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SENSITIVITY OF THE SEISMIC PERFORMANCE OF LIQUID STORAGE TANKS WITH NONLIEAR ISOLATION SYTEMS TO DEVIATIONS IN MECHANICAL CHARACTERISTICS OF THE SEISMIC ISOLATORS

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Abstract. *Liquid storage tanks, one of the important components of industrial production, may be out of service for a temporary period of time or become completely unserviceable when subjected to large earthquake ground motions that may cause severe damages. Many studies in literature suggest seismic base isolation technique in protecting liquid storage tanks from the harmful effects of strong ground motions. And, the dynamic behaviors of these structural systems, which are composed of the sloshing of the fluid inside and the dynamic response of the tank itself, are directly dependent on the isolation system design. While seismic base isolation is an emerging successful earthquake resistant design method for liquid storage tanks, seismic performances of such structures may be affected negatively from potential deviations that may occur in the mechanical properties of the isolators from the nominal design values. Deviations may come into scene due to a variety of reasons such as the errors and/or uncertainties in the properties of the materials, dimensions of the elements, manufacturing methods, quality control and installation steps. In this paper, the effects of subject deviations in the mechanical characteristics of the seismic isolators on the seismic performances of liquid storage tanks equipped with nonlinear isolation systems are investigated under different historical earthquake records. To this end, sensitivity analyses are carried out by first conducting nonlinear time history analyses of a benchmark liquid storage tank mounted on a nonlinear isolation system in 3DBASIS-ME and then comparing its seismic responses including bearing displacements and sloshing displacements, which are obtained separately for nominal and deviated cases. In the context of this study, the characteristic isolator parameters including the yield force and the post-yield to pre-yield stiffness ratio are considered as the mechanical properties which may deviate from their nominal design values.*

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1 INTRODUCTION

Liquid storage tanks are one of the important industrial-type structural systems which are generally used for storing water, chemicals, petroleum products, toxic and flammable fluids etc. [1]. These tanks play an extremely important role in production for many industries. In addition, these structures have to suffer no damage to be able to serve right after an external factor such as flood, landslide, and particularly earthquakes which may cause huge economic losses. For this reason, protecting these structures from the harmful effects of the abovementioned external factors may be of vital importance in a country's economy.

As is the case for building type of structural systems, the desired seismic performance level can be effectively provided using base-isolation, which is an effective alternative earthquake resistant design method based on the concept of seismic performance by lengthening the fundamental period of the structural system [2]. However, seismic performances of base-isolated structures may be affected negatively from potential deviations that may occur in the mechanical properties of the isolators with respect to their nominal design values due to a variety of reasons such as the errors and/or uncertainties in the properties of the materials, dimensions of the elements, manufacturing methods, quality control and installation steps. There are a number of research studies investigating the effects of such deviations in the mechanical isolator properties of the base-isolated buildings [3, 4]. And, the subject deviations are also important for the seismic performance of base-isolated liquid storage tanks, since the dynamic behaviors of the base-isolated liquid storage tanks, which are composed of the sloshing of the fluid inside and the dynamic response of the tank itself, are directly dependent on the isolation system design. However, limited number of studies [5, 6] investigate the effects of subject deviations on the seismic performances of base-isolated liquid storage tanks.

In order to shed light to this issue, in this study the effects of the deviations in the mechanical characteristics of the seismic isolators, including yield force and the post-yield to pre-yield stiffness ratio, on the structural response parameters of base-isolated liquid storage tanks, including bearing displacements and sloshing displacements, are investigated under two different historical earthquake records via sensitivity analyses that compare the subject seismic responses which are obtained for nominal and deviated cases.

2 BASE-ISOLATED LIQUID STORAGE TANK

A benchmark base-isolated liquid storage tank whose superstructure and overall geometrical properties are obtained from Tsopelas et al., 1994 [7] is used in this study. The superstructure and the isolation system are described in this section.

2.1 Superstructure

The circular tank, assumed to be used for water storage within the scope of this study, consists of a steel wall and a concave-down steel roof, and is mounted on a circular rigid concrete basemat which is placed on a nonlinear isolation system consisting of 52 identical rubber based isolators. The radius (R) and the total height of the subject tank are 18.29 m and 12.80 m, respectively while the steel thickness (h) for both the tank wall and its concave-down roof is 2.54 cm. The height (H) of the water inside the tank is 12.19 m, which results in a height to radius ratio (H/R) of 0.67. The weights for the steel tank (including the wall and the roof), the concrete basemat, and the stored water inside the tank are equal to 4998.91 kN, 11697.93 kN, and 126273.45 kN, respectively.

Numerical modelling and time history analyses of the subject storage tank are carried out in 3D-BASIS-ME [7] which is a computer program that can conduct nonlinear dynamic analyses of seismically isolated liquid storage tanks following the mechanical analog developed for this type of structural systems by Haroun and Housner, 1981 [8]. The details of the subject mechanical analog which takes into account the deformability of the tank wall and sloshing of the fluid can be found in [8]. As for the details of the numerical modelling of the tank, which is based on that analog, they can be found in [7] and also in [9] who used the tank superstructure and overall geometry presented by Tsopelas et al., 1994 [7] but introduced their own elastomeric isolation system properties.

2.2 Substructure

The circular rigid concrete basemat of the benchmark liquid storage tank sits on a nonlinear isolation system consisting of 52 identical rubber based isolators which are placed symmetrically in two horizontal orthogonal directions with a typical center-to-center distance of 5.18 m. In this study, the force-displacement relationship of all these isolators, exhibiting nonlinear material behavior as well as hysteretic energy dissipation, is modelled by a smooth bilinear hysteretic curve which is based on the Bouc-Wen [10] hysteretic model. One of the main mechanical parameters of the isolation system consisting of the subject isolators is the post-yield stiffness (K_2), which can be determined using its relationship with the isolation period (T_0) and the effective weight of the tank (W_{eff}) given in Equation 1 [11] where g is the gravitational acceleration. In this study, T_0 is assumed to be 4 s for the benchmark base-isolated liquid storage tank, while W_{eff} is obtained as 70388.66 kN for the subject tank by extracting the sloshing mode weight of 72581.63 kN from the total physical weight of 142970.29 kN. So, the total isolation system post-yield stiffness is obtained as K_2=17710.13 kN. As for the rest of the main mechanical parameters of the isolation system, i.e. the total isolation system pre-yield stiffness (K_1), the yield force (F_y), and the post-yield to pre-yield stiffness ratio (α), they are obtained as 487405.90 kN/m, 7304.27 kN, and 0.036, respectively using the relationships given in Equations 2-4 [12], assuming characteristic strength ratio (Q/W_{eff}), and yield displacement (D_y) as 10% and 1.5 cm, respectively.

$$T_0 = 2\pi\sqrt{W_{eff}/(K_2 \times g)} \tag{1}$$

$$Q = (K_1 - K_2) \times D_y \tag{2}$$

$$F_y = K_1 \times D_y \tag{3}$$

$$\alpha = K_2/K_1 \tag{4}$$

The values obtained above are considered as the nominal design values of the mechanical parameters of the isolators. And the deviated cases are generated by assuming F_y and α to be the mechanical properties which may deviate from their nominal values. The deviations from the nominal design values are considered as ±5%, ±15%, and ±25% for both of F_y and α (Table 1). As seen in Table 1, the deviated cases generated in the context of this study are divided into two main cases. And, each of the main deviated cases consists of six deviated subcases denoted with A, B, C, D, E, and F corresponding to to +5%, +15%, +25%, -5%, -15%, and -25% deviations, respectively. For the first main case, F_y is the deviated parameter while α keeps its nominal design value for the subcases of the first main deviated case and for the second main case α is the deviated parameter while F_y keeps its nominal design value for the subcases of the second main deviated case.

Main Case	Mechanical Parameter	Nominal Value	Subcases						
			Parameters	A (+5%)	B (+15%)	C (+25%)	D (-5%)	E (-15%)	F (-25%)
1st	F_y (kN)	7304.27	F_y (kN)	7669.48	8399.91	9130.34	6939.06	6208.63	5478.20
			α (-)	0.0360	0.0360	0.0360	0.0360	0.0360	0.0360
2nd	α (-)	0.0360	F_y (kN)	7304.27	7304.27	7304.27	7304.27	7304.27	7304.27
			α (-)	0.0378	0.0414	0.0450	0.0342	0.0306	0.0270

Table 1: Nominal and deviated case values of isolation system yield force (F_y) and isolation system post-yield to pre-yield stiffness ratio (α)

3 GROUND MOTION DATA

Two historical earthquake records used in this study are obtained from PEER Ground Motion Database [13]. The benchmark liquid storage tank with the nominal case isolation system and the tanks with the isolation systems of the deviated subcases are unidirectionally subjected to the earthquake records of I-ELC180 and SYL360, which are recorded during the 1940 Imperial Valley Earthquake and the 1994 Northridge Earthquake, respectively. Necessary information about these records are presented in Table 2. In this table, M_s is the earthquake magnitude, *PGA* is the peak ground acceleration, *PGV* is the peak ground velocity and *PGD* is the peak ground displacement. The response spectra (ζ=5%, 10%, and 15% damped) of the subject ground motions are presented in Figure 1.

Component name	Record station	Record date	M_s	*PGA* (g)	*PGV* (cm/s)	*PGD* (cm)
I-ELC180	El Centro	05/19/1940	7.2	0.313	29.8	13.32
SYL360	Sylmar	01/17/1994	6.7	0.843	129.6	32.68

Table 2: Characteristics of earthquake records.

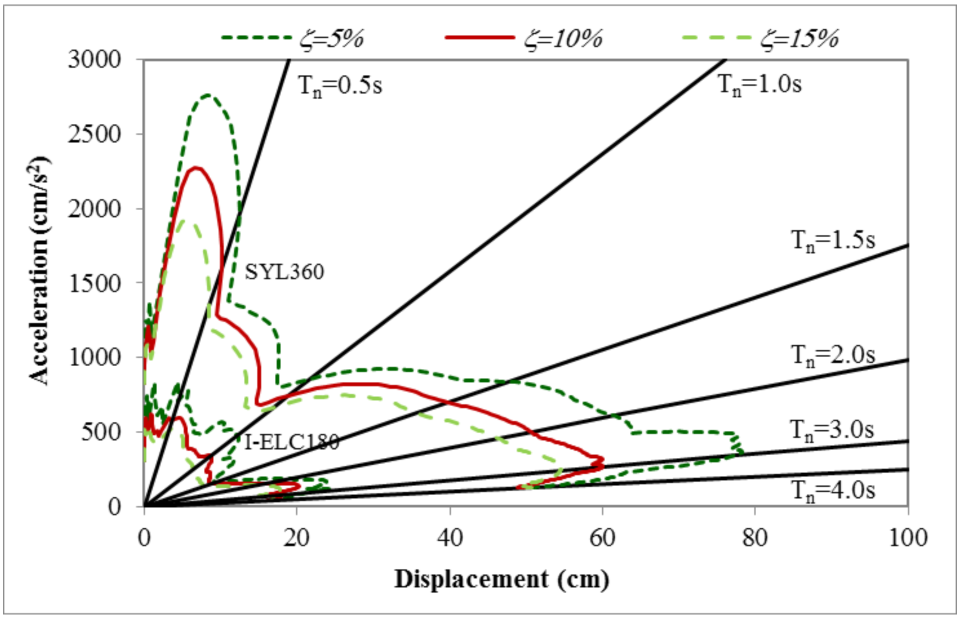

Figure 1: Response spectra (ζ=5%, 10%, and 15% damped) for I-ELC180 and SYL360 records.

4 SENSITIVITY ANALYSES

In this section, the results of the sensitivity analyses, which are carried out for investigating the effects of the deviations in the mechanical characteristics of the seismic isolators on the seismic performances of liquid storage tanks equipped with nonlinear isolation systems under historical earthquake records, are presented. In the context of the sensitivity analyses, unidirectional nonlinear time history analyses of the benchmark liquid storage tank equipped with the nominal case isolation system and the tanks equipped with the deviated subcase isolation systems (Table 1) are conducted under I-ELC180 and SYL360 ground motion records in order to obtain the seismic responses including the bearing displacements and the sloshing displacements corresponding to both nominal and deviated cases. Then, these responses are compared to each other.

As mentioned in Sec. 2, when F_y is the deviated parameter, α keeps its nominal design value for the subcases of the first main deviated case (i.e., 1A, 1B, 1C, 1D, 1E, and 1F) whereas, when α is the deviated parameter, F_y keeps its nominal design value for the subcases of the second main deviated case (i.e., 2A, 2B, 2C, 2D, 2E, and 2F). This approach makes it possible to determine the sensitivity of seismic performance of the subject structural systems to only the deviated isolator parameter.

The bearing and the sloshing displacement time history plots obtained under I-ELC180 and SYL360 records for the nominal case and the deviated subcases 1C and 1F (where F_y deviates from its nominal value (7304.27 kN) by +25% and -25% respectively), are presented in Figure 2. It is seen from the comparison of the time history plots given in Figure 2 that, the bearing displacements (Figures 2a and 2c) are more sensitive to the deviations in F_y than the sloshing displacements (Figures 2b and 2d). It is also seen that the deviations in the bearing and the sloshing displacements vary with respect to the ground motion record.

As for the bearing displacement and the sloshing displacement time history plots obtained under the I-ELC180 and SYL 360 records for the nominal case and the deviated subcases 2C and 2F (where α deviates from its nominal value (0.0360) by +25% and -25% respectively), they are presented in Figure 3. The comparison of the time history of plots given in Figure 3 shows that, both of the structural response parameters shows little sensitivity to the deviations in α and the comparison of the plots given in Figure 2 and Figure 3 indicate that both of the structural response parameters in question are more sensitive to the deviations in F_y than to the deviations in α, under the ground motion records used in this study.

In addition to the time history plots presented, positive and negative percent deviations in the peak response parameters are also calculated via Equations 5 and 6 which are named here as "error ratios" (e_{bd} and e_{sd}) using the peak values of the bearing displacements (*bd*) and sloshing displacements (*sd*). In these equations, the subscripts "*n*" and "*d*" refer to the nominal and the deviated cases, respectively.

$$e_{bd} = \frac{bd_d - bd_n}{bd_n} \times 100 \tag{5}$$

$$e_{sd} = \frac{sd_d - sd_n}{sd_n} \times 100 \tag{6}$$

The error ratios calculated for all of the deviated cases (Table 1) under the I-ELC180 and SYL360 records are presented in Table 3. Actual peak values of the subject response parameters (*bd* and *sd*) obtained for the nominal and deviated cases under both records are also provided in this table.

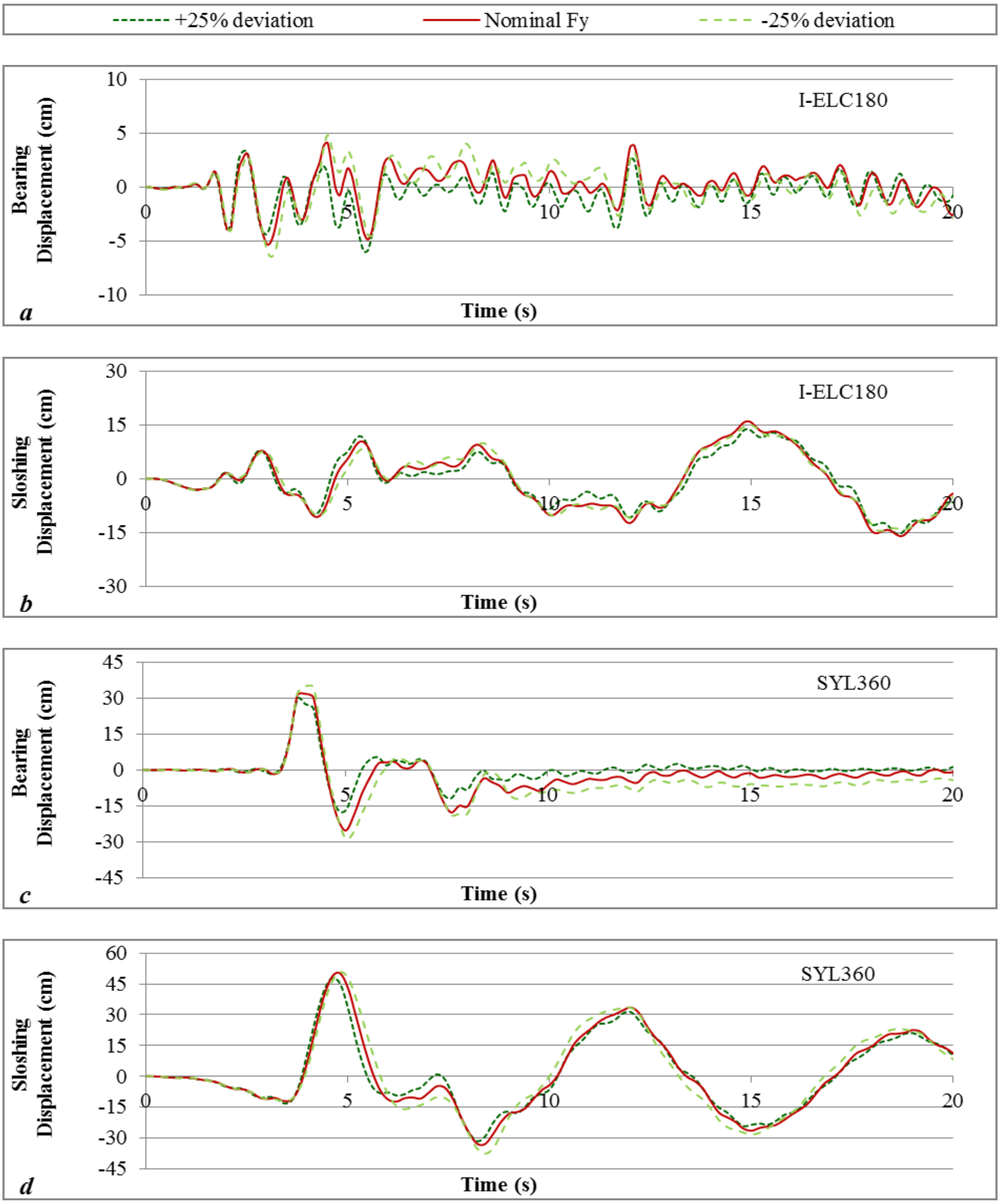

Figure 2: Sensitivity of the bearing and the sloshing displacements to the yield force - subcases 1C and 1F under I-ELC180 and SYL360 earthquake records.

It is seen from Table 3 that, the absolute values of the error ratios calculated for both of the response parameters under both of the records generally increase with the increasing deviation in the subject isolator parameter. Therefore, the largest (positive or negative) error ratios are obtained for C or F subcases corresponding to +25% and -25% deviations are in the isolator parameters, respectively. It is also seen from this table that, the peak error ratio for the bearing displacements is obtained as e_{bd} = 20.60% in subcase 1F, where F_y deviates by -25% from its nominal value, under the IELC-180 record. The peak error ratio for the sloshing displacements is obtained as e_{sd} = -5.85% in subcase 1C, where F_y deviates by +25% from its nominal value, under the IELC-180 record. On the other hand, the largest (positive or negative) error ratios for the 2nd main case (deviated α) are obtained for case 2F under SYL360 record. That is, a -25% deviation in α causes peak error ratios of 2.35% and -3.51% in the bearing displacements and the sloshing displacements, respectively as seen from Table3.

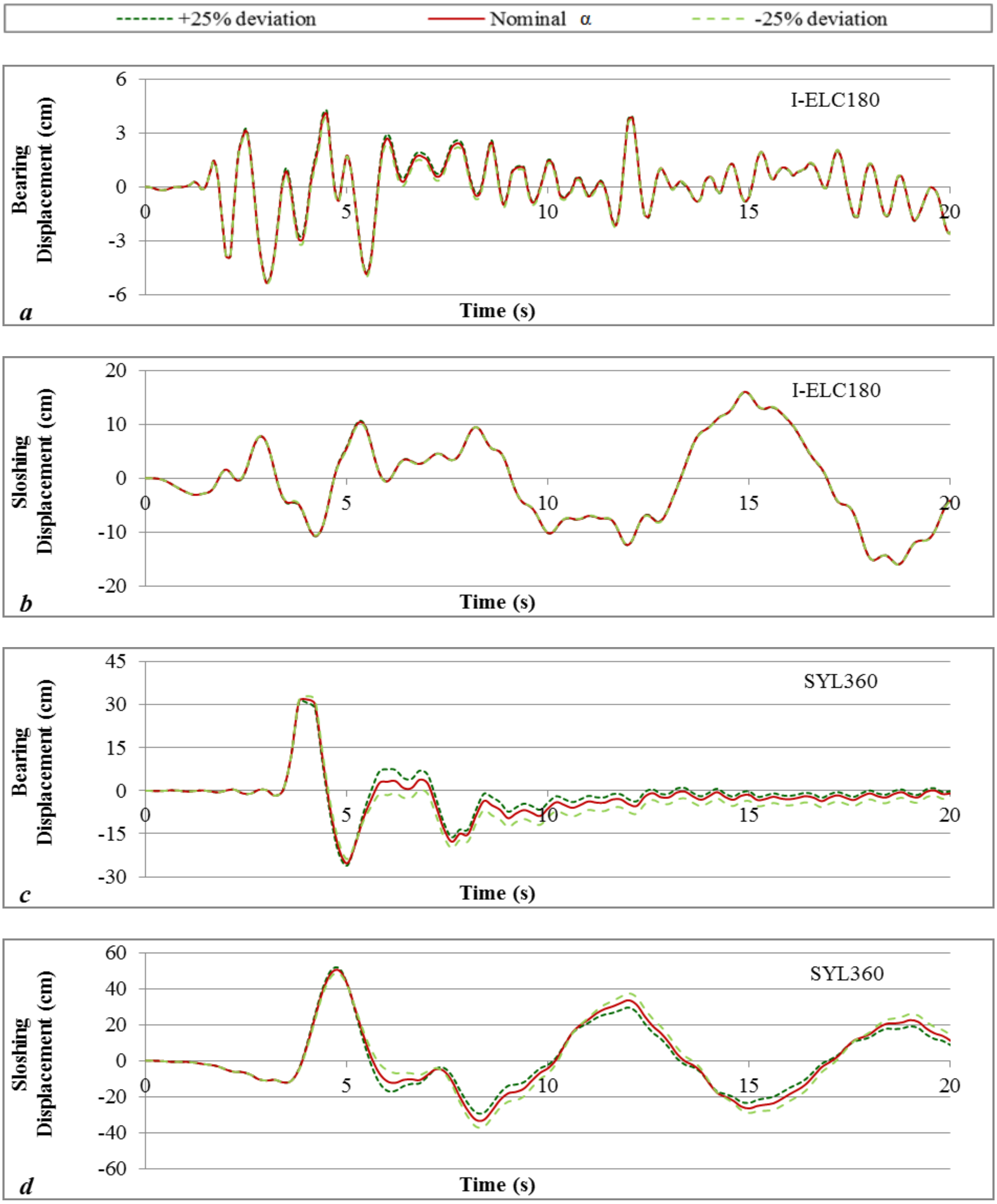

Figure 3: Sensitivity of the bearing and the sloshing displacements to the post-yield to pre-yield stiffness ratio - subcases 2C and 2F under I-ELC180 and SYL360 earthquake records.

Case	Subcase	Earthquake Records I-ELC180 bd (cm)	e_{bd} (%)	sd (cm)	e_{sd} (%)	SYL360 bd (cm)	e_{bd} (%)	sd (cm)	e_{sd} (%)
Nominal	-	5.39	0	19.00	0	33.45	0	50.65	0
1st main case (Deviated parameter: F_y)	1A (+5%)	5.18	-3.77	18.94	-0.33	33.12	-0.99	49.81	-1.65
	1B (+15%)	5.73	6.27	18.51	-2.59	32.36	-3.26	48.56	-4.11
	1C (+25%)	6.17	14.57	17.89	**-5.85**	30.94	-7.52	48.08	**-5.07**
	1D (-5%)	5.58	3.54	19.07	0.33	33.73	0.84	51.31	1.30
	1E (-15%)	6.01	11.55	18.61	-2.05	34.87	4.25	51.99	2.66
	1F (-25%)	6.50	**20.60**	18.22	-4.09	36.83	**10.10**	50.90	0.50
2nd main case (Deviated parameter: α)	2A (+5%)	5.37	-0.24	19.00	-0.03	33.30	-0.46	50.93	0.55
	2B (+15%)	5.36	-0.57	18.98	-0.11	33.07	-1.14	51.44	1.55
	2C (+25%)	5.34	-0.90	18.96	**-0.21**	32.87	-1.75	52.07	2.81
	2D (-5%)	5.40	0.19	19.01	0.03	33.58	0.38	50.37	-0.55
	2E (-15%)	5.42	0.66	19.01	0.04	33.83	1.14	49.71	-1.86
	2F (-25%)	5.45	**1.13**	19.01	0.07	34.24	**2.35**	48.87	**-3.51**

Table 3: Error ratios in peak values of bearing displacement (*bd*) and sloshing displacement (*sd*) responses under I-ELC180 and SYL360 earthquake records.

5 CONCLUSIONS

In this study, the sensitivity of the seismic performance of liquid storage tanks equipped with nonlinear isolation systems to the deviations in the mechanical properties of the seismic isolators are investigated under two historical earthquake records. Bearing displacements and sloshing displacements are considered as the seismic performance criteria while yield force and post-yield to pre-yield stiffness ratio are assumed as the deviated mechanical parameters. Based on the limited parametric analyses conducted here, the following conclusions are reached:

- Both bearing and sloshing displacements are more sensitive to the deviations in the yield force than to the deviations in the post-yield to pre-yield stiffness ratio.
- Bearing displacements seem to be more sensitive to the deviations in the mechanical properties of the seismic isolators compared to sloshing displacements.
- The level of the sensitivity of the seismic performance of liquid storage tanks with nonlinear isolation systems to deviations in mechanical characteristics of the seismic isolators depends on the mechanical property of the seismic isolator in question and the characteristics of the subject earthquake record.

In order to reach more comprehensive and generalizable conclusions, more subcases representing deviations of wider spectrum and more earthquake data should be used. Such a comprehensive parametric investigation considering other mechanical properties of the seismic isolators and different seismic responses under different earthquake records is currently being conducted by the authors of this paper.

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