmonic excitation. The performance of the TLD depends on the motion of shallow liquid in a rigid tank. One rectangular and one square tuned with different water depth ratios varying from 0.05 to 0.3 are examined for different frequency ratios and time histories of accelerations are precisely measured by shaking table tests. The behavior of the TLD is also examined for the changed orientation of rectangular TLD subjected to given range of harmonic excitation frequencies. TLD tanks made up of acrylic sheets with 4mm thick side walls and base plate are placed on the structural model of mild steel plate which is supported on four high tensile steel rods of size (6 x 6 x 500) mm. The slabs and base plates are connected to column by welding. It is found that square TLD is less effective than rectangular TLDs in controlling the response of the structure.

T. Novo, H. Varum, et al (2012), conducted a study of an earthquake protection system, tuned liquid damper, which can reduce earthquake demands on building if designed adequately. This effect is accomplished by taking into account the sloshing of free surface of the fluid inside a tank. The behavior of an isolated TLD subjected to sinusoidal excitation at its base, with different displacement amplitudes, was studied by finite element analysis. The efficiency of the TLD was also evaluated based on linear dynamic analysis. This paper presents a study of an earthquake protection system applied to an existing nine storeyed RC building. The analysis is done in ANSYS and SAP 2000. It is found that TLDs can be adopted as effective measure for efficient increase in energy dissipation and damping of the system.

Matt Jackson SE, et al (2010), suggested that more efficient and high performance tall structures can be designed considering the dynamic performance of a building separately from the strength needs of a tower. An example of this approach is shown for a 40-storey tower in New York of area 860,000 sq. ft which has 22psf weight of steel work and 7 viscous dampers. It is observed that the damped outrigger system offers more benefits with lower capital cost, reduced space and reduced maintenance compared to conventional tuned mass damper system. The damped outrigger system absorbs energy at all ranges of motion and is beneficial in high seismicity areas.

D. Ostermann (2009), conducted a study on the behavior of tuned liquid dampers experimentally and analytically. A small scale experiment is done and results are compared to an analytical solution. A liquid damper is located on the top of the concrete plate which is supported by 4 steel columns. The force between the liquid damper and concrete plate and as well the displacement of the concrete plate is measured. The natural frequency of the tuned liquid damper which depends on the form of the tank and the height of the liquid in it, should be tuned with the first natural frequency of the building. It is found that the damper mass of only 1% mass of the building is sufficient to reduce amplitude of vibrations by 50%.

K. K. F. Wong (2008), investigated the energy transfer process in improving the ability of an inelastic structure to dissipate earthquake input energy using a TMD. The force analogy method is employed to model the inelastic structural behavior. Numerical simulations are performed on a 6-storey moment resisting steel frame to study the energy responses of structures with or without TMD. It is found that use of TMD is effective in suppressing the plastic energy dissipation and damage in the structure but the effectiveness of TMD diminishes of the structure becomes plastic at a small displacement level. In this case, the structure's response becomes same as those without TMD.

O. Corbi (2006), studied the possibility of coupling Sloshing Water Dampers with rigid blocks moving on a foundation base subject to a horizontal ground motion. An experimental investigation is done on aluminium blocks moving by pure rocking, using shaking table facility and dynamic responses are compared for the blocks with or without the devices for various liquid levels of the tanks.

Nawawi chouw (2004), conducted a study on behavior of soil structure system with TMD during earthquakes. This paper addresses the influence of a tuned mass damper on the behavior of a frame structure during ground excitations. The effect of soil- structure interaction is considered and the natural frequency of the tuned mass damper is varied. A four storey frame structure is considered for the study. The TMD has damping ratio of 10% or 30%. The result shows that in both cases the effectiveness of TMD increases with time. It is found that the TMD is most effective if its natural frequency is equal to 85% of fundamental frequency of the considered system. It is observed that the effectiveness of the considered TMD depends not only on the frequency ratio and damping ratio, but also on the soil structure interaction and characteristic of ground motions.

III. Conclusions

Based on the study done, it can be concluded that TLD can be effectively used to reduce the structural response during dynamic excitation when properly designed with efficient design parameters such as tuning ratio, depth ratio and mass ratio. The natural frequency of a TLD can be easily adjusted by varying height of liquid in the tank. The required water level should be maintained in the tank by providing an exit pipe at some height. It is found that the TLD located near the centre of mass and rigidity of an irregular building shows maximum reduction in response as compared to TLD located away from it. Tuned liquid dampers have attracted significant attention as a result of easy installation, low initial cost, low maintenance, ease of frequency tuning, easy implementation on existing building and functional use of water used.

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