Behavior of seismically isolated liquid storage tanks equipped with nonlinear viscous dampers in seismic environment

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ABSTRACT: Seismic isolation is an emerging technology in protecting liquid storage tanks from detrimental effects of earthquakes. However, unacceptably large isolator and sloshing fluid displacements may be realized under near-fault earthquakes as such earthquakes may contain high-amplitude velocity pulses with long periods which may be close to the tank isolation periods and the sloshing periods of the liquid contained. Use of nonlinear viscous dampers at base may offer a solution in reducing isolator displacements but it may also cause amplifications in other seismic responses such as isolation system shear, sloshing fluid displacement, fluid-tank shear force or fluid shear force. In an effort to shed light to these issues, nonlinear time history analyses of benchmark seismically isolated liquid storage tanks -with and without nonlinear viscous dampers- are carried out under historical near-fault and far-fault earthquakes and the aforementioned seismic responses are reported in a comparative manner. It is shown that while use of supplemental nonlinear viscous damping reduces the base displacement both in near and far-fault earthquakes, a high amount of damping may result in amplifications in the isolation system shear, sloshing fluid displacement, fluid-tank shear force, and fluid shear force particularly in case of far-fault earthquakes.

1 INTRODUCTION

Seismic isolation is based on the concept of lengthening the fundamental period of a structure by placing it on laterally flexible bearings and thereby reducing effective earthquake forces (Cheng et al. 2008). A vast majority of the applications of seismic isolation covers buildings many times with critical missions such as hospitals, data centers, etc. Although there exist many research studies focusing on seismically isolated buildings in the last few decades (e.g Nagarajaiah and Xiaohong 2000, Alhan and Gavin 2005), the number of research studies conducted on other seismically isolated structures is relatively less. On the other hand, research interest on seismically isolated liquid tanks is growing recently (e.g Panchal and Jangid 2008, Abalı and Uçkan 2010, Shekari et al. 2010).

Although seismic isolation is now widely accepted as a successful earthquake resistant design method, seismically isolated buildings are shown to be challenged by near-fault earthquakes (Hall et al. 1995). Large base displacements can be observed if a base-isolated building located in a near-fault region is hit by a large magnitude earthquake owing to the high-amplitude long-period velocity pulses existent in such ground excitations which may be close to the isolation period. Although high isolation damping is suggested as a measure which has been shown to successfully reduce base displacements in near-fault earthquakes (Hall and Ryan 2000, Providakis 2008) it is also shown that it may on the other hand result in amplifications in the acceleration and story-drift responses of the seismically isolated buildings under far-fault earthquakes (Alhan and Gavin 2004).

Similarly, seismically isolated liquid storage tanks also face the near-fault earthquake challenge and supplemental damping may be used to reduce large base displacements in these structures, too. In particular, nonlinear viscous dampers would be more successful compared to linear ones in reducing displacements (Tsopelas et al. 1994), but at what cost? The behaviour of liquid storage tanks are more complex compared to buildings owing to sloshing of the liquid as well as the fluid-tank response. Thus, it is important to assess the influence of the use of nonlinear viscous dampers at the isolation system on the seismic responses including isolation system shear, sloshing fluid displacement, fluid-tank shear force, and fluid shear force. Therefore here, nonlinear time history analyses of benchmark seismically isolated liquid storage tanks -with and without nonlinear viscous dampers- are carried out under historical near-fault and far-fault earthquakes in order to determine the details of this influence.

2 SEISMICALLY ISOLATED LIQUID STORAGE TANK

In this parametric study, the seismically isolated water tank described by Tsopelas et al. (1994) is used as a benchmark liquid storage tank equipped with an isolation system composed of elastomeric isolators. In case of supplemental damping is considered, 24 nonlinear viscous dampers are placed in each direction in parallel with the isolators. 3D-BASIS-ME (Tsopelas et al. 1994) is used in numerical modeling, which is academic software developed to conduct seismic analyses of seismically isolated liquid storage tanks: Following Haroun and Housner (1981), the mathematical model takes the fundamental sloshing and the fundamental tank-fluid vibration modes into account.

2.1 Liquid Storage Tank

The tank has a circular plan with a radius of R = 60.0 ft (18.29 m) and a total height of 42 ft (12.80 m). The tank is assumed to be filled with water to a height of H = 40 ft (12.19 m) resulting in a height to radius ratio of H/R = 0.67 which represents a typical liquid storage tank. The steel tank is placed on a rigid concrete basemat with a thickness of 1.5 ft (0.457 m) which overhangs about 1ft (0.305 m) in plan around the steel tank. The thickness of the steel is h = 1 in (2.54 cm).

The volume of the water is $V_w=\pi\times60^2\times40=452{,}389.34$ ft^3 resulting in a water weight of 28,387.4 kips (126,273.5 kN) for a water unit weight of γ_w=62.75 lb/ft^3. The volume of the concrete basemat is $V_c=\pi\times61^2\times1.5$ = 17,534.80 ft^3 resulting in a concrete basemat weight of 2629.8 kips (11,697.9 kN) for a concrete unit weight of γ_c=150.0 lb/ft^3. The volume of the walls of the steel tank is $V_{sw}=2\times\pi\times60\times42\times(1/12)=1{,}319.47$ ft^3 resulting in a steel wall weight of 646.5 kips (2875.8 kN) for a steel unit weight of γ_{sw}=490.0 lb/ft^3. The total steel weight becomes 1123.8 kips (4998.9 kN) when a 477.3 kips (2123.1 kN) steel roof is accounted for. Thus the total weight of the full liquid storage tank sums to 32,141 kips (142,970.3 kN).

Following the mechanical analog described by Haroun and Housner (1981), which takes the tank wall deformability and sloshing of the fluid into account, the sloshing mode weight is 72,581.6 kN with a sloshing period of 6.89 s and the fluid-tank mode weight is 53,378.7 kN with a tank-fluid interaction vibration mode period of 0.162 s. The critical damping ratios for the sloshing and fluid-tank modes are assumed to be 0.005 and 0.02 respectively. The concrete basemat is assumed to move together with the 5312.1 kN rigid-convective fluid mode weight and thus the total of this rigid weight sums to 17,010.0 kN. The total weight of the sloshing mode, fluid-tank mode, rigid-convective fluid mode, and the basemat becomes 142,970.3 kN which is equal to the total isolated weight calculated explicitly above.

2.2 Isolation system

2.2.1 *Elastomeric Isolators*

A total of 52 isolators are placed in a double-symmetric way with a typical center to center distance of 17 ft (5.18 m) underneath the concrete basemat. Each isolator is defined as a softening biaxial hysteretic element with a post-yield stiffness of 340.464 kN resulting in a total isolation system post-yield stiffness of K_2=52×340.464=17,704.1 kN which provides an isolation period (based on the post-yield stiffness) of T_0=4.0 s and an isolation system characteristic strength ratio of Q/W=5% excluding the very flexible sloshing mode weight of 72,581.6 kN. Then, assuming a typical yield displacement of D_y=1.5 cm and using $K_1=Q/D_y+K_2$ relation that is set through the geometry of a bi-linear force-deformation curve (Naeim and Kelly 1999), the initial stiffness of the isolation system attains a value of K_1=252,552.1 kN (i.e the initial stiffnes of each isolator = 252,552.1/52 = 4856.8 kN).

2.2.2 *Nonlinear Viscous Dampers*

In cases where nonlinear viscous dampers are used, a total of 24 nonlinear viscous dampers are placed in a double symmetric way in each direction parallel to the elastomeric isolators. Representing nonlinear viscous damping coefficient with c, relative velocity with V_D, and velocity exponent with α, the force developed in a nonlinear viscous damper can be obtained by (Tsopelas et al. 1994):

$$F_D = c \times V_D^{\alpha} \tag{1}$$

Here, the velocity exponent α accounts for the level of nonlinearity and is equal to 1.0 for a linear case. It attains values in the range of 0.5 to 1.2 for nonlinear cases (Constantinou and Symans 1992) and assumed as 0.5 in this study. Two sub-cases are examined where a low and a high level of supplemental nonlinear viscous damping are considered by employing dampers with nonlinear viscous damping coefficients of c_{low}=886 kNs/m and c_{high}=3×886=2,658 kNs/m, respectively. Note that c_{low} corresponds to a critical damping ratio of about ζ = 10% if linear dampers developing equivalent peak forces were used in lieu of the nonlinear dampers under the design earthquake (i.e. RRS228 causing the largest damper force among the selected ground excitations in this study).

3 NEAR-FAULT AND FAR-FAULT HISTORICAL GROUND MOTIONS

Two sets of historical earthquake ground motion records, each containing two records, are used from the PEER Ground Motion Database (Berkeley 2013). While the LGP000 record of the 1989 Loma Prieta Earthquake and the RRS228 record of the 1994 Northridge Earthquake are among the set of near-fault earthquake records, the CAP000 and WAH090 records of the 1989 Loma Prieta Earthquake constitute the set of far-fault earthquake records. Acceleration time histories of these ground motions are given in Figure 1. As seen from these figures, LGP000 and RRS228 contain long-period pulses while the other two do not.

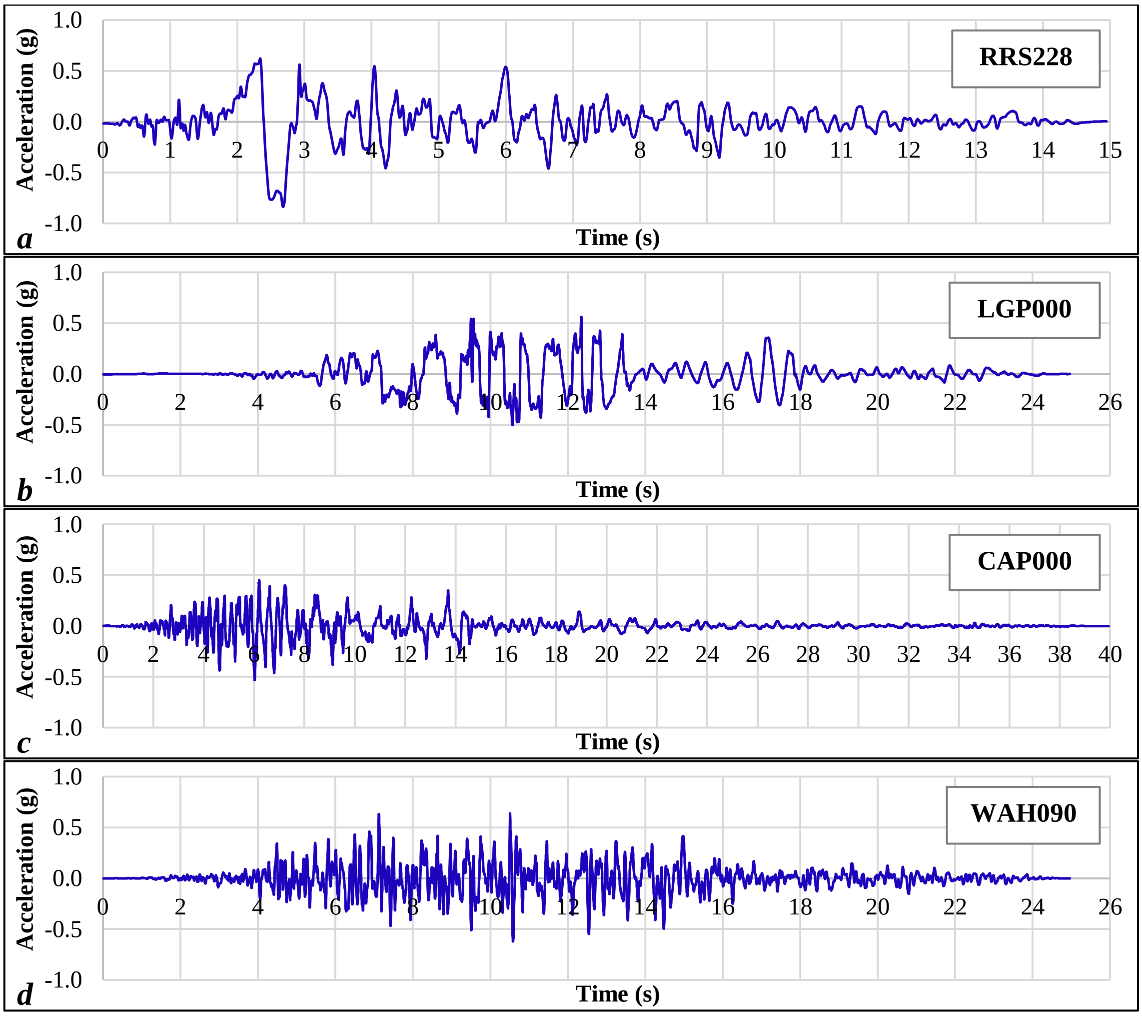

Figure 1: Acceleration time histories of the near-fault (a, b) and far-fault (c, d) ground motions.

The acceleration and displacement response spectra (10% damped) for the historical earthquake records used in this study are given in Figure 2. It is clear that the near-fault records (LGP000 and RRS228) cause much larger displacements (6 to 9 times larger) than far-fault records (CAP000 and WAH090) at around the isolation period of 4 seconds.

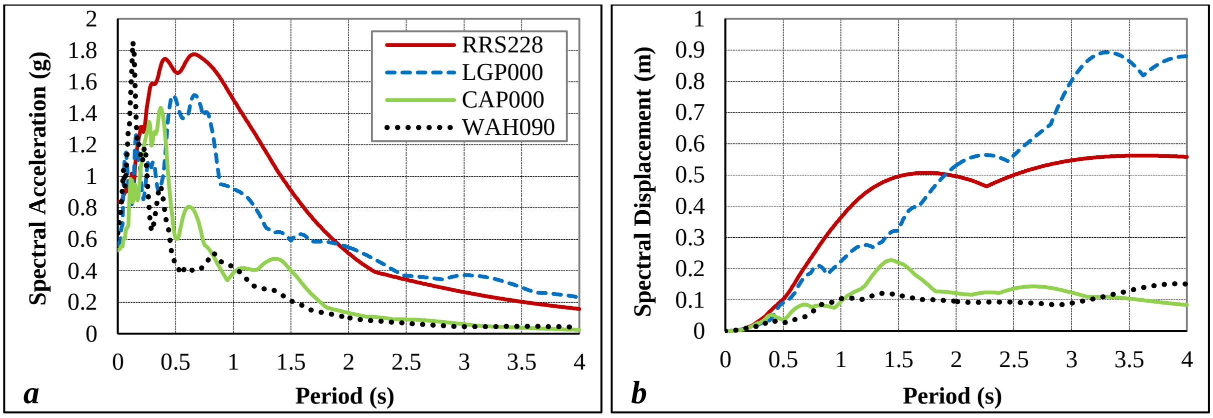

Figure 2: Acceleration (a) and displacement (b) response spectra – 10% damped.

4 DISCUSSION OF RESULTS

Nonlinear time history analyses of the benchmark seismically isolated liquid storage tanks are conducted under unidirectional loadings of the earthquake records described in Section 3 for three different cases (i) isolation system with *no* supplemental nonlinear viscous damping (c=0 kNs/m), (ii) isolation system with nonlinear viscous dampers providing *low* supplemental damping ($c=c_{low}$=886 kNs/m), and (iii) isolation system with nonlinear viscous dampers providing *high* supplemental damping ($c=c_{high}=3\times c_{low}$=2658 kNs/m). Time history plots of base displacement, sloshing fluid displacement, isolation system shear force, sloshing fluid shear force, and fluid-tank shear force are depicted in Figure 3 corresponding to CAP000 and LGP000 as representatives of the far-fault and near-fault earthquakes, respectively. As it can be seen from these figures, base displacement decreases as the level of nonlinear viscous damping is increased for both CAP000 and LGP000 records. However, there exist differences between the trends obtained under CAP000 and LGP000 records depending on the level of damping for all other seismic responses. While sloshing fluid displacement, isolation system shear force, sloshing fluid shear force, and fluid-tank shear force responses mostly decrease as the supplemental damping is increased under the near-fault LGP000 earthquake record, they tend to increase as the supplemental damping is increased under the far-fault CAP000 record.

In order to present a complete quantitave comparison, the peak values of all seismic responses obtained under all earthquake records are reported in Table 1. As it is seen, base displacements and sloshing displacements are rather high for the near-fault records and adding nonlinear viscous damping effectively reduces them to acceptable levels. For far-fault records, supplemental damping appears not to be necessary as the displacements are already at low levels. Furthermore, supplemental damping may even result in amplifications in other seismic responses under far-fault earthquakes.

In order to visually portray the influence of supplemental nonlinear viscous damping on the seismic responses investigated in this study, all responses are normalized with respect to no supplemental damping (c=0 kNs/m) case and given as bar chart plots in a comparative manner in Figure 4. It is seen that as the supplemental nonlinear viscous damping is increased, the base displacements monotonically decrease for all earthquakes and may reduce down to 37% of no supplemental damping case as observed under LGP000 (Fig. 4a). On the other hand, while sloshing fluid displacement (and sloshing fluid shear force which follows the same trend) reduces significantly via use of supplemental nonlinear viscous damping under near-fault earthquakes (up to 66% of c=0 case for LGP000 and c_{high}), it is only slightly reduced in case of far–fault WAH090 earthquake for c_{low} (7% reduction) and then starts increasing when damping is further increased to c_{high}. More strikingly it is increased to 121% of c=0 case when c_{high} is used under far-fault CAP000 earthquake (Figs 4b and 4d).

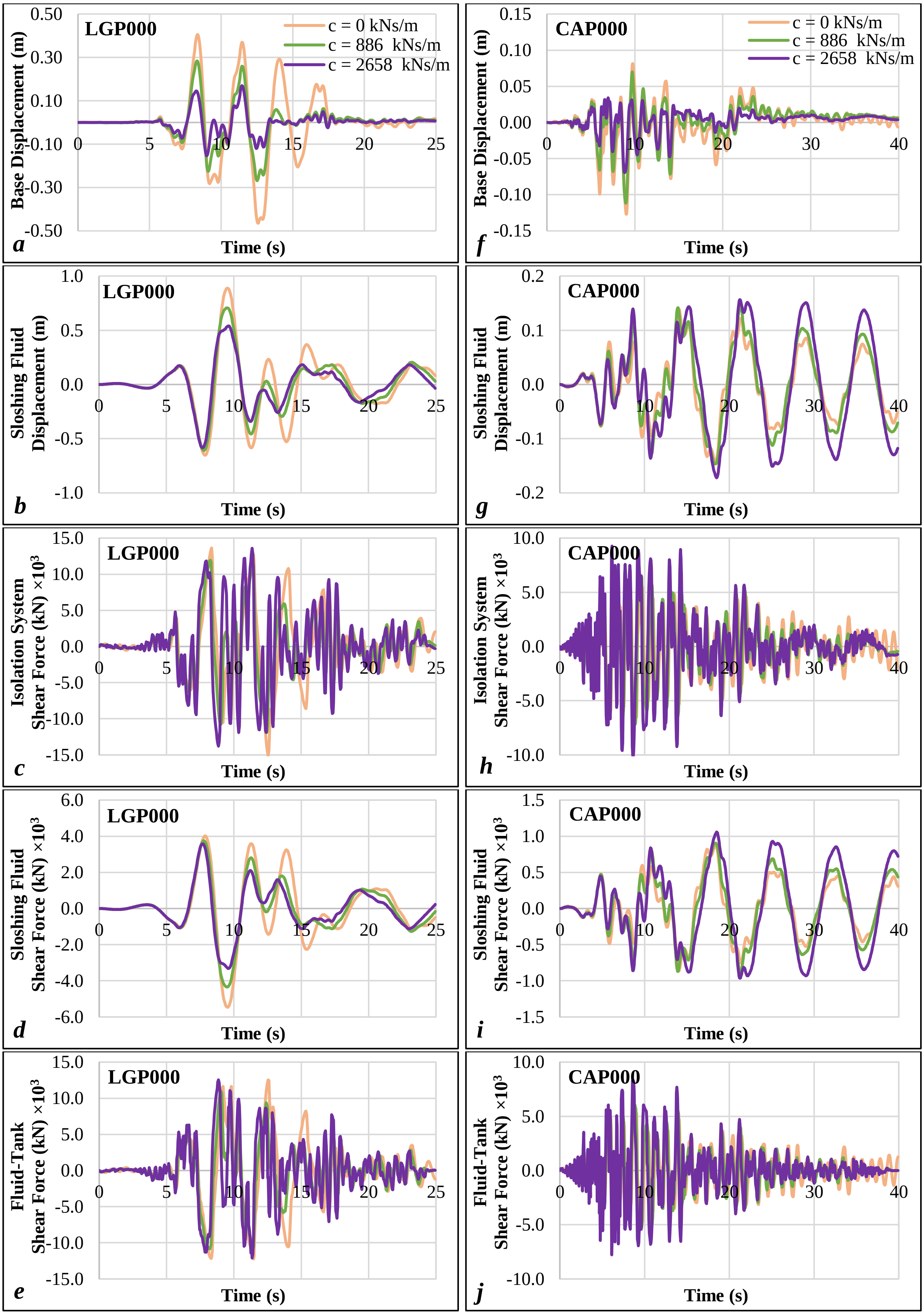

Figure 3: Time histories of the seismic responses under the near-fault LGP000 (a - e) and the far-fault CAP000 (f - j) earthquake records for different levels of supplemental nonlinear viscous damping.

Table 1. Comparison of peak seismic responses for different levels of supplemental nonlinear viscous damping under RRS228, LGP000, CAP000, and WAH090 earthquake records.

Peak Seismic Response	Nonlinear Viscous Damping Coefficient (kNs/m)	Earthquake Record			
		RRS228	LGP000	CAP000	WAH090
Base Displacement (cm)	c=0	44.3	46.6	12.7	7.7
	c=886	38.2	28.4	11.2	6.7
	c=2658	29.3	17.0	6.9	4.1
Sloshing Fluid Displacement (cm)	c=0	62.2	88.9	14.2	8.3
	c=886	55.0	70.7	14.8	7.7
	c=2658	49.9	58.3	17.2	8.0
Isolation System Shear Force (kN)	c=0	14,590.2	15,172.9	6623.4	5351.2
	c=886	15,279.6	11,983.5	7344.0	6320.9
	c=2658	19,251.9	13,789.5	10,253.2	8892.0
Sloshing Fluid Shear Force (kN)	c=0	3825.5	5466.9	875.4	512.9
	c=886	3382.4	4348.1	910.1	475.5
	c=2658	3070.6	3586.2	1059.1	493.8
Fluid-Tank Shear Force (kN)	c=0	11,138.3	12,628.5	5360.1	4369.5
	c=886	11,787.8	11,067.2	6200.8	5382.3
	c=2658	15,043.9	12,632.9	8852.0	8900.9

It is observed from Figure 4c that isolation system shear force tends to increase as nonlinear viscous damping is increased particularly under far-fault earthquakes (up to 166% of c=0 case for WAH090 earthquake). Under near-fault earthquakes, isolation system shear force may decrease (as observed for LGP000) for a low level of supplemental nonlinear viscous damping (i.e. for $c=c_{low}$) but may also increase significantly for higher levels of nonlinear viscous damping (up to 132% of c=0 case for RRS228 and $c=c_{high}$).

Finally, fluid-tank shear force follows a trend similar to one observed for the isolation system shear force (Fig. 4e). It increases as nonlinear viscous damping is increased particularly under far-fault earthquakes (about 100% increase observed under WAH090 earthquake). Under near-fault earthquakes, fluid-tank shear force may decrease slightly for a low level of supplemental nonlinear viscous damping (i.e. for $c=c_{low}$) but may also increase significantly for high levels of nonlinear viscous damping (up to 35% as observed under RRS228 for $c=c_{high}$).

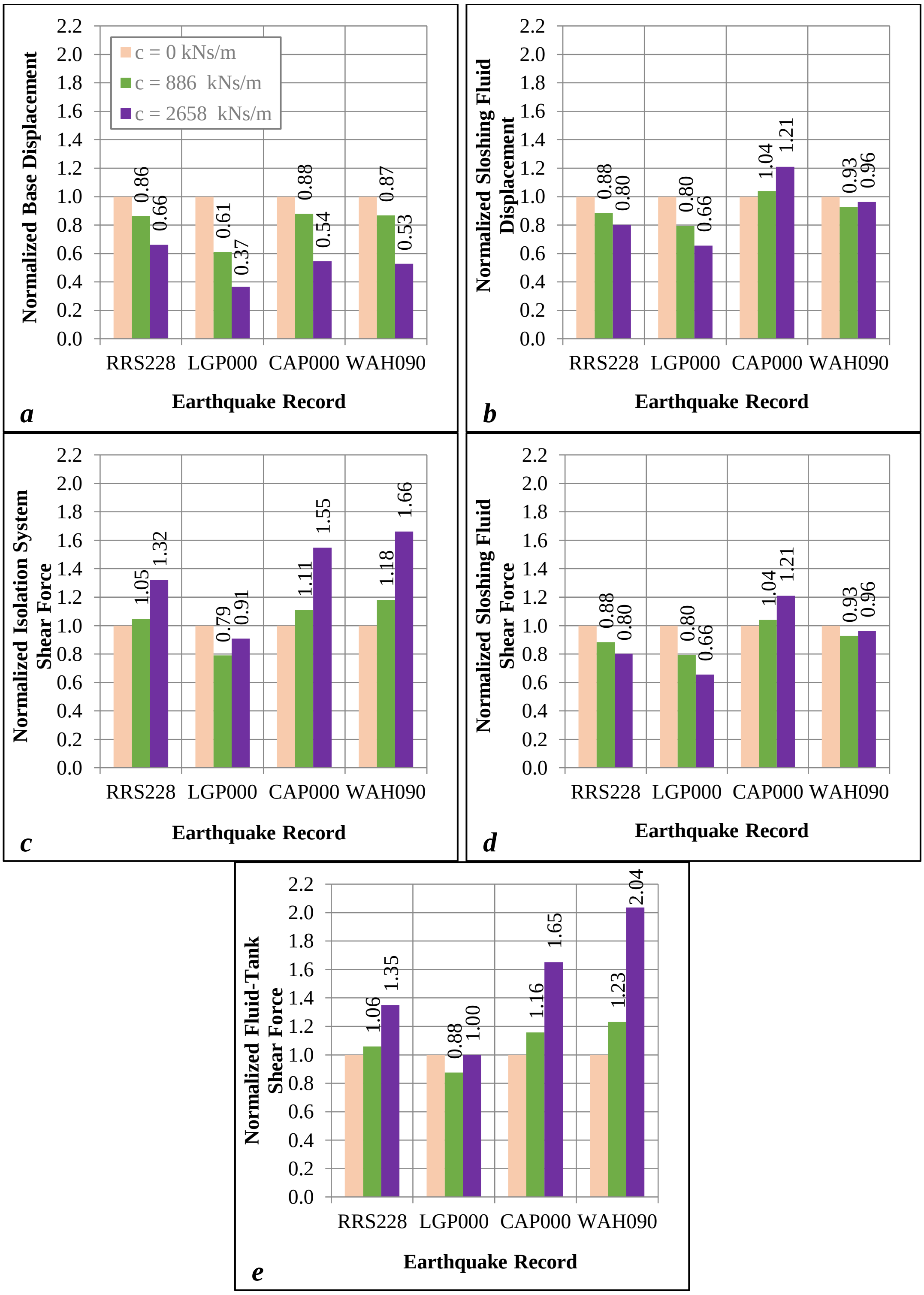

Figure 4: Seismic responses normalized with respect to no supplemental nonlinear viscous damping (c=0) case: (a) base displacement, (b) sloshing fluid displacement, (c) isolation system shear force, (d) sloshing fluid shear force, (e) fluid-tank shear force.

5 CONCLUSIONS

In this study, nonlinear time history analyses of benchmark seismically isolated liquid storage tanks with and without nonlinear viscous dampers of low to high levels of damping are carried out under historical near-fault and far-fault earthquakes in order to assess the effectiveness of the use of supplemental nonlinear viscous damping in reducing base displacement under near-fault earthquakes and its influence on the other seismic responses including isolation system shear, sloshing fluid displacement, fluid-tank shear force, and fluid shear force. Based on the results of the parametric analyses conducted herein, it is concluded that

- Use of supplemental nonlinear viscous dampers at base reduces the base displacement both in near and far-fault earthquakes and the reduction monotonically increases as the damping level increases.
- A high amount of nonlinear viscous damping may result in significant amplifications in the isolation system shear, sloshing fluid displacement, fluid-tank shear force, and fluid shear force particularly in case of far-fault earthquakes.

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