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Experimental and Numerical Study on a New Double-walled Tuned Liquid Damper

V. R. Meshkat Rouhani, G. Zamani Ahari*, H. Saeed Monir

Department of Civil Engineering, Faculty of Engineering, Urmia University, Urmia, Iran

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ABSTRACT

To endure strong ground motions in large earthquakes, structures need to be equipped with tools to damp the huge amounts of energy induced by these excitations. In conventional buildings, seismic energy is often handled by a combination of rigidity-ductility measures and energy dissipation solutions. Since these buildings often have very low damping capability, the amount of energy dissipated within their elastic behavior phase tends to be negligible. Passive dampers are vibration control systems that can serve as valuable tools for controlling strong forces and reducing the probability of structural failure under seismic loads. In Tuned Liquid Dampers (TLDs), energy is dissipated by exploiting the behavior and characteristics of the liquid contained in the damper's tank. When the structure is subjected to external stimuli, the force transferred to the damper starts moving the liquid that lies stationary in the damper's tank, getting dissipated in the process. There are various classes of TLDs with different tank shapes, aspect ratios, and mechanisms of action, each with its properties and features. Another cause of energy dissipation in TLDs, in addition to the viscosity of the liquid, is the base shear force that is applied to the damper's intersection with the main structure with a phase difference relative to the external excitation, because of the difference between hydrostatic forces exerted on the walls at the two ends of the tank. Therefore, the level of liquid interaction with the damper's walls is also a determinant of the damping of external forces and thus the seismic response of the structure. The study investigated a new type of TLD with a double-walled cylindrical tank. To examine the effect of this TLD on the seismic response, a series of models were built with different liquid heights in the tank's inner and outer walls and subjected to several seismic excitations on a shaking table. The results showed that using this type of damper reduced the seismic response of the structures. Also, the reduction in seismic response was found to change significantly with the amount of liquid in the damper.

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NOMENCLATURE

Ms	Surface wave magnitude	PGV	Peak ground velocity
D	Focal depth	PGA	Peak ground acceleration
PGD	Peak ground displacement		

1. INTRODUCTION

To endure strong ground motions in large earthquakes, structures need to be equipped with tools to damp the huge amount of energy induced by these motions. This can be done through methods such as increasing the damping capability of the structure, which will allow it to absorb, damp, and reflect some portion of the input energy, thus reducing the amount of energy transferred to the structure and therefore the level of energy dissipation required for structural members, which allows the structure to be constructed with less ductility. One of the common methods of vibration control in large structures is to use tuned liquid dampers (TLDs). The most common form of TLD is the one consisting of a half-filled water tank that is rigidly mounted on the top floors of the main structure (usually the last floor) of the building. The tanks of TLDs can be built with a variety of geometries, including rectangular and circular shapes (rectangular tanks tend to be somewhat heavier than circular tanks).

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*Corresponding Author Institutional Email: *g.zamani@urmia.ac.ir*
(G. Zamani Ahari)

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One of the main causes of energy dissipation in TLDs is the viscosity of the water moving inside the tank in steady and turbulent states, which can be strengthened mechanically by placing mesh screens inside the tank compartment. Another important cause of energy dissipation in these dampers is the base shear force that is applied to the place where the damper is attached to the main structure with a phase difference relative to the external excitation because of the difference in hydrostatic force on the walls at the two ends of the tank. Instead of water tanks, TLDs can be built with interconnected tube-shaped containers with columns of liquid moving inside. This modified version of TLD is called the Tuned Liquid Column Damper (TLCD). Since TLDs fall in the category of passive dampers, another group of TLDs called the Active Tuned Liquid Column Damper (ATLCD) have also been designed by combining TLCD with an active mechanism, which offers higher effectiveness in controlling the oscillation amplitude and acceleration response of the structure.

In [1], it was stated that in Japan, where earthquakes are common and strong seismic activities can cause catastrophic damages every 2 or 3 years, structures of a refinery, petrochemical, chemical, and other such plants have to be designed and constructed to endure such seismic loads. In these plants, the equipment called pressure vessels, which must work under high pressures and temperatures, are often designed to endure these operating loads rather than seismic loads. However, in cylindrical tanks where the integrity is determined by the seismic loads, the structure may be designed with thin walls and the contained liquid can more easily interact with the structure. Thus, during an earthquake, the motion of the contained liquid can damage the wall or roof of the cylindrical tank or cause the liquid to spill out of the tank, causing fire [1].

TLD is a passive vibration control device consisting of a rigid tank filled with water that relies on the movement of water inside it to dissipate energy. Research has shown that TLD is more effective when it has a larger base acceleration amplitude because this allows it to dissipate more energy through increased fluid movement. This feature has been emphasized in some TLD configurations. In one of such configurations, the damper is rigidly connected to a secondary mass, which itself is connected to the main structure through a spring system. This alternative configuration is known as the Hybrid Mass Liquid Damper (HMLD). It should be noted that when the secondary spring is stiff, the alternative and standard TLD configurations will be similar. It has been observed that for a given structure with HMLD, there is an optimal secondary spring stiffness at which the effectiveness of HMLD will be maximal [2].

In [3], researchers studied the effect of various components of the earthquake on the motion response of liquid storage tanks. Firstly, they reviewed the theories that are commonly used for the unidirectional analysis of liquid behavior in cylindrical tanks. Then they used the Finite Element Modeling (FEM) method to simulate the dynamic response of the liquid tank system. To validate the FEM method, they applied it to a set of experimental data available in the literature. They then conducted a parametric study on a series of vertical cylindrical tanks with different aspect ratios under various earthquake acceleration time series, where each tank was subjected to unidirectional and bidirectional excitations. They also examined the suggestions of some seismic codes for the estimation of Maximum Sloshing Wave Height (MSWH) and evaluated the accuracy of the proposed prediction methods numerically. In the end, the simple equation available for estimating MSWH under unidirectional excitation was extended for bidirectional excitation [3].

As structures become taller and thinner, their vibrational response and weight become increasingly challenging design considerations. TLDs are cost-effective vibration dampers that can be used to suppress structural vibrations. In TLDs, energy is dissipated through the friction of the liquid boundary layer and wave breaking. The potential behaviors of TLDs and their interaction with structures could be very complex. In [4], an advanced experimental method called the Real-Time Hybrid Simulation (RTHS) was used to conduct a comprehensive parametric study to evaluate the effectiveness of TLDs. In RTHS, the effect of TLD is determined experimentally while the structure is modeled and analyzed, and this allows the TLD structure interactions to be determined in real-time. By treating the structure as an analytical model, RTHS offers a unique level of flexibility in the analysis. In this study, researchers considered a wide range of values for parameters including TLD/structure mass ratio, TLD/structure frequency ratio, and structural damping. They also experimentally evaluated the accuracy of FVM/FEM, which combines the finite element method (FEM) with finite volume method (FVM), in the modeling of liquid and solid domains to capture the TLD-structure interactions. The results of this study provided a better understanding of TLDs and their interaction with structures and also contributed to the advanced design of these devices [4].

In another study, researchers investigated the application of TLDs in reducing wind-induced vibrations of base-isolated structures. They modeled TLD as an equivalent linearized mechanical system where natural frequency and damping of the fluid motion are amplitude-dependent. These researchers also modeled the base-isolated structure as a modified version of the linearized Bouc-Wen model, so that the behavior of Stable Unbonded Fiber Reinforced Elastomeric Isolators (SU-FREIs) could be described. They combined TLD and base-isolated structures to form a system of coupled ordinary differential equations. They also presented a preliminary TLD design method for determining the proper tank dimensions and screen properties. The equivalent linearized mechanical model was validated through time simulations of the nonlinear behavior of the structure and fluid. This study reported that TLD can serve as an effective means to control wind-induced vibrations of base-isolated structures [5].

Crowley and Porter studied the effect of screens on the natural frequency and performance of TLDs. The experimental investigations of these researchers showed that the screen's solidity ratio is usually determined for using TLD as a means of frequency shift [6, 7]. When a TLD is subjected to large amplitude excitations, because of the horizontal velocity component in the wave motion, the wave threshold decreases as the amplitude increases. This is known as wave breaking. At this stage, simple linear models can no longer describe the behavior of the liquid, and the wave breaking changes the motion frequency of the liquid [8]. Furthermore, this complex nonlinear phenomenon affects the shear force generated due to TLD and the motion of the structure, an effect that is difficult to model accurately. Various numerical and experimental studies have been carried out on the use of other configurations of TLDs, including TLCDs, in suppressing the structural vibrations induced by seismic and wind loads [9, 10]. In [11], researchers studied the seismic interaction of tall buildings and TLDs with internal screens by replacing TLDs with equivalent amplitude-dependent tuned mass dampers (TMDs). In these models, parameters of equivalent TMDs were applied to the equation of motion of structures with the assumption that TLD is of the single degree of freedom type [11]. The majority of previous experimental studies and nonlinear modeling efforts have been focused on understanding the behavior of rectangular or circular TLDs. However, Love and Tait [12] developed a nonlinear multivariate model to describe the behavior of liquid inside a flat tank with arbitrary geometry. They also used a modal expansion technique for the nonlinear simulation of TLDs with damping screens [13]. Recently, Malekghasemi et al. [14] presented a new analytical method using the finite volume and finite element methods (FVM and FEM) for modeling the liquid and solid domains of TLDs. In this FVM/FEM model, the fluid and solid domains are discretized independently, and the interaction between the two domains is represented by alternating iterations at the interface.

A tuned liquid damper (TLD) is a passive vibration control device consisting of a rigid tank filled with water that relies on the motion of water inside it for energy dissipation. In a TLD with a standard configuration, the damper is rigidly connected to the top of the building structure. Research has shown that TLD is more effective when the base acceleration amplitude is larger, as increased liquid motion results in more energy dissipation. This feature has been used in alternative TLD configurations. In one alternative configuration, the damper is rigidly connected to a secondary mass, which itself is connected to the main structure through a spring system. This alternative configuration is known as the Hybrid Mass Liquid Damper (HMLD). For a secondary spring with a given stiffness, the TLD base is subjected to a large amplitude acceleration that increases its effect. It should be noted that when the secondary spring is stiff, the alternative and standard TLD configurations will be similar. It has been reported that for a given structure with HMLD, there is an optimal secondary spring stiffness at which the effectiveness of HMLD will be maximal. The optimized HMLD configuration has shown to be a more effective control device than the standard TLD configuration for both harmonic and large earthquake motions [2]. As structures become taller and thinner, their vibrational response and weight become increasingly challenging design considerations. TLDs are cost-effective vibration dampers that can be used to suppress structural vibrations. In TLDs, energy is dissipated through the friction of the liquid boundary layer, free surface interactions, and wave breaking. The dynamic features of TLD and its interaction with the structure are quite complex. In a study, an advanced experimental method called the Real-Time Hybrid Simulation (RTHS) has been used to conduct a comprehensive parametric study to evaluate the effectiveness of TLDs. In RTHS, the effect of TLD is determined experimentally while the structure is modeled by a computer, and this allows the TLD structure interactions to be determined in real-time. By treating the structure as an analytical model, RTHS offers unique flexibility that allows a wide range of parameters to be tested without changing the experimental setting. In this study, a wide range of values for parameters including TLD/structure mass ratio, TLD/structure frequency ratio, and structural damping have been considered. Also, the accuracy of FVM/FEM, which combines finite element method (FEM) with finite volume method (FVM), in the modeling of liquid and solid domains to capture the TLD-structure interactions have been experimentally investigated. The results of this study offer a better understanding of TLDs and their interaction with structures and also contributes to the advanced design of TLDs, which in turn may result in wider use of these devices [4].

An important cause of energy dissipation in TLDs, in addition to the viscosity of the liquid, is the difference between hydrostatic forces on the walls at the two ends of the tank and the phase difference relative to the external excitation. Therefore, it can be stated that the level of liquid interaction with the damper's walls is a determinant of the damping of forces applied to the structure. Thus, the more the liquid collides with the tank wall, or in other words the higher the contact level between the liquid and the walls, the greater will be the capacity for energy dissipation.

In an experiment, the TLD-adjusted fluid on a reduced shear frame under harmonic loads was also investigated. In this research, a seismic table test is applied to 3-layer shear frame models with TLD under harmonic loading. In the first stage, free vibration tests are performed on the structure, and first, the free vibration frequency of the structure is determined. Displacement and acceleration are measured in different classes of structures. A container in the form of a rectangular prism is then created as a TLD model. The liquid is poured into a container and the same experiments are repeated at different heights of the liquid. The effect of the TLD program on structural models concerning displacement and acceleration of structures has been investigated. As a result of the experiments performed, most TLD models are determined by changing behavior and acceleration. The results show that all damping models significantly reduce the level of seismic behavior of the structure under harmonic loading [4].

In another experiment, instead of using TLD, TLCD was used under the same conditions as before. As a result of the experiments performed, the most convenient TLCD models are determined according to the displacement behavior. The results show that all damping models significantly reduce damping in the seismic behavior of structures under harmonic loading. Experimental results show that all TLCD models effectively reduce the response of the structure in terms of displacement [4].

Also, series of experimental studies were performed on tuned liquid column damper as an effective device for seismic control in structures [17].

In this study, through series of shaking table tests and statistical analysis, the efficiency of Uniform Tuned Liquid Column Damper (UTLCD) in structures resting on loose soils, considering soil-structure interaction was investigated. Through statistical analysis of the experimental tests was demonstrated that the mentioned factors are effective in response to the structure. Using Response Surface Methodology (RSM), the optimum values of the factors to minimize the top story displacement have been found. [4].

The tuned liquid column damper (TLCD) having a uniform cross-sectional tube of U-shaped, occupied with liquid is used as a vibrational response mitigation device. Different studies on the unconstrained optimization performance of TLCBD subjected to the stochastic earthquake have been performed where limitations on the maximum amplitude of liquid present in the vertical portion of the tube were not imposed. The present investigation considers the optimum performance of the structure with TLCBD for mitigating the vibrational response with limited liquid movement in the vertical portion of the tube. A numerical study has been carried out to demonstrate the difference between constrained and unconstrained optimization of the structure-TLCBD system. Numerical results show the influence of constraining cases on optimum parameters and performance behavior of the structure-TLCBD system[4].

The innovation of the proposed TLD model in the current study versus TLDs with a similar mechanism is that, by doubling the water reservoir, the behavior of water movement in the outer and the inner tank becomes different. There are two relaxation conditions at the bottom of the reservoirs. The internal wall network controls the water movement, and in this way an appropriate damping behavior is created.

The present study investigated the behavior of a TLD with a double-walled cylindrical tank, where using the double-walled design is intended to increase the interaction of the liquid with walls and thus the capability of better damping. For this investigation, the following objectives were pursued:

1. Investigating the optimal liquid height, which depends on the optimal weight of the liquid relative to the total weight of the structure
2. Investigating the effect of liquid type on the effect of dampers on the seismic response of the structure

In the damper considered in this research, the interaction between the liquid and tank walls has been increased by using two walls with placing fins between them.

2. EXPERIMENTAL INVESTIGATION

The TLD considered in this research is a cylindrical damper with two walls, an inner wall and an outer wall, with a diameter of 30 and 50 cm, respectively. The walls are interconnected with fins at two different levels, which control the interaction of the liquid with the tank. The diagram of this TLD is shown in Figure 1.

For this investigation, several laboratory specimens with and without this TLD were constructed and subjected to several seismic records on the shaking table. The liquid used in this study was water. The height of the water column in the inner and outer wall was considered as a variable. To investigate the effects of the damper on the seismic response of the structure on the shaking table, the displacement and acceleration history of the specimens with the damper was studied and compared with that of the specimens without the damper.

The shaking table of the laboratory is 3×2 meters in size, has a weight capacity of 6 tons, and can produce a maximum acceleration of 1g and displacement of ±10 cm at frequencies of up to 50 Hz. This table provides one-dimensional movements. The constructed structure was restrained against lateral movements by four roller supports and was free to move only in the longitudinal direction of the shaking table. The measurements were made with four acceleration sensors and two displacement sensors. One acceleration sensor was mounted on the table floor, another was installed on the foundation, and the other two were placed on the floors in the middle of the floor beam. The test setup and details are shown in Figures 2 to 7. The dimensions of the damper and the specifications of the studied models are mentioned in Table 1 and Table 2, respectively.

A good level of consistency was observed between the accelerations recorded on the table and the foundation, indicating the suitable rigidity of the table. Since the goal was to measure the relative displacement of the foundation and the structure itself, a vertical 4×8 cm rectangular steel hollow section was installed on the foundation and the displacement sensors were mounted on this member in the middle of each floor. Thus, being connected to the foundation on one side and the structure on the other side, the displacement sensors were measuring the relative displacement during vibration.

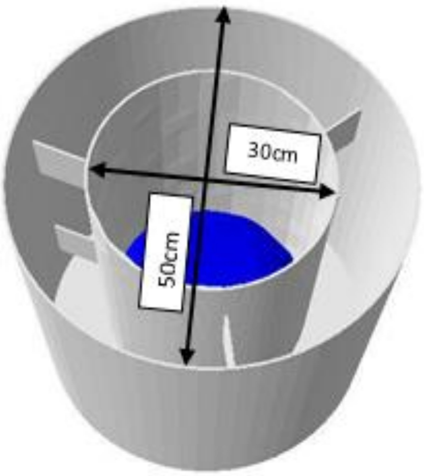


Figure 1. Three-dimensional diagram of the double-walle TLD

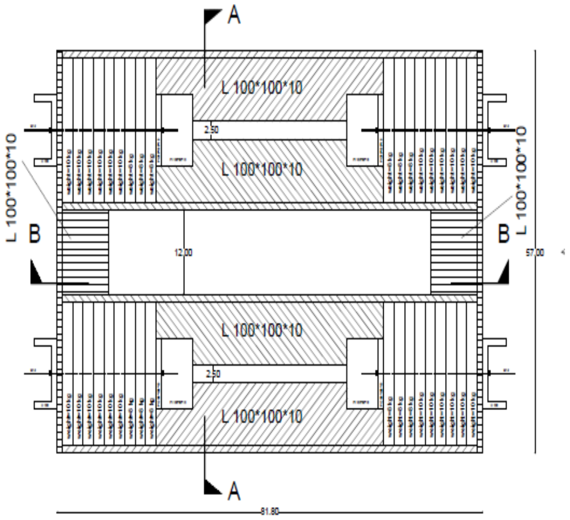


Figure 2. Plan of the structure with weights

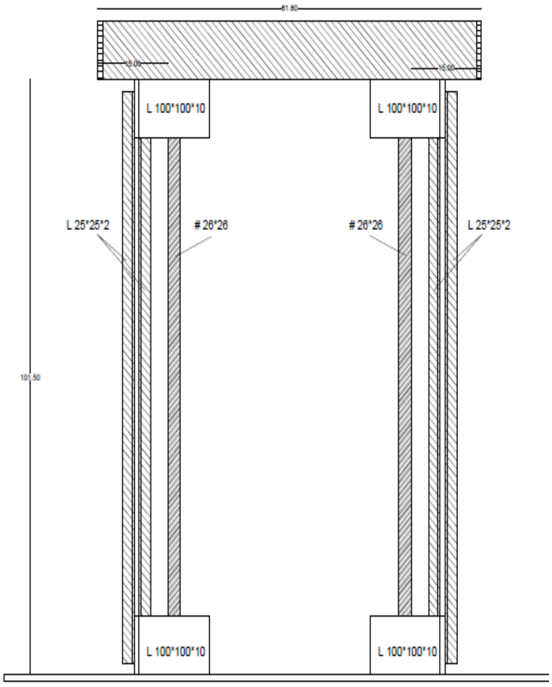


Figure 3. Transverse cross-section

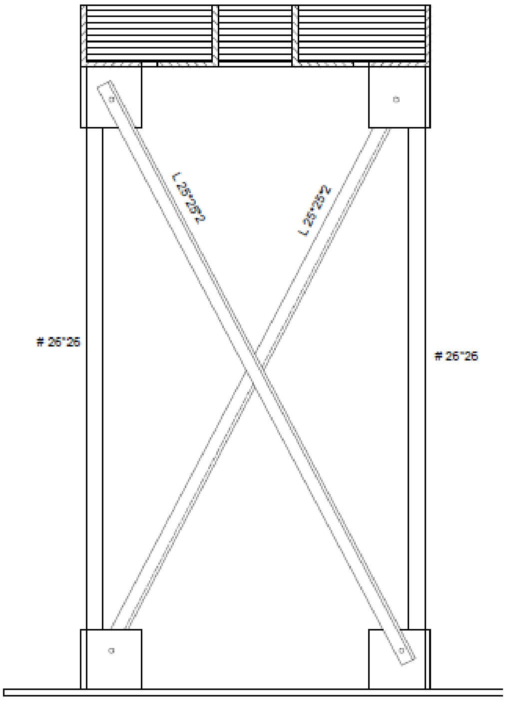


Figure 4. Longitudinal cross-section

Figure 5. Installation of the structure and the damper on th shaking table

Figure 6. Position of the strain gauge (LVDT) on the shakin table

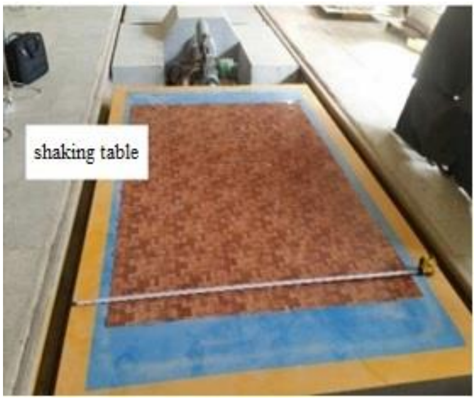


Figure 7. The shaking table used in the experiments

TABLE 1. Dimensions of the used damper

Dimension	Outer tank	Inner tank
Diameter	50 cm	30 cm
Height	60 cm	50 cm
Thickness	0.5 mm	0.5 mm

TABLE 2. Specifications of the studied models

Specimen	Liquid height in the inner tank (cm)	Liquid height in the outer tank (cm)
I0-O0	0	0
I0-O20	0	20
I0-O40	0	40
I15-O0	15	0
I15-O20	15	20
I15-O40	15	40
I30-O0	30	0
I30-O20	30	20
I30-O40	30	40

3. CHARACTERISTICS OF ACCELERATION RECORDS

Three earthquake records were used to investigate the effects of the double-walled TLD on the seismic response on the shaking table. The characteristics of these records are given in Table 3.

4. RESULTS

4. 1. Displacement Results

This section presents and discusses the displacement history of the models with and without the considered TLD under different seismic excitations. In this section, the comparisons are made to the results of model I0-O0, where the outer and inner tanks are empty. The displacement history diagrams of the models for the El Centro, Tabas, and Kobe records are illustrated in Figures 8 to 15, Figures 16 to 23, and Figures 24 to 31, respectively. In the following, these results are also tabulated for better and more accurate comparisons. To obtain these results, first, the height of the water in the inner tank was assumed to be variable while keeping the height of the liquid in the outer tank constant. Then, the height of the water in the outer tank was taken as a variable while keeping the height of the liquid in the inner tank constant. Finally, the height of the water in both inner and outer tanks was assumed as a variable. It should be noted that all the results presented in the following tables are relative to the I0-O0 model.

TABLE 3. Characteristics of acceleration records used in the shaking table experiment

Record	Symbol	Ms	d (km)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)
El Centro 1940	El Centro	6.95	6.1	312.7	36.1	21.3
Kobe 1995	Kakogawa	6.9	22.5	317.8	26.8	8.8
Tabas 1978	Tabas	7.35	1.79	837.8	98.8	37.5

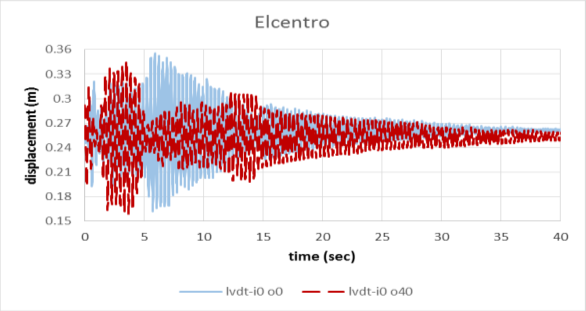


Figure 8. Comparison of the displacement history diagram
the I0-O40 model under the El Centro record

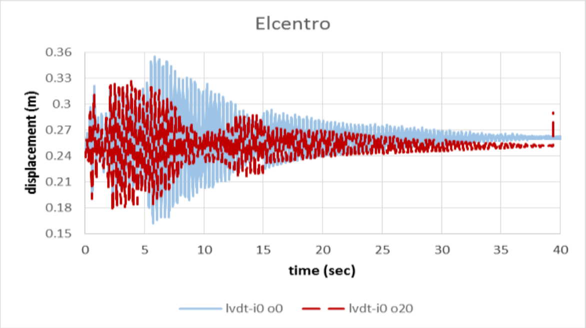


Figure 9. Comparison of the displacement history diagram
the I0-O20 model under the El Centro record

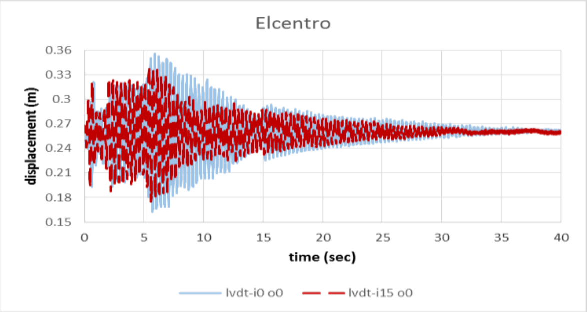


Figure 10. Comparison of the displacement history diagram
the I15-O0 model under the El Centro record

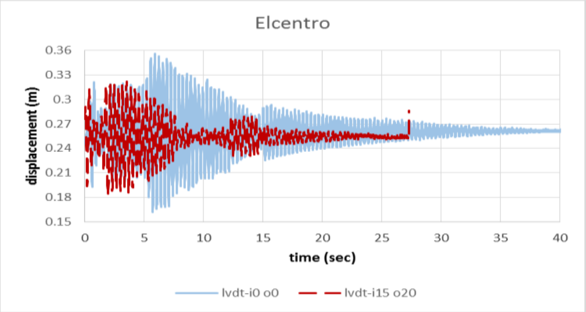


Figure 11. Comparison of the displacement history diagram
the I15-O20 model under the El Centro record

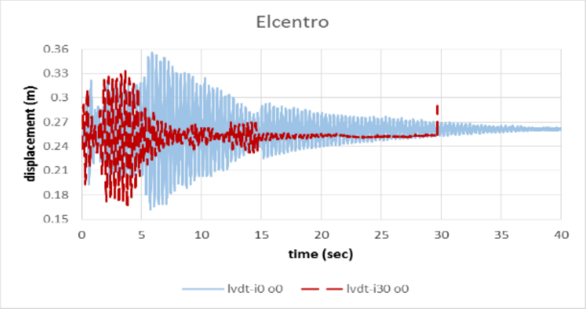


Figure 12. Comparison of the displacement history diagram
the I30-O0 model under the El Centro record

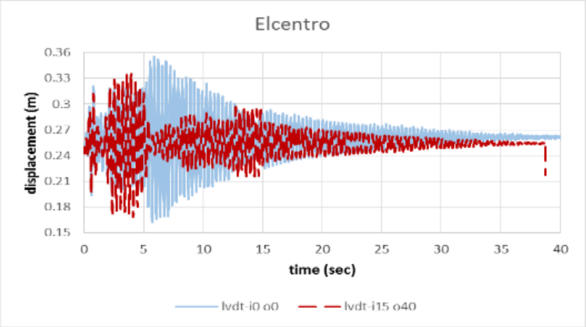


Figure 13. Comparison of the displacement history diagram
the I15-O40 model under the El Centro record

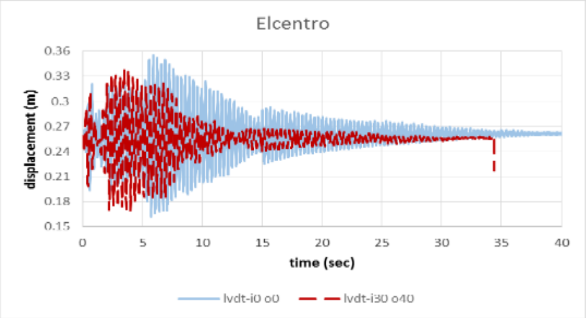


Figure 14. Comparison of the displacement history diagram
the I30-O40 model under the El Centro record

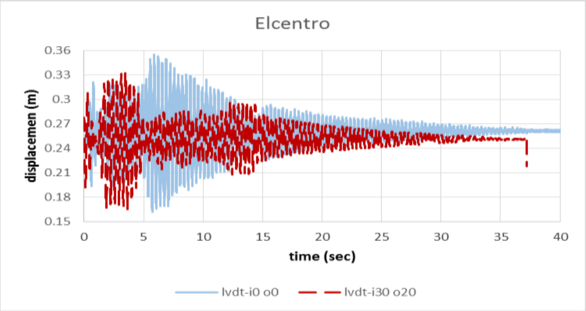


Figure 15. Comparison of the displacement history diagram
the I30-O20 model under the El Centro record

As the above diagrams demonstrate, the displacement history diagram under the El Centro record shows greater variation in the I0-O0 model than in others. Regarding the effect of liquid, the results suggest that the presence of liquid in the tank has reduced the displacement. The best possible result, i.e., the lowest displacement, under this excitation has occurred when the liquid height in the inner and outer tanks has been 15 cm and 20 cm, respectively.

The maximum displacement of all models under the El Centro record and their displacement reduction ratios relative to I0-O0 are provided in Tables 4 and 5, respectively.

TABLE 4. Effect of the liquid in the inner and outer tanks of the considered TLD on the displacement response under the El Centro record

Effect of the liquid in the outer tank on the displacement response under the El Centro record

Specimen	I0-O0	I0-O20	I0-O40	I15-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
Max. Disp. (m)	0.35	0.326	0.344	0.340	0.322	0.336	0.332	0.332.	0.339

Effect of the liquid in the inner tank on the displacement response under the El Centro record

Specimen	I0-O0	I15-O0	I30-O0	I0-O20	I15-O20	I30-O20	I0-O40	I15-O40	I30-O40
Max. Disp. (m)	0.35	0.340	0.332	0.326	0.322	0.332	0.344	0.336	0.339

TABLE 5. Displacement reduction ratio relative to I0-O0 under the El Centro record

Specimen	I0-O0	I0-O20	I0-O40	I1-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
%	__	8%	3%	4.20%	9.20%	5.30%	6.40%	6.30%	4.50%

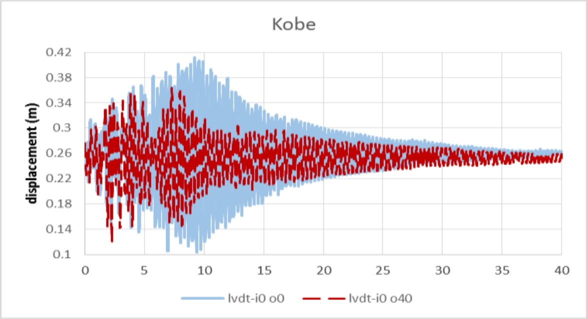


Figure 16. Comparison of the displacement history diagram of the I0-O40 model under the Kobe record

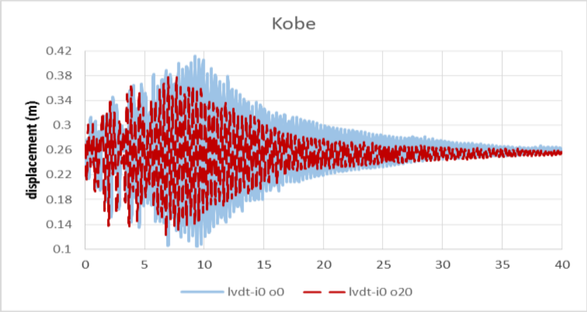


Figure 17. Comparison of the displacement history diagram of the I0-O20 model under the Kobe record

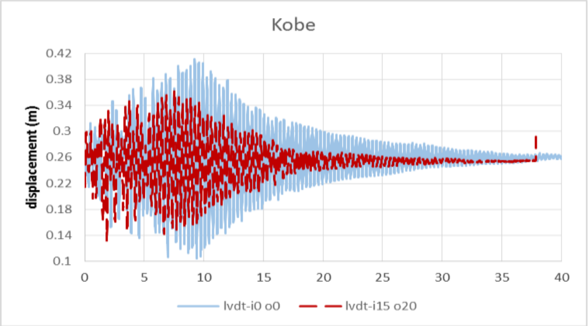


Figure 18. Comparison of the displacement history diagram of the I15-O20 model under the Kobe record

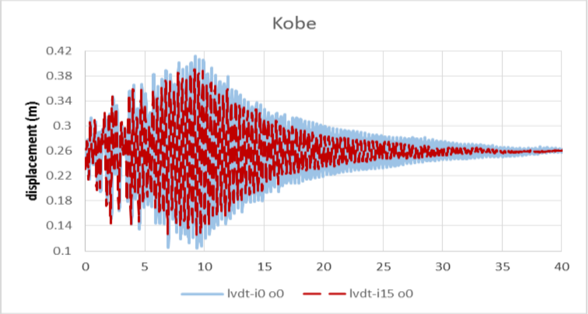


Figure 19. Comparison of the displacement history diagram of the I15-O0 model under the Kobe record

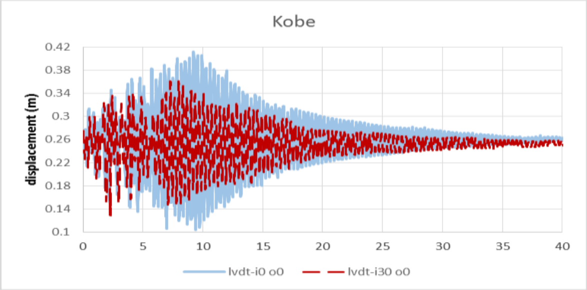


Figure 20. Comparison of the displacement history diagram of the I30-O0 model under the Kobe record

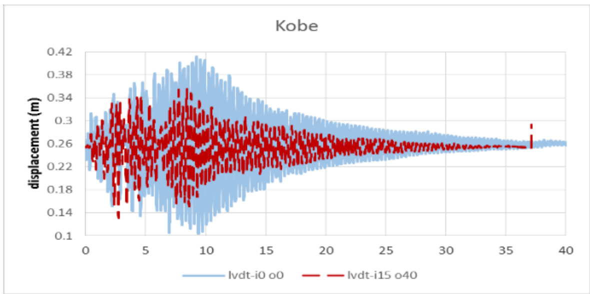


Figure 21. Comparison of the displacement history diagram of the I15-O40 model under the Kobe record

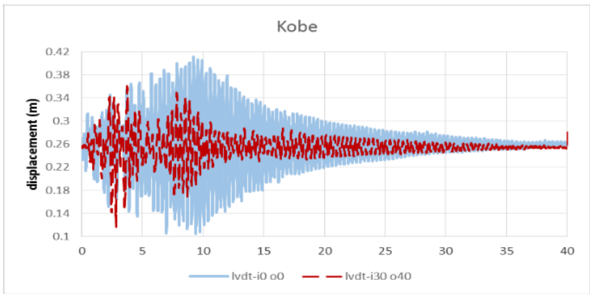


Figure 22. Comparison of the displacement history diagram of the I30-O40 model under the Kobe record

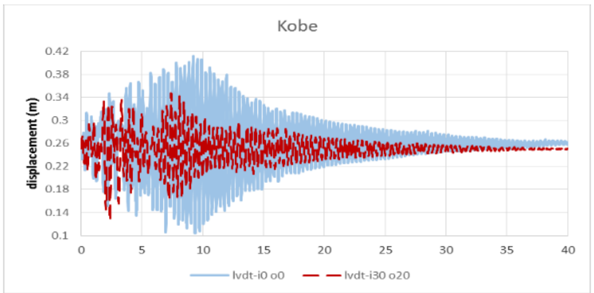


Figure 23. Comparison of the displacement history diagram of the I30-O20 model under the Kobe record

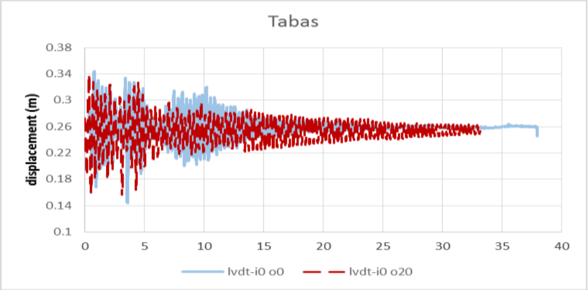


Figure 24. Comparison of the displacement history diagram c the I0-O20 model under the Tabas record

In the above diagrams, it can be seen that under the Kobe record, the displacement history diagram of the I0-O0 model has greater variation than that of other models. These results also show that the presence of liquid in the tank has resulted in reduced displacement. The lowest displacement under the Kobe record has occurred when the liquid height in the inner and outer tanks has been 30 cm and 20 cm, respectively.

Tables 6 and 7 show the maximum displacement of all models under the Kobe record and their displacement reduction ratios relative to I0-O0.

TABLE 6. Effect of the liquid in the inner and outer tanks of the considered TLD on the displacement response under the Kobe record

Effect of the liquid in the outer tank on the displacement response under the El Centro record									
Specimen	I0-O0	I0-O20	I0-O40	I15-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
Max. Disp. (m)	0.411	0.377	0.363	0.390	0.363	0.355	0.36	0.347	0.361
Effect of the liquid in the inner tank on the displacement response under the El Centro record									
Specimen	I0-O0	I15-O0	I30-O0	I0-O20	I15-O20	I30-O20	I0-O40	I15-O40	I30-O40
Max. Disp. (m)	0.411	0.390	0.36	0.377	0.363	0.347	0.363	0.355	0.361

TABLE 7. Displacement reduction ratio relative to I0-O0 under the Kobe record

Specimen	I0-O0	I0-O20	I0-O40	I1-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
%	__	8.20%	11.70%	5.10%	11.67%	13.70%	12.40%	15.50%	12.16%

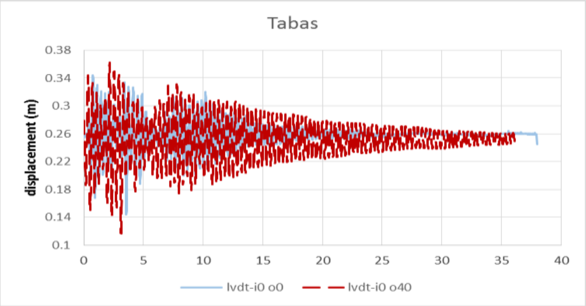


Figure 25. Comparison of the displacement history diagram
the I0-O40 model under the Tabas record

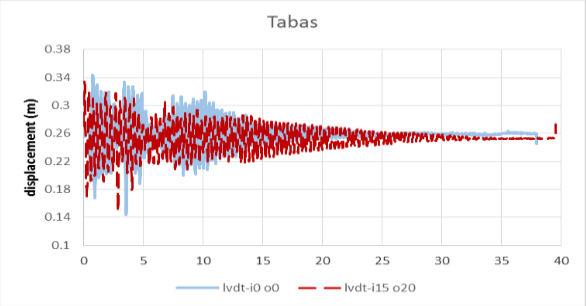


Figure 26. Comparison of the displacement history diagram
the I15-O20 model under the Tabas record

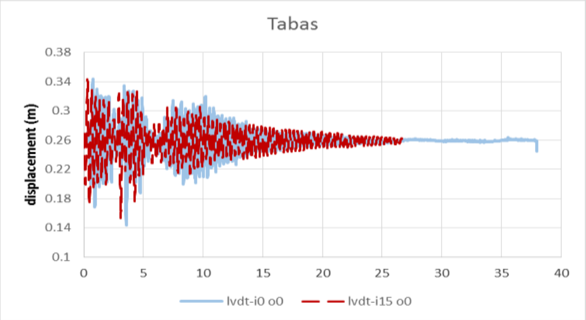


Figure 27. Comparison of the displacement history diagram
the I15-O0 model under the Tabas record

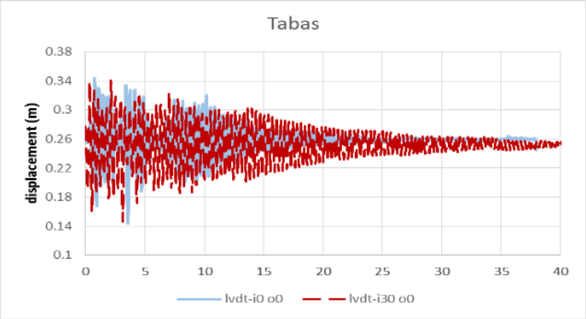


Figure 28. Comparison of the displacement history diagram
the I30-O0 model under the Tabas record

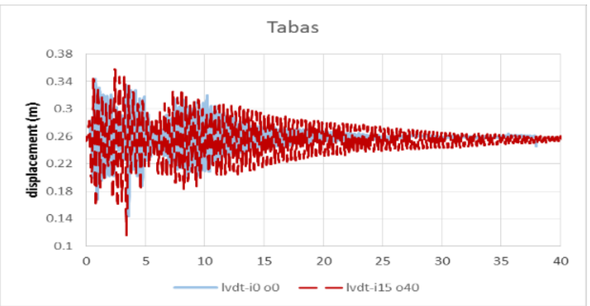


Figure 29. Comparison of the displacement history diagram
the I15-O40 model under the Tabas record

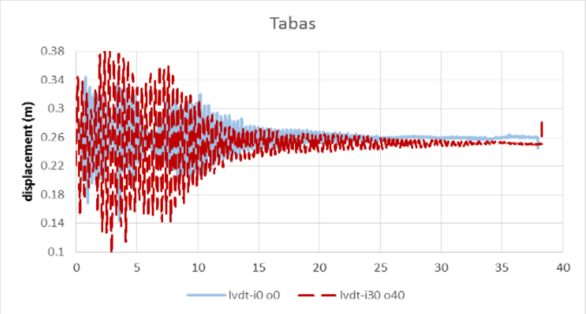


Figure 30. Comparison of the displacement history diagram
the I30-O40 model under the Tabas record

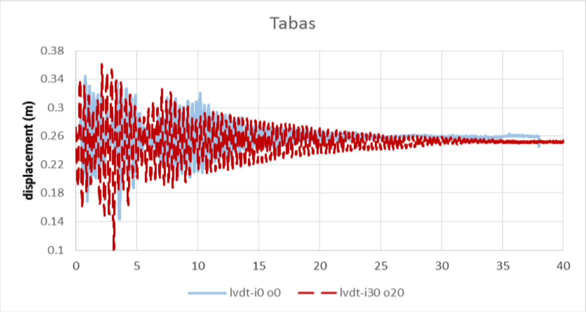


Figure 31. Comparison of the displacement history diagram
the I30-O20 model under the Tabas record

In the above diagrams, it can be seen that unlike under Kobe and El Centro records, the displacement history diagram with the greatest variation under the Tabas record is the one belonging to the I30-O40 model. This means that under the Tabas record, the considered TLD not only does not have a positive effect but increases the displacement. Regarding the effect of liquid, the results suggest under the Tabas record, the presence of liquid in the tank has reduced the displacement in some cases and increased it in others. Under this record, the lowest displacement has occurred when the liquid height in the inner and outer tanks has been 15 cm and 20 cm, respectively.

The maximum displacement values of all models under the Tabas record are given in Table 8 and the displacement reduction ratios of these models relative to I0-O0 are provided in Table 9.

4. 2. Acceleration Results

This section presents the acceleration history of the models with and without the considered TLD under the seismic excitations of El Centro, Tabas, and Kobe records. As before, all comparisons made in this section are relative to the results obtained with I0-O0. The acceleration history diagrams of the models for the El Centro, Tabas, and Kobe records are presented in Figures 32 to 39, Figures 40 to 47, and Figures 48 to 55, respectively. For a more accurate comparison, these results are also presented in more detail in the following tables. Again, to obtain these results, first, the height of the water in the inner tank was assumed to be variable and the height of the liquid in the outer tank was kept constant. Then, the height of the water in the outer tank was considered to be variable and the height of the liquid in the inner tank was kept constant. And finally, the height of the water in both inner and outer tanks was assumed to be variable. As mentioned, all the results presented in the tables are relative to the results of the I0-O0 model.

As can be seen, the greatest variation in the acceleration history diagram under the El Centro record belongs to the I0-O40 model. Regarding the effect of liquid, the results show that the presence of liquid in the tank has reduced the acceleration in some cases and increased it in others. The best possible result or in other words the lowest acceleration under this excitation has occurred when the liquid height in the inner and outer tanks has been 30 cm and 40 cm, respectively.

The maximum acceleration of all models under the El Centro record and their acceleration reduction ratios relative to I0-O0 are given in Tables 10 and 11, respectively.

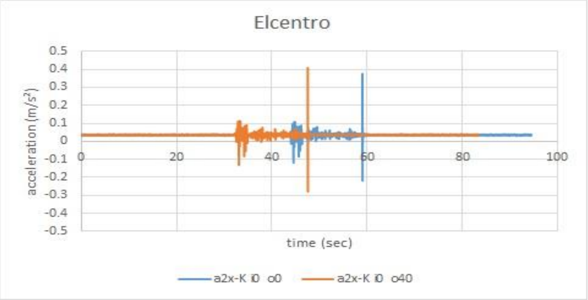


Figure 32. Comparison of the acceleration history diagram
the I0-O40 model under the El Centro record

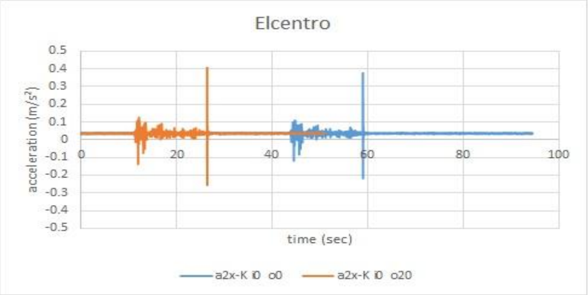


Figure 33. Comparison of the acceleration history diagram
the I0-O20 model under the El Centro record

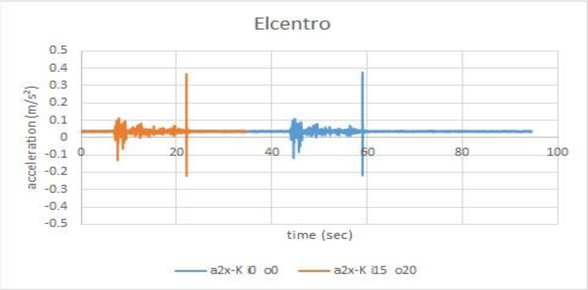


Figure 34. Comparison of the acceleration history diagram
the I15-O20 model under the El Centro record

TABLE 8. Effect of the liquid in the inner and outer tanks of the considered TLD on the displacement response under the Tabas record

Effect of the liquid in the outer tank on the displacement response under the El Centro record

Specimen	I0-O0	I0-O20	I0-O40	I15-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
Max. Disp. (m)	0.343	0.339	0.362	0.342	0.334	0.358	0.340	0.360	0.400

Effect of the liquid in the inner tank on the displacement response under the El Centro record

Specimen	I0-O0	I15-O0	I30-O0	I0-O20	I15-O20	I30-O20	I0-O40	I15-O40	I30-O40
Max. Disp. (m)	0.343	0.342	0.340	0.339	0.334	0.360	0.362	0.358	0.400

TABLE 9. Displacement reduction ratio relative to I0-O0 under the Tabas record

Specimen	I0-O0	I0-O20	I0-O40	I1-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
%	__	1%	5%	0.20%	2.60%	4.30%	0.80%	4.90%	16.60%

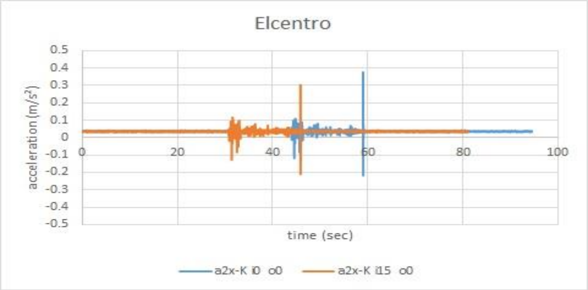


Figure 35. Comparison of the acceleration history diagram c the I15-O0 model under the El Centro record

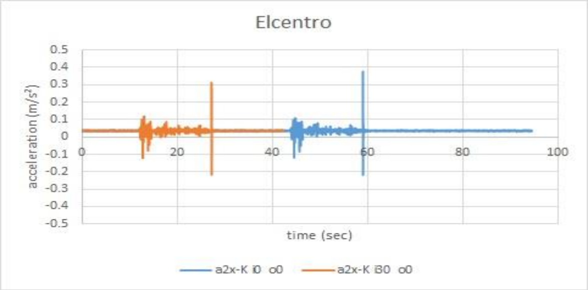


Figure 36. Comparison of the acceleration history diagram c the I30-O0 model under the El Centro record

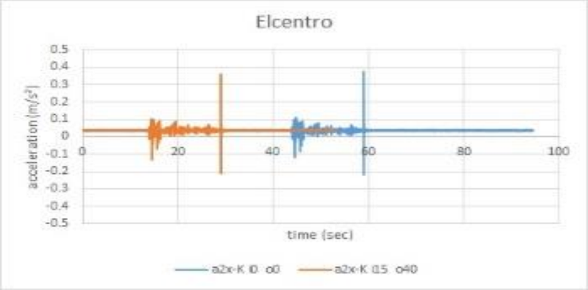


Figure 37. Comparison of the acceleration history diagram c the I15-O40 model under the El Centro record

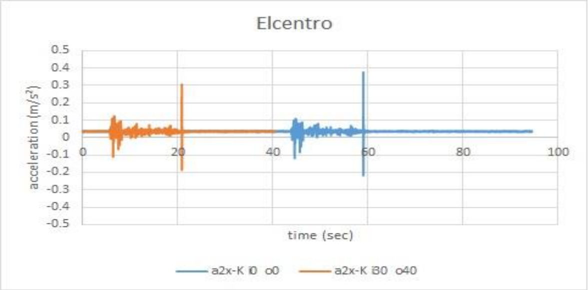


Figure 38. Comparison of the acceleration history diagram c the I30-O40 model under the El Centro record

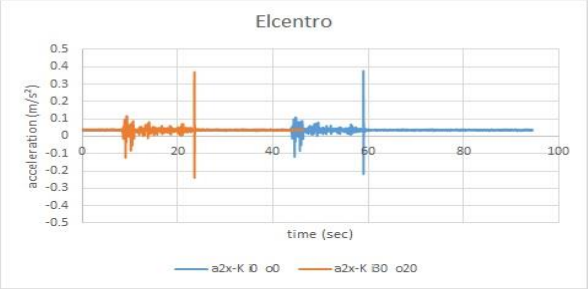


Figure 39. Comparison of the acceleration history diagram c the I30-O20 model under the El Centro record

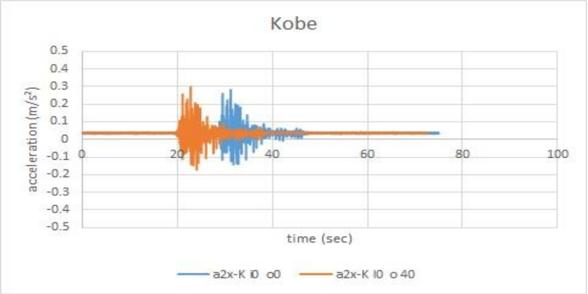


Figure 40. Comparison of the acceleration history diagram c the I0-O40 model under the Kobe record

TABLE 10. Effect of the liquid in the inner and outer tanks of the considered TLD on the acceleration response under the El Centro record

Effect of the liquid in the outer tank on the acceleration response under the El Centro record									
Specimen	I0-O0	I0-O20	I0-O40	I15-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
Max. Acc.(m/s^2)	0.376	0.406	0.406	0.301	0.365	0.356	0.310	0.369	0.296
Effect of the liquid in the inner tank on the acceleration response under the El Centro record									
Specimen	I0-O0	I15-O0	I30-O0	I0-O20	I15-O20	I30-O20	I0-O40	I15-O40	I30-O40
Max. Acc.(m/s^2)	0.376	0.301	0.310	0.406	0.365	0.369	0.406	0.356	0.296

TABLE 11. Acceleration reduction ratio relative to I0-O0 under the El Centro record

Specimen	I0-O0	I0-O20	I0-O40	I1-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
%	__	7.90%	8%	19.40%	2.90%	5.30%	18%	1.80%	21.20%

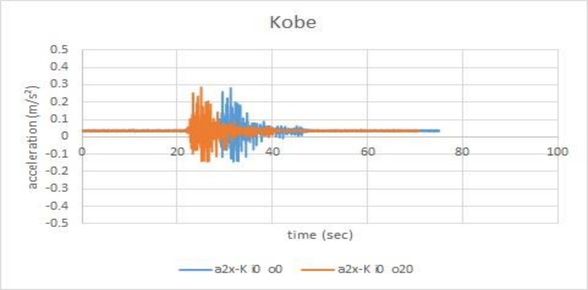


Figure 41. Comparison of the acceleration history diagram c the I0-O20 model under the Kobe record

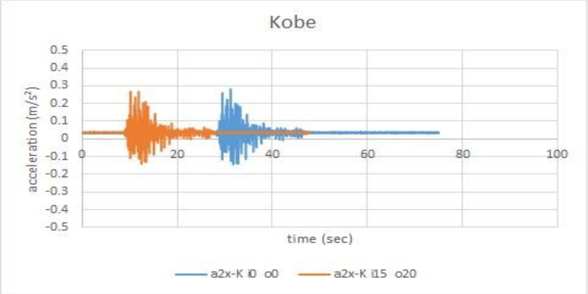


Figure 42. Comparison of the acceleration history diagram c the I15-O20 model under the Kobe record

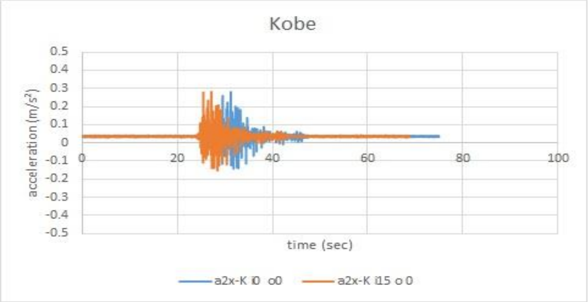


Figure 43. Comparison of the acceleration history diagram c the I15-O0 model under the Kobe record

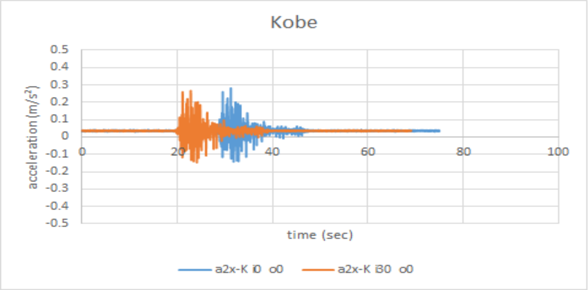


Figure 44. Comparison of the acceleration history diagram c the I30-O0 model under the Kobe record

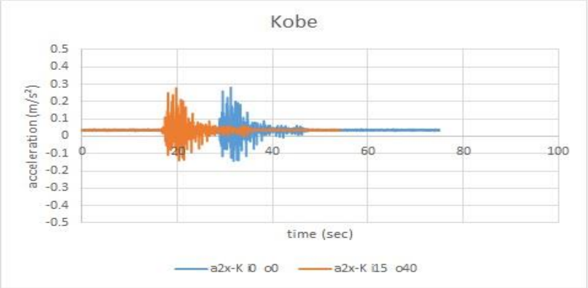


Figure 45. Comparison of the acceleration history diagram c the I15-O40 model under the Kobe record

4. 3. Numerical Investigation

In this part of the study, the finite element software ABAQUS was used for modeling. The structure, tank, and water inside the tank were all modeled with the C3D8R elements as shown in Figures 56 to 58.

The C3D8 element is an eight-node three-dimensional solid linear element with reduced integration.

4. 4. Modelling Verification

All laboratory experiments were modeled in ABAQUS software and the analytical models were verified in comparison to the

TABLE 14. Effect of the liquid in the inner and outer tanks of the considered TLD on the acceleration response under the Tabas record

Effect of the liquid in the outer tank on the acceleration response under the Tabas record

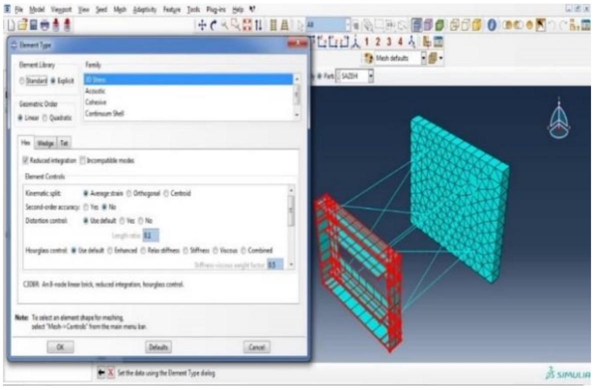
Specimen	I0-O0	I0-O20	I0-O40	I15-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
Max. Acc.(m/s^2)	0.179	0.182	0.180	0.194	0.178	0.176	0.184	0.190	0.173

Effect of the liquid in the inner tank on the acceleration response under the Tabas record

Specimen	I0-O0	I15-O0	I30-O0	I0-O20	I15-O20	I30-O20	I0-O40	I15-O40	I30-O40
Max. Acc.(m/s^2)	0.179	0.194	0.184	0.182	0.178	0.190	0.180	0.176	0.173

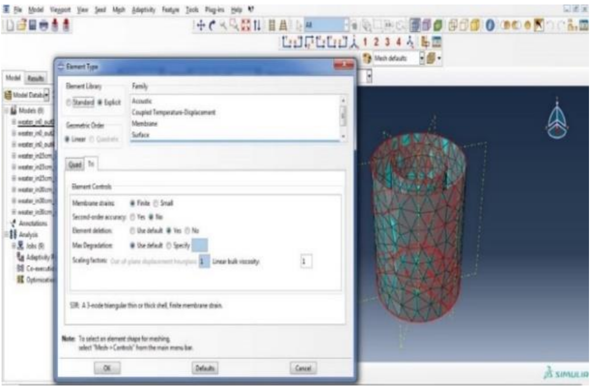
TABLE 15. Acceleration reduction ratio relative to I0-O0 under the Tabas record

Specimen	I0-O0	I0-O20	I0-O40	I1-O0	I15-O20	I15-O40	I30-O0	I30-O20	I30-O40
%	__	1.60%	1%	8.30%	0.50%	1.60%	2.70%	6.10%	3.30%



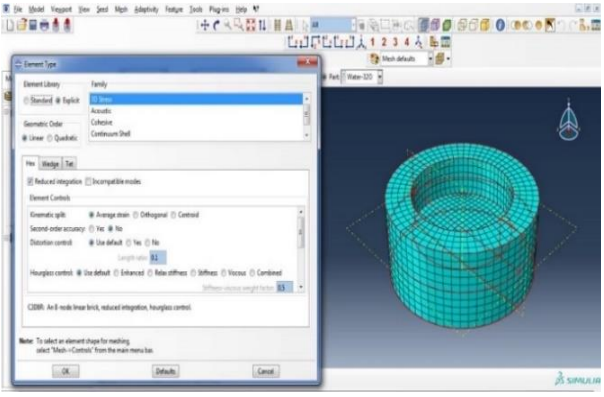
C3D8R: An 8-node linear brick, reduced integration, hourglass control.

Figure 56. Modeling of the structure in ABAQUS



S3R: A 3-node triangular thin or thick shell, finite membrane strain.

Figure 57. Modeling of the tank in ABAQUS



C3D8R: An 8-node linear brick, reduced integration, hourglass control.

Figure 58. Modeling of the water inside the tank in ABAQUS

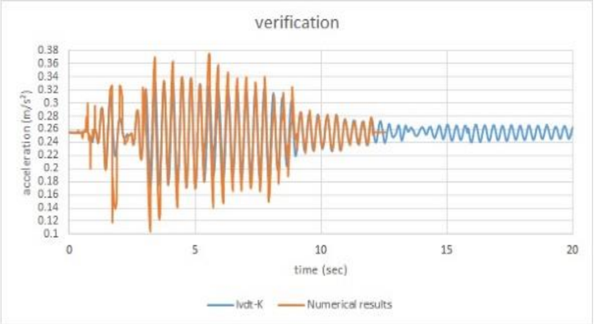


Figure 59. Comparison of analytical and experimenta acceleration responses, El Centro I30-O40

experiment results. Displacement and acceleration responses were used for model verification in various conditions. As an example, the verification of acceleration response of specimen I30-O40 subjected to the El Centro earthquake is shown in Figure 59.

4. 5. Numerical Results As the numerical investigation of the effect of the considered TLD, the height of water in the inner and outer tanks was considered as 130 and 320 mm, respectively. The results were obtained once without any water in the damper, another time by water only in the inner tank, and the third time by water only in the outer tank. The seismic record used in this investigation was that of the Varzeqan earthquake. The acceleration records of this earthquake are shown in Table 16.

To evaluate the performance of the proposed damper, the effect of water level on the outer and inner walls of the reservoir in reducing the response of the structure was numerically investigated. For this purpose, the results were studied in three scenarios; without water inside the damper, water inside the inner tank, and water inside the outer tank. The response parameters employed for this evaluation are lateral displacement, acceleration, and energy which some of which are shown in Figures 60 to 63.

The results of the study on the displacement history show that the amount of lateral displacement of the structure in the case of damping has been significantly reduced. It can also be observed that the amount of lateral displacement in the case where the fluid is located in the inner or outer wall of the damper is reduced by 50% compared to the waterless state.

TABLE 16. Characteristics of acceleration records of Varzeqan earthquake

Record	Symbol	d (km)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)
Varzeqan 2012	Varzeqan	9	478	41.23	9.45

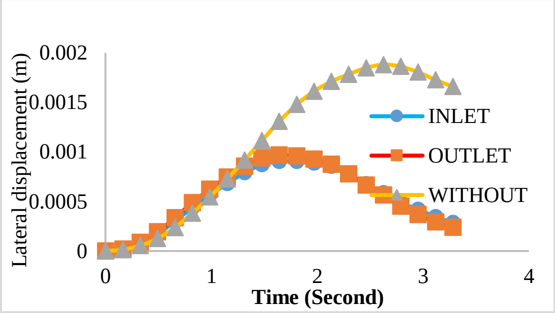


Figure 60. Numerical comparison of displacement history

From the experimental displacement and acceleration diagrams of the considered TLD modeling and analysis performed in this study, the following can be concluded:

- The models showed different displacement history results under different seismic excitations. Under El Centro and Kobe records, the I0-O0 model (the model without liquid) had a higher displacement than all liquid-containing models. This is indicative of the positive effect of the liquid on the displacement. Under the Tabas record, however, the highest displacement was observed in the model where the liquid height in the inner and outer tanks was 30 cm and 40 cm, respectively. This discrepancy can be attributed to different frequency characteristics of different records. Examining the amount of energy exerting the structure, it is observed that the damper greatly reduces the input energy, and the amount of this reduction in both types of dampers, whether the fluid is placed in the outer or inner wall, is approximately equal and reduced by 53%.

Moreover, the results of acceleration analysis show that the use of the damper also greatly reduces the amount of acceleration response.

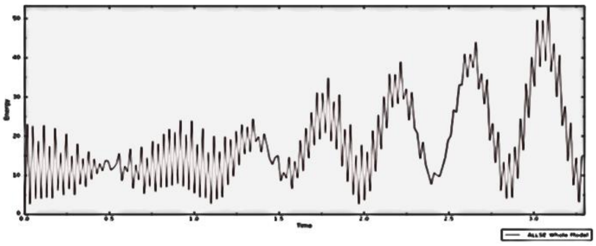


Figure 61. Numerical history of energy input when water wa placed in the inner tank of the damper

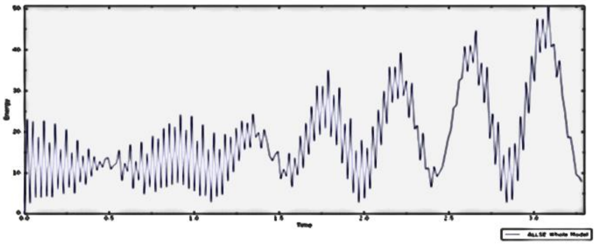


Figure 62. Numerical history of energy input when water was placed in the outer tank of the damper

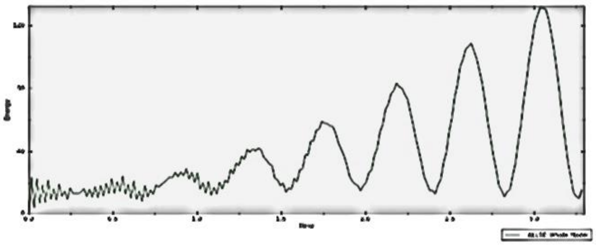


Figure 63. Numerical history of energy input in the absence c water in the damper

As an extension of the current study, the optimal state of the water amount in the modeling has been evaluated and a reduction of 16 to 33% has been achieved.

5. CONCLUSION

From the experimental displacement and acceleration diagrams of the considered TLD modeling and analysis performed in this study, the following can be concluded:

1. The models showed different displacement history results under different seismic excitations. Under El Centro and Kobe records, the I0-O0 model (the model without liquid) had a higher displacement than all liquid-containing models. This is indicative of the positive effect of the liquid on the displacement. Under the Tabas record, however, the highest displacement was observed in the model where the liquid height in the inner and outer tanks was 30 cm and 40 cm, respectively. This discrepancy can be attributed to different frequency characteristics of different records.
2. The lowest displacement was also found to somewhat vary depending on the applied seismic excitation.

For example, under the El Centro record, the lowest displacement (relative to I0-O0) was related to the model where the liquid height in the inner and outer tanks was 15 cm and 20 cm, respectively. But under the Kobe record, the lowest displacement belonged to the model I30-O20. Finally, under the Tabas record, the lowest displacement was again related to the model I15-O20.

3. Regarding the acceleration history, the results suggest that in certain cases the presence of liquid in the considered TLD significantly increases the acceleration instead of decreasing it. The highest acceleration under the El Centro and Kobe records occurred in the model I0-O40. Under the Tabas record, the highest acceleration was observed in the model I15-O0.
4. The lowest acceleration was also found to be dependent on the applied seismic excitation. Under the El Centro record, the lowest acceleration belonged to the model where the inner and outer tanks contained 30 cm and 40 cm of liquid respectively, which had a lower acceleration than I0-O0. The lowest acceleration under the Kobe record occurred in the model I30-O40. Finally, under the Tabas record, the lowest acceleration was observed in the model I30-O40.

6. REFERENCES

1. Shoji, Y. and Munakata, H., "Sloshing of cylindrical tank due to seismic acceleration", in Abaqus Users Conference, Newport, Rhode Island., (2008).
2. Banerji, P. and Samanta, A., "Earthquake vibration control of structures using hybrid mass liquid damper", ***Engineering Structures***, Vol. 33, No. 4, (2011), 1291-1301. doi:10.1016/j.engstruct.2011.01.006.

3. Goudarzi, M. and Sabbagh-Yazdi, S., "Evaluating 3d earthquake effects on sloshing wave height of liquid storage tanks using finite element method", ***Journal of Seismology and Earthquake Engineering***, Vol. 10, No. 3, (2020), 123-136.
4. Ashasi-Sorkhabi, A., Malekghasemi, H., Ghaemmaghami, A. and Mercan, O., "Experimental investigations of tuned liquid damper-structure interactions in resonance considering multiple parameters", ***Journal of Sound and Vibration***, Vol. 388, (2017), 141-153. doi:10.1016/j.jsv.2016.10.036.
5. Love, J., Tait, M. and Toopchi-Nezhad, H., "A hybrid structural control system using a tuned liquid damper to reduce the wind induced motion of a base isolated structure", ***Engineering Structures***, Vol. 33, No. 3, (2011), 738-746. doi:10.1016/j.engstruct.2010.11.027.
6. Crowley, S. and Porter, R., "An analysis of screen arrangements for a tuned liquid damper", ***Journal of Fluids and Structures***, Vol. 34, (2012), 291-309. doi:10.1016/j.jfluidstructs.2012.06.001.
7. Crowley, S. and Porter, R., "The effect of slatted screens on waves", ***Journal of Engineering Mathematics***, Vol. 76, No. 1, (2012), 33-57.
8. Reed, D., Yu, J., Yeh, H. and Gardarsson, S., "Investigation of tuned liquid dampers under large amplitude excitation", ***Journal of Engineering Mechanics***, Vol. 124, No. 4, (1998), 405-413. doi:10.1061/(ASCE)0733-9399(1998)124:4(405).
9. Gao, H., Kwok, K. and Samali, B., "Optimization of tuned liquid column dampers", ***Engineering Structures***, Vol. 19, No. 6, (1997), 476-486. doi:/10.1016/S0141-0296(96)00099-5.
10. Zhu, F., Wang, J.-T., Jin, F., Altay, O. and Hara, T., "Real-time hybrid simulation of single and multiple tuned liquid column dampers for controlling seismic-induced response", in Proceedings of the 6th International Conference on Advances in Experimental Structural Engineering., (2015).
11. Halabian, A. and Torki, M., "Numerical studies on the application of tuned liquid dampers with screens to control seismic response of structures", ***The Structural Design of Tall and Special Buildings***, Vol. 20, No. 2, (2011), 121-150. doi:10.1002/tal.515.
12. Love, J. and Tait, M., "Non-linear multimodal model for tuned liquid dampers of arbitrary tank geometry", ***International Journal of Non-Linear Mechanics***, Vol. 46, No. 8, (2011), 1065-1075. doi:10.1016/j.ijnonlinmec.2011.04.028.
13. Love, J. and Tait, M., "Nonlinear simulation of a tuned liquid damper with damping screens using a modal expansion technique", ***Journal of Fluids and Structures***, Vol. 26, No. 7-8, (2010), 1058-1077. doi:10.1016/j.jfluidstructs.2010.07.004.
14. Malekghasemi, H., Ashasi-Sorkhabi, A., Ghaemmaghami, A.R. and Mercan, O., "Experimental and numerical investigations of the dynamic interaction of tuned liquid damper–structure systems", ***Journal of Vibration and Control***, Vol. 21, No. 14, (2015), 2707-2720. doi:10.1177/1077546313514759.
15. Ersin, Aydin. Baki, Ozturk. Maciej, Dutkiewicz. Huseyin, Cetin. "Experiments of tuned liquid damper (TLD) on the reduced shear frame model under harmonic loads." In EPJ web of conferences (2017), Vol. 143, 02001.
16. Ersin, Aydin. Baki, Ozturk. "Experiments of tuned liquid column damper (TLCD) on the reduced shear frames under harmonic loads. "(2018) 16th European Conference on Earthquake Engineering (16ECEE), Thessaloniki, Greece.
17. Aydın, E., ÖZTÜRK, B., Batı, M., Kavaz, Y. and Kılıç, B., "Effects of tuned liquid column damper properties on the dynamic response of structures", ASCE-EMI 2019 International Conference, Lyon, France.
18. A. Sarlak, H. Saeedmonir, C. Gheyratmand. "Experimental Study on Using Uniform Tuned Liquid Column Damper for Structural Control of Buildings Resting on Loose Soil." ***International Journal of Engineering, Transactions A: Basics,*** Vol. 31, No. 7, (2018) 1028-1037. doi: 10.5829/ije.2018.31.07a.04.
19. S. Pal, B. K. Roy, S. Choudhury "Comparative Performance Study of Tuned Liquid Column Ball Damper for Excessive Liquid Displacement on Response Reduction of Structure" ***International Journal of Engineering, Transactions B: Applications,*** Vol. 33, No. 5, (2020) 753-759. doi:10.5829/ije.2020.33.05b.06.

Persian Abstract

چکیده

برای تحمل حرکات قوی زمین در زمین لرزه‌های بزرگ، سازه‌ها باید به ابزارهایی مجهز شوند تا مقادیر عظیم انرژی ناشی از این تحریکات را خنثی کنند. از آنجایی که این ساختمان‌ها اغلب قابلیت میرایی بسیار پایینی دارند، مقدار انرژی تلف شده در فاز رفتار الاستیک آنها ناچیز است. کلاس‌های مختلفی از TLDها با اشکال مخزن، نسبت ابعاد و مکانیسم‌های عمل متفاوت وجود دارد که هر کدام دارای خواص و ویژگی‌های خاص خود هستند. یکی دیگر از علل اتلاف انرژی در TLDها، علاوه بر ویسکوزیته مایع، نیروی برشی پایه است که به دلیل تفاوت بین نیروهای هیدرواستاتیکی، به تقاطع دمپر با ساختار اصلی با اختلاف فاز نسبت به تحریک خارجی وارد می‌شود. بر روی دیواره‌های دو سر مخزن اعمال می‌شود. بنابراین، سطح برهمکنش مایع با دیواره‌های میراگر نیز تعیین‌کننده میرایی نیروهای خارجی و در نتیجه پاسخ لرزه‌ای سازه است. این مطالعه نوع جدیدی از TLD را با یک مخزن استوانه‌ای دو جداره بررسی کرد. برای بررسی تأثیر این TLD بر پاسخ لرزه‌ای، یک سری مدل با ارتفاع‌های مایع مختلف در دیواره‌های داخلی و خارجی مخزن ساخته شد و تحت چندین تحریک لرزه‌ای بر روی میز لرزان قرار گرفت. نتایج نشان داد که استفاده از این نوع میراگر باعث کاهش پاسخ لرزه‌ای سازه‌ها می‌شود. همچنین، کاهش پاسخ لرزه‌ای به طور قابل توجهی با مقدار مایع در دمپر تغییر می‌کند.