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# Influence of Application of Tuned Liquid Dampers to Enhance Building Resistance to Earthquake

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**Abstract** A Tuned Liquid Damper (TLD) is a passive damper that is capable of reducing the dynamic response of a structure to earthquake through an anti-phase sloshing fluid mechanism that has been settled. TLD can be very effective for structural stability if its parameters are designed properly. The parameters that determine the effectiveness of the TLD are mass ratio, which is the ratio of the liquid mass to the structure mass, and frequency ratio, which is the ratio of the sloshing frequency to the natural frequency of the structure. This study investigated the performance of TLD in a building under different time history characteristics, which are classified as Near- and Far-Fault Earthquakes. In addition, six excitation frequency ratios were also investigated. A 15-story building with and without TLD was modeled using SAP2000. The building model was tested with various excitation frequency ratios and various ground motion characteristics. The reduction of peak displacement under time history and excitation frequency ratios has been investigated. The results show that TLD will be more effective under far-fault earthquakes and also if it is subjected to a dynamic load that is close to resonant frequency ($f_e/f_s \approx 1$).

**Keywords** Disaster Risk Reduction, Dynamic Load, Far Fault, Near Fault Time History, Tuned Liquid Damper

## 1. Introduction

Land availability in metropolitan regions is constantly decreasing due to continuous urbanization and industrialization. As a result, the demand for tall buildings has increased. The buildings that are designed must have appropriate structural strength while remaining cost-effective both during construction and operation. Tall buildings, on the other hand, are more vulnerable to dynamic forces like earthquakes and winds [1]. High-rise buildings are more vulnerable to earthquakes because of their higher displacements compared to shorter buildings. In high seismic zones, dampers are frequently used in the construction of tall buildings [2,3]. The use of dampers, such as a base isolator, is widely used but has an expensive cost that is not commensurate with the possibility of a strong earthquake [4]. A damper installed on the structure must have an affordable price commensurate with the possibility of a strong earthquake [5,6].

A Tuned Mass Damper (TMD) is one of the passive dampers. Tuned mass dampers require rubber bearings, springs, dashpots, and sophisticated mechanical components. The Tuned Liquid Damper (TLD) is a kind of damper that uses a mass of liquid as a damper instead of the pendulum mass. It has been applied to high-rise buildings. This damper model is more affordable because it uses liquid mass to substitute pendulum mass [7].

TLD is normally installed in a tank attached to the structure as a liquid mass. TLD's operating mechanism is based on vibrations that strike the structure and generate force as a result of the liquid sloshing. To suppress vibrations, the force due to this sloshing must be adjusted so that it is in exactly the opposite direction of the dynamic force [8]. TLD applications have been investigated in order to minimize vibrations in construction. Previous studies have developed an analytical model for TLD based on shallow water wave theory [7]. TLDs can efficiently control structural vibration if the parameters are properly designed [7]. The efficiency of the dampers is dependent on the frequency spectrum of the earthquake and the arrangement of the dampers, according to theoretical models created to anticipate the shallow motion of liquids in rectangular tanks. Reed [9] used laboratory tests and computer modeling to study the behavior of TLD. Based on his studies, it was discovered that the TLD response to large excitation amplitudes differs significantly from the TLD response to small excitation amplitudes due to changes in the probability of the appearance of waves on the liquid surface. Fujino [10] evaluated the effectiveness of multiple TLDs in damping structural vibrations and discovered that MTLD is more efficient for small vibration amplitudes and has the same results for large vibration amplitudes based on their experimental results. The influence of three different densities and viscosities of liquids in a TLD was explored by Ocak et al. [11]. They discovered that water was the optimum liquid. Dou [12] studied the influence of mass and frequency ratios in reducing vibrations of platform structure and found that a mass ratio of 2% and a frequency ratio of 1 provided the best responses.

The scope of the current research is limited to simple structures that can be evaluated in a laboratory. This study aims to investigate the effect of TLD application on building structures subjected to various excitation seismic loads. This investigation included a wide variety of ground motion characteristics as well as sine loads. In order to analyze the performance of a structure that utilizes TLD, it is also important to obtain a schematic model of TLD in order to perform various simulations.

## 2. Structural Design

The structural elements were designed using the SAP2000 program. The structural element design rules are in compliance with AISC 360-16 [13]. A specific moment-resistant frame structure was used as the structural system. SAP2000 is used to perform structural modeling in 3D models. Building structures are considered to be steel structures with special moment-resistant frames. It is also designed to be used as an apartment. The seismic load parameter will refer to the location in Surabaya, Indonesia.

For standards and codes for design, refer to SNI 1727:2020 [14] and SNI 1726:2019 [15]. Design considerations will include dead load, live load, and seismic load. The dead load consists of the self-weight of the structure and the super-dead load. The self-weight of the structure is calculated automatically using software with a steel density of 7850 kg/m$^3$. The super dead load is 89 kg/m$^2$ to consider the finishing material on an apartment. Live loads refer to all moving loads, including people, equipment, and other temporarily stored equipment. The live load determines the building's function. The designed live load for living space in the category of public space is 4.79 kN/m$^2$ [14].

The seismic load on building structures is analyzed using 3D structural models. The seismic region map from SNI-1726:2019 [15] is used to determine the response spectrum function. The seismic map zoning is used in compliance with SNI 1726:2019 [15]. The necessary risk category II facilities, such as residences, storehouses, markets, and office buildings, must follow the performance targets for earthquake-affected apartment buildings. The seismic parameters obtained are listed in Table 1.

**Table 1.** Seismic parameter

| Parameter | Value |
|---|---|
| Ss | 0.665 |
| S1 | 0.249 |
| Importance Factor, I | 1 |
| Reduction Factor, I | 8 |
| Site Class | E |
| $F_a$ | 0.9 |
| $F_v$ | 2.4 |

The design of structural elements is checked automatically using the SAP2000 program based on AISC 360-16 [13]. The demand/capacity ratio for all structural elements is less than 1, so the steel elements are strong enough to withstand the design loads as shown in Table 2.

**Table 2.** Demand/Capacity ratio

| Type of Element | Section Property | D/C Ratio |
|---|---|---|
| Column | WF400×400×12×19 | 0.946 |
| Beam-I | WF500×200×10×16 | 0.905 |
| Beam-II | WF300×150×6.5×9 | 0.494 |

## 3. Ground Motion Selection

This section will define specific categories of ground motions based on frequency characteristics. The frequency characteristics of the ground motions are related to peak ground acceleration (PGA), peak ground velocity (PGV), seismic-tectonic characteristics, and seismic location [16]. The two varieties of ground motions that have been chosen are Near Fault and Far Fault.

For each near-fault and far-fault ground motion, 6 data sets were extracted from the PEER database [17]. Bam 2003, Helena Montana 1935, Imperial-Valley 1979, Kobe 1995, Landers 1992, and Managua 1972 collected near-fault ground motions data. For Far Fault ground motions data, Borrego 1942, Chi-Chi 1992, Helena Montana 1935, Imperial-Valley 1979, Kobe 1995, Landers 1992, and Managua 1972 were used. Tables 3 and 4 show the acceleration, velocity, and time history spectra of the near-fault and far-fault ground motion's horizontal components, respectively.

**Table 3.** Near-fault ground motion

| Record | Station | Year | PGA | PGV (cm/s) |
|---|---|---|---|---|
| Bam | Bam | 2003 | 6.60 | 0.59 |
| Helena Montana | Carroll College | 1935 | 6.00 | 0.44 |
| Imperial-Valley | El Centro Array | 1979 | 6.53 | 0.43 |
| Kobe | Takatori | 1995 | 6.9 | 0.61 |
| Landers | Lucerne | 1992 | 7.28 | 0.44 |

**Table 4.** Far-fault ground motion

| Record | Station | Year | PGA | PGV (cm/s) |
|---|---|---|---|---|
| Borrego | El Centro Array | 1942 | 6.50 | 0.6 |
| Chi-Chi | Tap95 | 1999 | 7.62 | 0.15 |
| Coalinga-01 | Parkfield | 1983 | 6.36 | 0.24 |
| Kobe | Hik | 1995 | 6.90 | 0.14 |
| Irpinia | Arienzo | 1980 | 6.90 | 0.13 |

The speed and acceleration of near-fault ground motions appear to differ significantly from far-fault ground motions. Near-fault ground motions have higher acceleration and velocity than far-fault ground motions. This results in variances in the frequency content and characteristics. This variation has been designed to consider the potential for various seismic load characteristics and magnitudes.

Time history data is scaled based on the targeted PGA. The PGA target value for Surabaya, Indonesia is 0.3144g [18]. The magnitude of the scale factor is calculated by dividing the response value of the targeted spectrum by the PGA value of each time history data. The scalable time history can be obtained by knowing the scale factor.

# 4. Tuned Liquid Damper (TLD) Analysis

## 4.1. Calculation of TLD properties

The following is the procedure carried out to determine the Tuned Liquid Damper design that will be used in this study. A mass ratio of 4% and a frequency ratio of 1 were used in this study, which is an optimum parameter for TLD [12]. From the structural analysis, one can obtain natural frequency and structural mass as shown in Table 5.

**Table 5.** Natural frequency and structural mass

| Natural Frequency (Hz) | Structural mass (kN) |
|---|---|
| 1.06 | 7235.7 |

$$f_f = \gamma f_s \tag{1}$$

$$\frac{1}{2}\sqrt{\frac{g}{\pi L} tanh\left(\frac{\pi h_f}{L}\right)} = \gamma f_s \tag{2}$$

$$\frac{1}{4}\frac{g}{\pi L} tanh\left(\frac{\pi h_f}{L}\right) = (\gamma f_s)^2 \tag{3}$$

where, $f_f$ is frequency sloshing, γ is the frequency ratio between frequency sloshing and natural frequency of the structure, L is the length of the tank, and $h_f$ is the height of the fluid.

In order to reduce the impacts of the depth ratio D/L on sloshing waves and the natural frequency, D/L was maintained at 35%, which is a medium depth ratio value [12].

$$h_f = 0.35 L \tag{4}$$

$$\frac{1}{4}\frac{g}{\pi L} tanh(0.35\pi) = (\gamma f_s)^2 \tag{5}$$

$$L = \frac{1}{4}\frac{g}{\pi (\gamma f_s)^2} tanh(0.35\pi) \tag{6}$$

As a result of the effect of the difference in mass ratio, the calculation of the number of tanks required is as follows:

$$M_f = \mu M_s \tag{7}$$

$$n\ w\ h_f\ L\ \rho = \mu M_s \tag{8}$$

where $M_f$ is the mass of fluid, $M_s$ is the mass of the structure, n is the number of tanks, ρ is liquid density, and μ is the mass ratio.

For this study, a rectangular tank was used, leading to w = L, then:

$$n = \frac{\mu M_s}{h_f L^2 \rho} \tag{9}$$

To simulate the behavior of the TLD, simplification methods are used, namely the lumped mass method [19]. Hydrodynamic forces will occur due to the movement of liquid waves due to the dynamic forces that occur. The movement of this liquid wave is divided into two namely impulse pressure and sloshing pressure. The impulse pressure is proportional to the acceleration in the tank but in the opposite direction. While the sloshing pressure is related to the wave height and the sloshing frequency of the liquid [20]. The value of TLD properties has been estimated by Newmark and Jind [20].

$$M_o = \frac{tanh(1.7\frac{(\frac{L}{2})}{h_f})}{1.7\ (\frac{L}{2})/h_f} m_f \tag{10}$$

$$M_1 = \frac{0.83\ tanh(1.6\ h_f/(\frac{L}{2}))}{1.6\ h_f/(\frac{L}{2})} m_f \tag{11}$$

$$k = \frac{3\ g\ {M_1}^2\ h_f}{m_f\ L^2} \qquad (12)$$

$$\zeta_f = \sqrt{\frac{\upsilon_f\ \omega_f}{2}}\ \left[1 + \left(\frac{2h_f}{b}\right) + S\right]\ \frac{L}{h_f\ \sqrt{g\, h_f}} \qquad (12)$$

where $M_o$ represents the passive mass connected rigidly to the tank, $M_1$ represents the active mass connected to the springs with stiffness $k$, $\zeta_f$ represents the damping fluid, $\upsilon_f$ represents fluid viscosity, and $\omega_f$ represents frequency sloshing.

The results of the calculation of sloshing mass, impulse mass, stiffness, and TLD damping value for the building are given in Table 6.

**Table 6.** TLD properties

| Active Mass $M_1$ (kN) | Passive Mass $M_o$ (kN) | Stiffness TLD $k$ (kN/m) | Damping TLD $\zeta_f$ (kN s/m) |
|---|---|---|---|
| 277.86 | 185.00 | 2471.27 | 0.33 |

### 4.2. TLD Modeling

The calculated TLD properties are then assigned as link elements in SAP2000 modeling. The link element is attached to the column at the top of the structure to ensure that the energy generated by the excitation load is efficiently transferred to TLD.

A stiffness and damping value are assigned to the link element. The stiffness and damping in the u2 and u3 directions represent the stiffness and damping of set TLD in the x and y directions. The axial stiffness of the set TLD, which is not involved in the liquid motion, is the stiffness in the u1 direction.

The joint mass and joint load are applied at the free joint once the linear link has been formed. The joint load inputted in the vertical plane corresponds to the passive mass, whereas the joint mass inputted in the x and y axes corresponds to the active mass. In Figure 1, the input data is displayed.

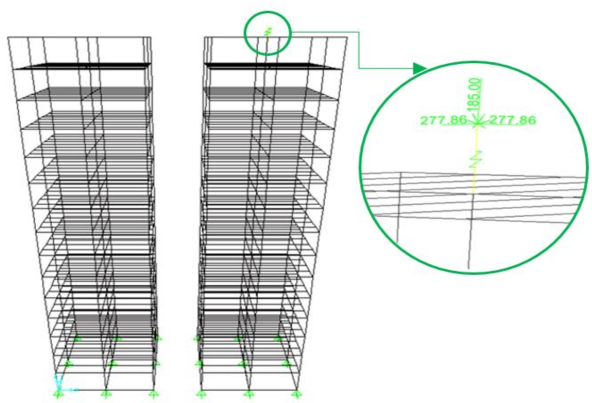


**Figure 1.** 3D structural model

## 5. Analytical Results and Discussion

### 5.1. Effect of Frequency Ratio

The following is the procedure carried out to determine the influence of the excitation frequency ratio on TLD performance, an investigation of displacement reduction was conducted for various excitation frequency ratios. A sine load is used to ensure that the excitation frequency is a single frequency. The frequency ratios used for excitation include 0.8, 0.9, 1, 1.1, 1.2, and 1.3. This excitation frequency ratio is the ratio between the sine load and the natural frequency of the structure.

When the excitation frequency is below the resonant frequency, the peak displacement reduction shows an increasing trend, as shown in Figure 2. When the excitation frequency ratio reaches 0.9-1, there is no significant displacement reduction. When the excitation frequency ratio is above the resonant frequency, displacement decreases significantly. This means that the excitation frequency ratio for a TLD-equipped structure should range between 0.90 and 1.

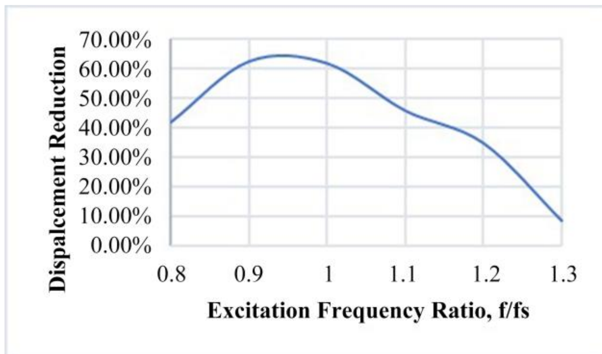


**Figure 2.** Displacement reduction vs, excitation frequency ratio

### 5.2. Effect of Ground Motion

To determine the effect of ground motion on TLD performance, an investigation of displacement reduction was also carried out for different ground motion characteristics. The ground motions were selected as mentioned in the previous section. The results of time history displacement for various ground motions were plotted in Figures 3 and 4. A clear comparison of peak displacement with different ground motions is shown in Figures 5 and 6.

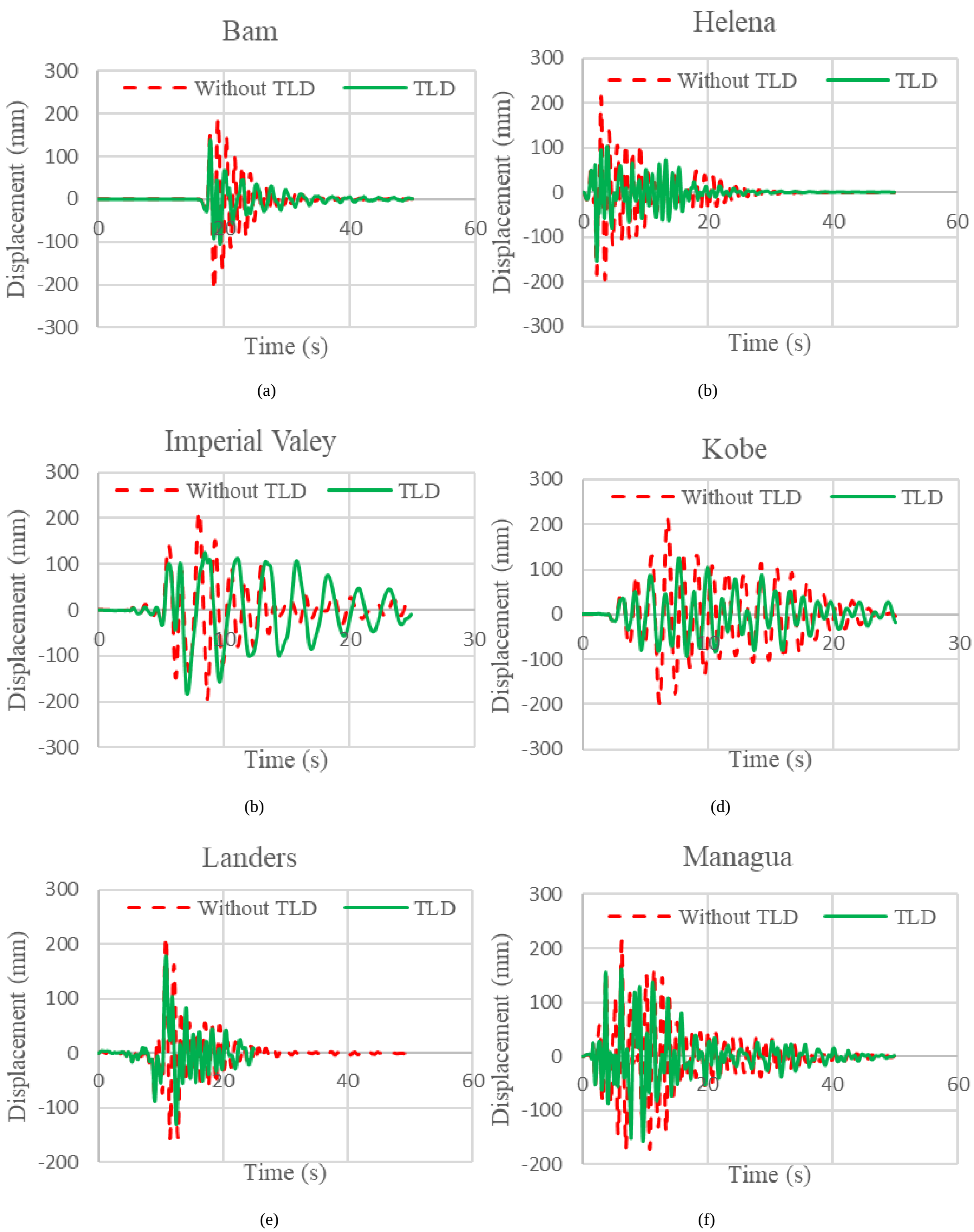


**Figure 3.** Plotted-function near-fault earthquakes: (a) Bam; (b) Helena Montana; (c) Imperial-Valley; (d) Kobe; (e) Landers; (f) Managua

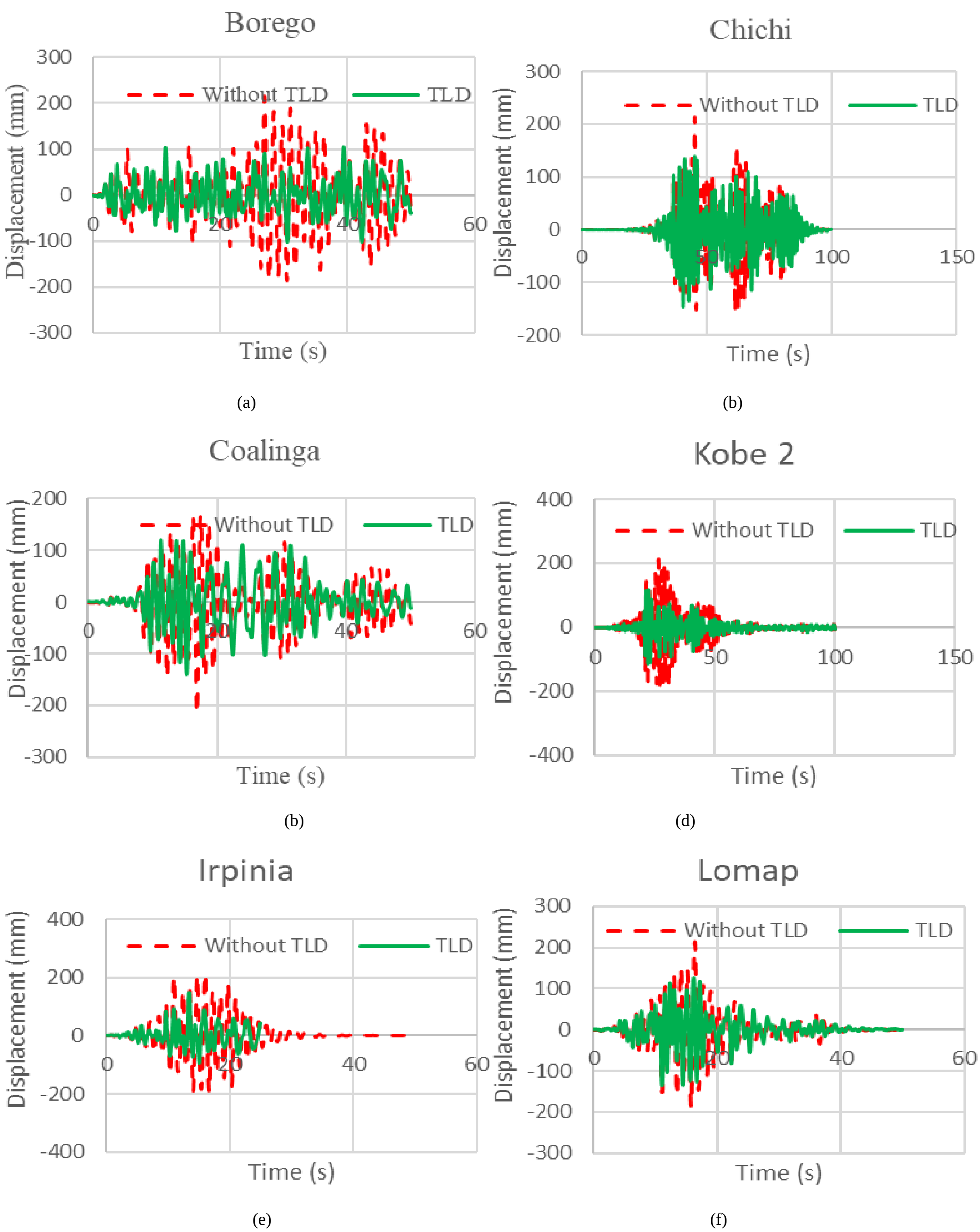


**Figure 4.** Plotted-function far-fault earthquakes: (a) Borrego; (b) Chi-Chi; (c) Coalinga-01; (d) Kobe; (e) Irpinia; (f) Loma Prieta

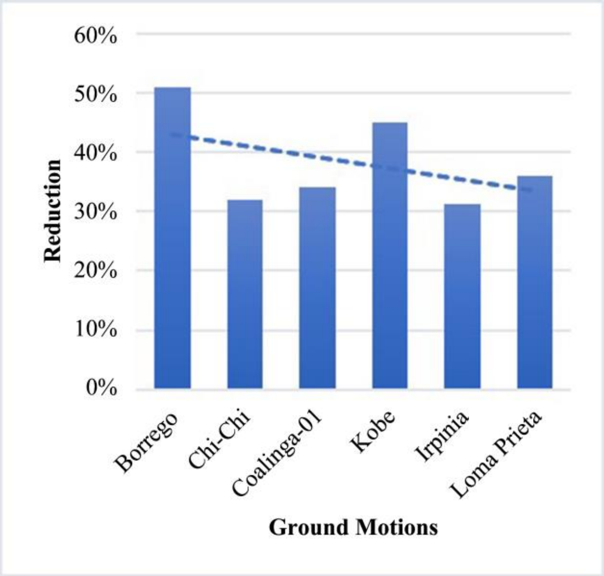


**Figure 5.** Reduction in near-fault earthquakes

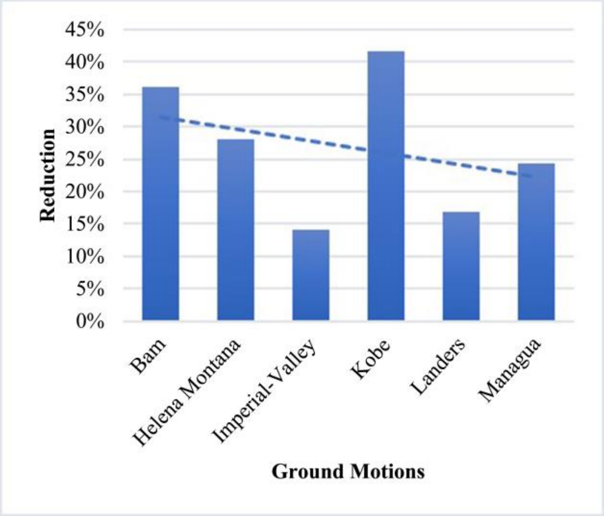


**Figure 6.** Reduction in far-fault earthquakes

As indicated by the displacement response figure in the plot function, TLD is more effective for far-fault ground motions than for near-fault ground motions. Based on the results of the plot function that occurs during an earthquake, displacement reduction in far-fault ground motions is more dominant. Also, the reduction of peak displacement on far-fault ground motions tends to be significant. According to the trend of data for near-fault ground motions, the peak displacement decrease is in the range of 26 percent, while it is in the range of 36 percent for far-fault ground motions.

Based on the results of the analysis, displacement reduction in far-fault ground motions is more effective. As indicated by the displacement response in the plot function (see Figures 3 and 4), displacement reduction is more significant for far-fault ground motions than for near-fault ground motions. Also, the reduction of peak displacement on far-fault ground motions tends to be significant (see Figures 5 and 6). According to the trend of data for near-fault ground motions, the peak displacement decrease is in the range of 26 percent, while it is in the range of 36 percent for far-fault ground motions.

## 6. Conclusions

In this study, the influence of TLD application on buildings was observed with various dynamic loads. The reduction of peak displacement with different excitation frequencies and ground motion characteristics was checked. From the investigation, the following conclusions can be obtained:

1. The effectiveness of TLD in reducing structural vibration is influenced by its design parameters and excitation load.
2. The effectiveness of the TLD is influenced by the ratio frequency of the excitation seismic load. TLD will be very effective if it is loaded with dynamic load at a frequency close to the resonant frequency. Based on the test results, the most optimum excitation frequency ratio is between 0.9 and 1.0.
3. Ground motion influences the TLD performance. Comparing the near- and far-fault ground motions, it has been found that the TLD will be more effective when used in the far-fault ground motion.

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