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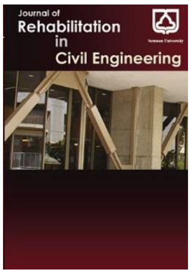

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Seismic Retrofitting the Steel Storage Tanks using Single Concave Friction Isolators under the Long Period Earthquakes

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ABSTRACT

Cylindrical liquid storage tanks are contemplated as vital structures in industrial complex whose nonlinear dynamic behavior is of crucial importance. Some of these structures around the world have demonstrated poor seismic behavior over the last few decades; consonantly a major improvement is required to reach their level of applicability. There are several methods and techniques for rehabilitation and reducing damages in these structures which among them the devices for passive control, particularly base isolators, are perceptible. Friction Pendulum System (FPS) is the most popular base isolation system which its period does not depend on the structural weight. In this research work, the efficiency of FPS is examined on decreasing the seismic responses of base isolated steel storage tanks as well as the impact effect of slider to the side restrainer. To this end, the whole mass of liquid storage tank is contemplated as three lumped masses known as convective mass, impulsive mass which is connected to tanks with corresponding spring, and rigid mass which is connected rigidly. By means of state space method the time history analysis is done applying 60 earthquake records to acquire dynamic responses under the various hazard levels i.e. SLE, DBE and MCE ground motions. The results show that the normalized base shear force in squat tank decreased 59%, 62% and 33% respectively under SLE, DBE and MCE ground motions. The reduction of normalized base shear force in slender tank is 53%, 49% and 35% under the aforementioned hazard levels. Examining the effect of side restrainer's stiffness on the maximum responses exhibit that the impact effect must be considered particularly when the system is excited by MCE's ground motions.

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1. Introduction

Cylindrical steel storage tanks are applied extensively in chemical and petrochemical industries, and nuclear power plant. As these structures play essential role in the industry and can sometimes store risky chemical liquids, they are connected directly and/or indirectly to the human life. Hence, protection their structural reliability against earthquake ground motions constitutes a significant matter towards increased safety. Due to the interaction between fluid and structure, cylindrical steel storage tanks behave in a different way rather than other structures such as bridges and dames and have several particularities. Cooper and Wachholz [1] reported extensive damage of petroleum steel tanks as a result of some earthquake ground motions such as Long Beach 1933, Kern County 1952, Alaska 1964, San Fernando 1971, Imperial Valley 1979, Coalinga 1983, Loma Prieta 1989, Landers 1992, Northridge 1994, and Kobe 1995. Shell buckling, roof damage, failure of anchorage, tank support system failure, foundation failure and connecting piping failure operate the inappropriate operation of these structures during the previous earthquakes. Several methods have been developed for reducing and retrofitting damages in these structures such as enhancing wall thickness, coupling the wall plate, applying device along the perimeter of the reservoir compensation toroidal shell open cross section and using energy dissipating devices (dampers and base isolators).

Increasing the thickness of wall reduce axial stress and consequently preventing the buckling of wall. Notwithstanding, during the earthquake these structures must behave linearly and boosting the wall and plate thickness cause increasing the seismic input energy. Base isolation has been employed for several decades to diminish the seismic input energy and structural retrofitting. Besides in recent years, devices for passive control such as dampers and mechanical energy dissipaters are being applied for retrofitting of steel storage tanks and liquefied natural gas (LNG) tanks. Although there are several studies on the base isolated storage tanks, a few studies have been manifested regarding the effect of long period earthquakes on the base isolated storage tanks. Because finite element modeling a base isolated steel storage tank in three-dimensional environment is absolutely intricate as a result of interaction between fluid and structure.

Housner [2] proposed the first procedure for dynamic analysis of liquid storage tanks. Rosenblueth and Newmark [3] modified the expression suggested by Housner. These models presented for rigid liquid storage tanks. Haroun [4] modified the expression suggested by Housner, assuming the liquid contained in the tank as incompressible with irrotational flow and the tank wall is flexible. Chalhoub and Kelly [5] performed shake table test on the fixed base and base isolated tanks and reported an slightly increase in the sloshing displacement, while the dynamic responses decreases considerably. Friction pendulum system was applied by Zayas and Low [6] in 1995 for retrofitting a liquefied natural gas (LNG) tank. The results indicated that base isolation reduce the damages, base shear force, overturning moment and impulsive mass displacement. Malhotra [7, 8] explored the effect of base isolation on seismic response of liquid storage tank. He applied elastomeric bearings for reducing the axial force and consonantly the probability of elephant foot buckling. Shrimali and Jangid [9] examined seismic behavior of base isolated liquid storage tanks through comparing the seismic behavior of elastomeric bearings and sliding bearings. Results showed that sliding bearings operate better than elastomeric bearings. They compare the seismic behavior of base isolated storage tanks by R-FBI, FPS and P-F isolating systems [10]. Bagheri and Farajian inspected the effect of earthquake characteristic on seismic responses of liquid storage tanks [11]. They found that the FPS has better performance under the far-field ground motions. Since during the earthquake the volume of infill fluid in the storage tank and therefore the weight of the structure is not exactly specified, the FPS has a better performance as the period of isolator does not depend on the weight of structure [12]. Figure 1 displays the cross section of a single concave friction isolator.

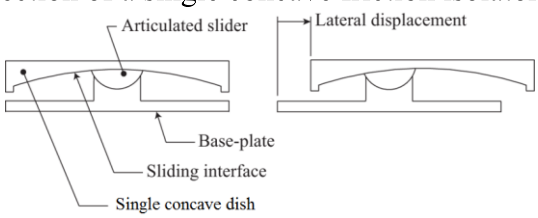

Fig. 1. Cross section of a single concave friction isolator.

Virella et al. [13] examined the dynamic buckling of aboveground steel tanks with conical roofs under the horizontal components of some earthquake records. The results revealed that the elastic buckling at the conical roof occurred as a critical condition for the medium- and high-rise models regardless of the accelerogram contemplated, for the reason that plasticity was extended for a PGA higher than the critical PGA.

Alembagheri and Estekanchi [14] investigated nonlinear response of above-ground anchored steel tanks by means of a new dynamic pushover procedure entitled Endurance Time (ET) technique with common nonlinear time history response. The outcomes revealed that ET method has a good potential for practical applying the time history response based analysis and design techniques for thin walled structures such as steel tanks. Yong-Chul et al. [15] proposed a theoretical model of a FPS to survey its application for the seismic base isolation of spatial lattice shell structures. They proposed that the friction coefficient must be contemplated 0.05 to 0.15. By proposing a new seismic isolation system, Gaofeng and Zhifei educed that the offered system can quietly affect the seismic response of structure and mitigate its seismic response [16].

The connector in FPS opposes tensile forces, slides to harmonize translation along the rails and supplies rotational capacity about a vertical axis. The impact can be occurred where the slider of FPS impacts with the side restrainers. Therefore, in this research work, the seismic performance of steel storage tanks isolated by single concave friction isolator is studied under the variety range of long period earthquakes. In agreement to that, comparing the responses of different configurations of base isolated storage tanks with fixed ones are done applying nonlinear time history analysis. Afterward, the effects of impact and side restrainer’s stiffness are examined on the seismic responses of base isolated steel storage tanks.

2. Fluid-Structure Interaction

Seismic energy is transferred to the fluid through the tank vibration. A portion of fluid which accelerated with tank wall is represented by “impulsive mass”, the portion which move with the rigid base is represented by “rigid mass” and the other part of the fluid in the upper part of the storage tank which moves independently with tank wall, sloshes and generates seismic waves is represented by "convective mass" [17]. The interaction between fluid and structure is contemplated by springs with specified stiffness and damping, K_c and C_c which denotes convective stiffness and damping, and, K_i and C_i which denotes impulsive stiffness and damping, respectively. The simplified mass-spring model is illustrated in Fig. **2**.

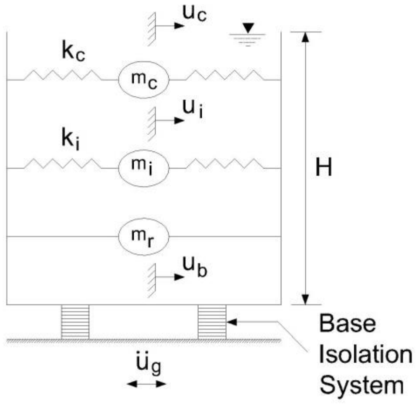

Fig. 2. Simplified mass-spring model [12].

The parameters for the tank can be stated as liquid height (H), tank radius (R) and average thickness of tank wall, t_h . The convective, impulsive and rigid lumped masses are computed by:

$$m_c = m \times \gamma_c \tag{1}$$

$$m_i = m \times \gamma_i \tag{2}$$

$$m_r = m \times \gamma_r \tag{3}$$

$$m = \pi . R^2 . h . \rho_w \tag{4}$$

While there are several modes which contribute to response, the response can be calculated by first sloshing and impulsive mass mode. The natural frequencies of first sloshing (ω_c) and impulsive mass (ω_i) can be expressed by:

$$\omega_c = \sqrt{1.84 (\frac{g}{R}) tgh (1.84 S)} \tag{1}$$

$$\omega_i = \frac{P}{H} \sqrt{\frac{E}{\rho_s}} \tag{2}$$

The gravity acceleration and tank aspect ratio is represented by g and S ($S=H/R$). E and ρ_s are elasticity modules and density of tank wall material, respectively. $P, \gamma_c, \gamma_i, \gamma_r$ are non-dimensional parameters which are function of S and t_h/R. These parameters for t_h/R=0.004 can be expressed as:

$$\begin{Bmatrix} \gamma_c \\ \gamma_i \\ \gamma_r \\ P \end{Bmatrix} = \begin{bmatrix} 1.01327 & -0.8757 & 0.35708 & 0.06692 & 0.00439 \\ -0.15467 & 1.21716 & -0.62839 & 0.14434 & -0.0125 \\ -0.01599 & 0.86356 & -0.30941 & 0.04083 & 0 \\ 0.037085 & 0.084302 & -0.05088 & 0.012523 & -0.0012 \end{bmatrix} \times \begin{Bmatrix} 1 \\ S \\ S^2 \\ S^3 \\ S^4 \end{Bmatrix} \tag{3}$$

The equivalent stiffness and damping of the sloshing and impulsive masses are represented as:

$$K_c = m_c \times \omega_c^{\ 2} \tag{8}$$

$$K_i = m_i \times \omega_i^{\ 2} \tag{9}$$

$$C_c = 2 \zeta_c m_c \omega_c \tag{10}$$

$$C_i = 2 \zeta_i m_i \omega_i \tag{11}$$

ξ_c and ξ_i are convective and impulsive damping ratios, respectively. The corresponding values of ξ_c and ξ_i are 0.5% and 2%.

2.1 Developing Motion Equations

Figure 3 shows the model of a liquid storage tank mounted on a sliding system. The equation of motion can be expressed as follows:

$$m_c \ddot{u}_c + c_c (\dot{u}_c - \dot{u}_r) + k_c (u_c - u_r) = -m_c \ddot{u}_g \tag{12}$$

$$m_i \ddot{u}_i + c_i (\dot{u}_i - \dot{u}_r) + k_i (u_i - u_r) = -m_i \ddot{u}_g \tag{13}$$

$$m_r \ddot{u}_r - k_c (u_c - u_r) - k_i (u_i - u_r) - c_c (\dot{u}_c - \dot{u}_r) - c_i (\dot{u}_i - \dot{u}_r) + c_b \dot{u}_r + F = -m_r \ddot{u}_g \tag{14}$$

Where C_b is damping at base level and is expressed by:

$$C_b = 2 (m_r + m_i + m_c) \xi_b \omega_b \tag{15}$$

F is the horizontal force applied by FP element and is derived by:

$$F=\frac{W}{R_{eff}}(u_r)+\mu WZ+k_r(|u_r|-d)sign(u_r)H(|u_r|-d) \tag{16}$$

W denotes the vertical load of the bearing, R_{eff} is effective radius, d is displacement capacity of the, surface Z which changes between -1 and 1 is a hysteretic variable and determined applying equation (18), k_r is the stiffness operated by displacement restrainer, and μ is coefficient of velocity dependent of friction which has been presented by Mokha et al. [18]:

$$\mu=f_{\max}-(f_{\max}-f_{\min})\exp(-a|\dot{u}|) \tag{17}$$

a is velocity of sliding, f_{max} and f_{min} are coefficients of sliding of friction at extreme sliding velocity, respectively. The hysteretic variable Z is computed applying differential equation:

$$\frac{dz}{dt}=\frac{1}{u_y}\left\{A-|Z|^{\eta}\left[\gamma sign(\dot{u}_r Z)+\beta\right]\right\}\dot{u}_r \tag{18}$$

The u_y is the yield displacement and its value is contemplated as 0.0001 m to represent the PTFE [19]. The shape of hysteresis loop is controlled by some dimensionless variables such as A, γ, β and η, and assumed as $A=1$ and $\beta=\gamma=0.5$ [20] in this study. Based on above equations, the MATLAB program [21] is employed to solve the equations of motions using state space method.

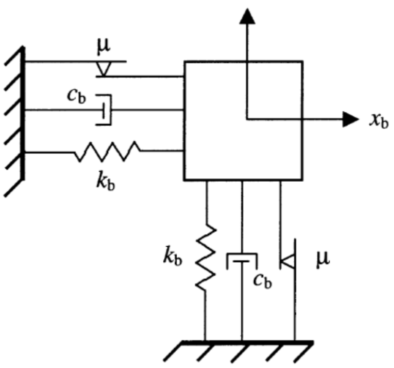

Fig. 3. Model of a liquid storage tank mounted on a sliding system [22].

3. Parametric Study

An extensive numerical study has been performed to evaluate the efficacy of friction isolators under the various ground motion records, and to explore the consequence of impact on the response of friction isolated steel storage tanks as well. To this end, tree different forms of steel storage tanks namely slender, medium and squat tanks have been contemplated with base isolators which followed by comparing seismic responses with fixed ones. Geometric and material properties of the selected tank samples such as height, radius and aspect ratio have been presented in Table 1.

Table 1. Properties of tree different forms of steel storage tanks used in this study.

Type of Tanks	*H(m)*	*R(m)*	*S=H/R*	*E (Gpa)*	*ρ_s (kg/m^3)*
Squat	12.35	22.45	0.55	210	7900
Medium	13.13	12.50	1.05	210	7900
Slender	11.7	6.5	1.80	210	7900

Due to the current growth in the number of high-rise structures and liquid storage tanks, long period earthquakes have received special attention. The long period component of seismogram which produced by earthquake causes damage in near-fault region because of source effects such as forward directivity. Long period ground motions reduce slowly with distance and site effects intensify these motions so that they can cause extensive damage. In liquid storage tanks, this damage is caused mainly by sloshing of the liquid inside the tanks. As the vibration of liquid sloshing requires long duration seismic ground motion, it can be related to the long period earthquake. As can be observed in Table 2, Koketsu and Miyake [23] presented 14 cases of tank damage because of liquid sloshing.

Table 2. Tank damage list because of liquid sloshing.

	Earthquake	Year	M_W	Damage
1	Kanto	1923	7.9	Oil tanks
2	Long Beach	1933	6.2	Water tank
3	Kern County	1952	7.5	Oil tanks
4	Alaska	1964	9.2	Many oil tanks, fires
5	Niigata	1964	7.6	Many oil tanks, fires
6	Central Chile	1965	7.1	Oil tanks
7	San Fernando	1971	6.6	Oil tanks
8	Miyagi-oki	1978	7.4	Oil tanks
9	Imperial Valley	1979	6.5	Oil tanks
10	Coalinga	1983	6.2	Many oil tanks
11	Japan Sea	1983	7.7	Many oil tanks, fires
12	Kocaeli	1999	7.6	Many oil tanks, fires
13	Chi-Chi	1999	7.7	Oil tanks
14	Tokachi-oki	2003	8.3	Many oil tanks, fires

The study presented here explores the performance of liquid storage tank applying Single Concave Friction Isolators (SCFI) at different levels of hazard. Accomplishing this target requires earthquake records related to the multiple hazard levels. In this regard, the earthquake records which presented in Table 1, were provided in three probabilities of occurrence: SLE (50% in 50 years), DBE (10% in 50 years) and MCE (2% in 50 years) [24, 25]. Table 3 presents the characteristics of selected records applied in this paper for nonlinear time history analysis. Figure 4 indicates the response spectra of 5% damped acceleration for considered ground motions.

The free surface displacement (d_x), convective (x_c), impulsive (x_i) relative to the base and rigid mass displacements (u_b), moment of overturning (OM) and base shear in normalized form (F_b/W) are considered as main response parameters.

Table 3. Properties of selected ground motions in this paper.

DBE			MCE			SLE		
Record	Earthquake	Scale Factor	Record	Earthquake	Scale Factor	Record	Earthquake	Scale Factor
RT 01	Kanto	0.442	RT 21	Artificial	1.265	RT 41	Artificial	0.552
RT 02	Long Beach	0.684	RT 22	Artificial	0.942	RT 42	Artificial	0.378
RT 03	Kern County	0.405	RT 23	Artificial	0.528	RT 43	Artificial	0.112
RT 04	Alaska	0.471	RT 24	Artificial	0.512	RT 44	Artificial	0.114
RT 05	Niigata	0.295	RT 25	Artificial	0.912	RT 45	Artificial	0.178
RT 06	Central Chile	0.256	RT 26	Artificial	0.936	RT 46	Artificial	0.154
RT 07	San Fernando	0.435	RT 27	Artificial	0.9757	RT 47	Artificial	0.396
RT 08	Miyagi-oki	0.433	RT 28	Artificial	1.170	RT 48	Artificial	0.363
RT 09	Imperial Valley	0.553	RT 29	Artificial	0.719	RT 49	Artificial	0.332
RT 10	Coalinga	0.351	RT 30	Artificial	0.892	RT 50	Artificial	0.521
RT 11	Japan Sea	0.674	RT 31	Artificial	1.357	RT 51	Artificial	0.754
RT 12	Kocaeli	0.989	RT 32	Artificial	1.337	RT 52	Artificial	0.656
RT 13	Chi-Chi	0.652	RT 33	Artificial	0.822	RT 53	Artificial	0.687
RT 14	Tokachi-oki	0.641	RT 34	Artificial	0.625	RT 54	Artificial	0.769
RT 15	Northridge	0.565	RT 35	Artificial	0.969	RT 55	Artificial	0.458
RT 16	Kocaeli	0.525	RT 36	Artificial	0.225	RT 56	Artificial	0.452
RT 17	Chi-Chi	0.563	RT 37	Artificial	0.629	RT 57	Artificial	0.357
RT 18	Northridge	0.858	RT 38	Artificial	0.639	RT 58	Artificial	0.236
RT 19	North Palm	0.985	RT 39	Artificial	0.456	RT 59	Artificial	0.852
RT 20	San Fernando	0.953	RT 40	Artificial	0.725	RT 60	Artificial	0.369

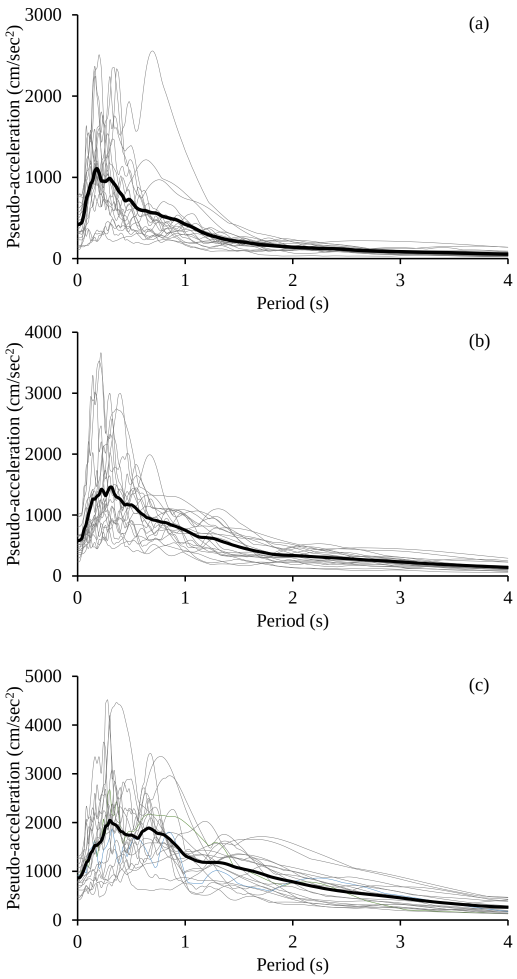

Fig. 4. Pseudo-acceleration of (a) SLE, (b) DBE and (c) MCE ground motions.

4. FINDINGs and Discussion

4.1 The Effect of Friction Isolator

Time history response of considered parameters under RT01, RT21 and RT41 are presented as representative of DBE, MCE and SLE ground motion excitations in both fixed and isolated conditions through Figures 5 to 7 for two forms of steel storage tanks, i.e. squat and slender tanks, respectively. For these models, the isolation system factors are isolation system period, T_b = 2.2 sec, lower and upper limit factors of sliding friction, f_{max}=0.075 and f_{min} =0.041. It is detected that a noteworthy decrease happen in the normalized base shear force (F_b/W), overturning moment (OM) and impulsive mass displacement (x_i) of both forms of tanks; operating that single concave friction isolator is quiet efficient in decreasing the seismic response of cylindrical steel storage tanks. Such decreasing will end with better behavior and performance of cylindrical steel storage tank during earthquake events. The normalized base shear force (F_b/W) of squat tank under SLE, DBE and MCE ground motions has been decreased 59%, 62% and 33%, on average. The mean reduction percentages of normalized base shear force (F_b/W) of slender tank under SLE, DBE and MCE ground motion are 53%, 49% and 35%, respectively. The moment of overturning (OM) of squat tank under considered ground motions has been reduced 62%, 63% and 31%, and for impulsive mass displacement (x_i) has been decreased 53%, 60% and 48%, respectively. The aforementioned responses under contemplated ground motions in slender tanks have been reduced 61%, 56% and 36% for overturning moment and 56%, 56% and 47% for impulsive displacement, respectively. This results reveal that, the single concave friction isolator is more efficient in decreasing the demands under SLE and DBE ground motions.

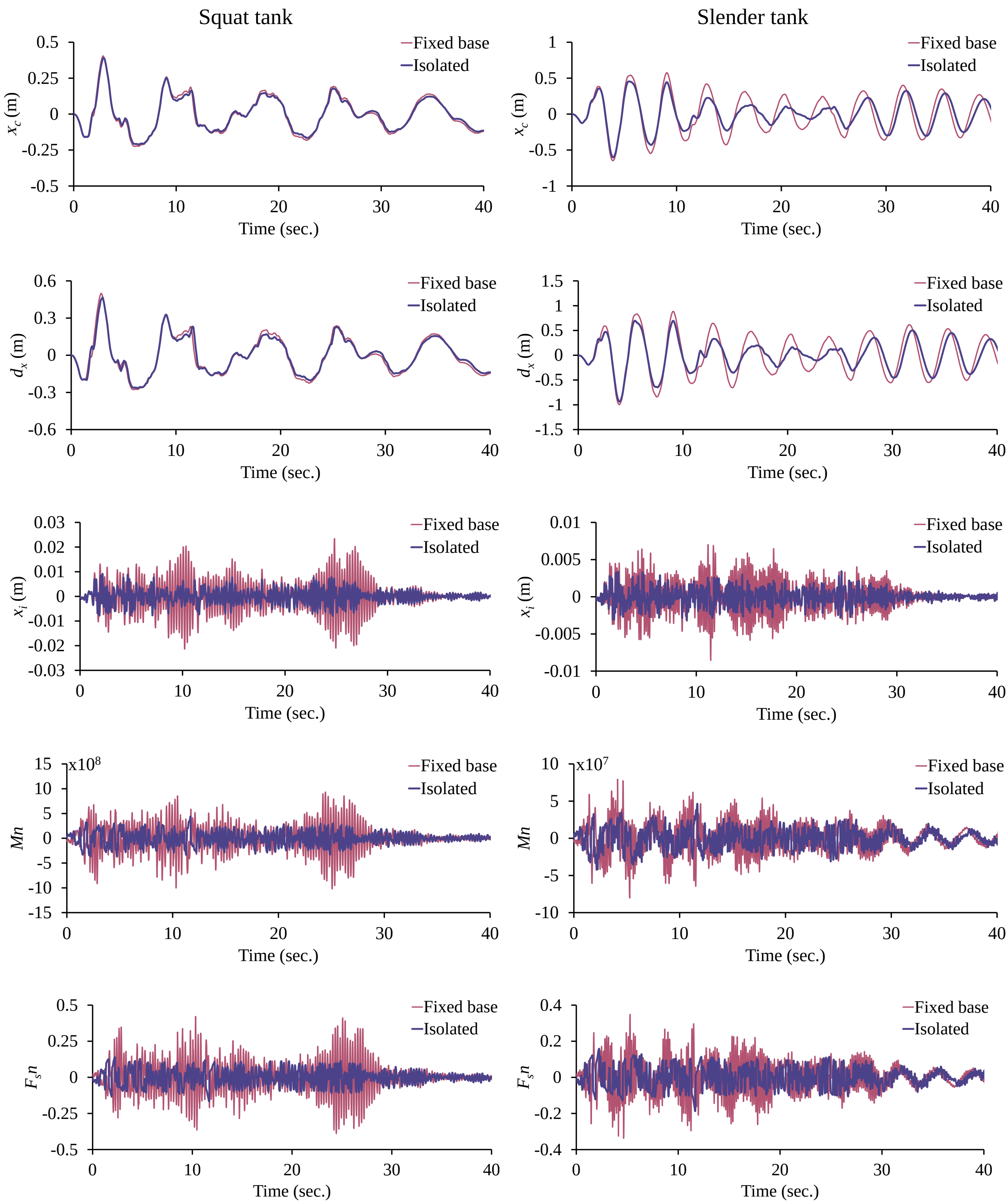

Fig. 5. Time history of various responses in fixed and isolated conditions under RT01 earthquake.

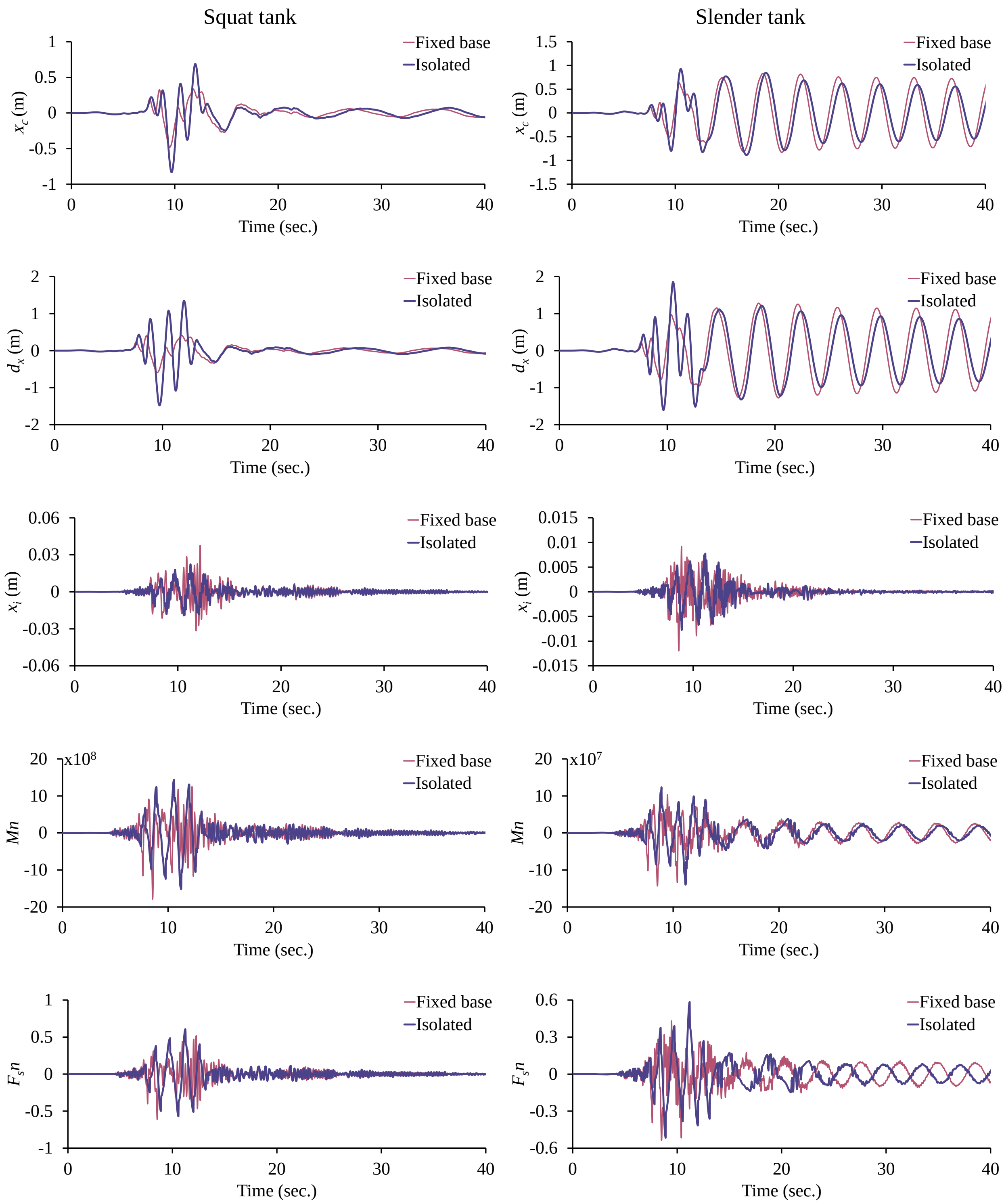

Fig. 6. Time history of various responses in fixed and isolated conditions under RT21 ground motion.

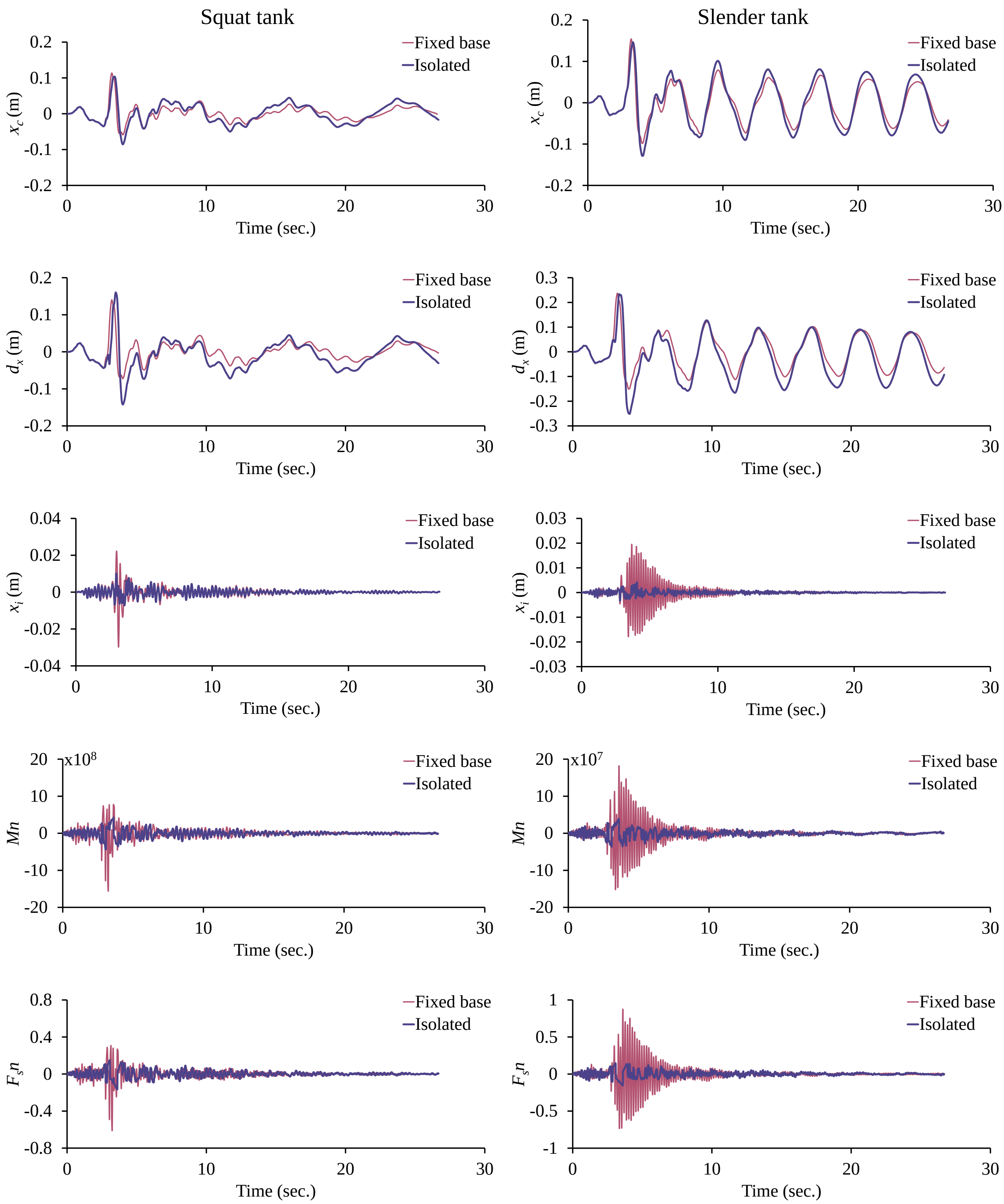

Fig. 7. Time history of various responses in fixed and isolated conditions under RT41 ground motion.

Instead, as the convective displacement has long period, this response is less affected by earthquake ground motions and isolation is less efficient in the responses decreasing. However, in order to reveal the effectiveness of isolation on three contemplated hazard levels, it could be stated that for the squat tank the convective mass displacement has been reduced 34%, 14% for SLE and DBE ground motions while it has been increased 9%, indicating that the friction isolator is increased the convective mass displacement under MCE ground motions. For the slender tank, the average of reduction percentage in convective displacement is 21%, 13% and 0%, respectively. These results also reveal that intensifying the hazard level of earthquake records leads to decrease the effectiveness of friction isolator. The mean reduction percentages of considered responses are displayed as bar plot in Figure 8 as well.

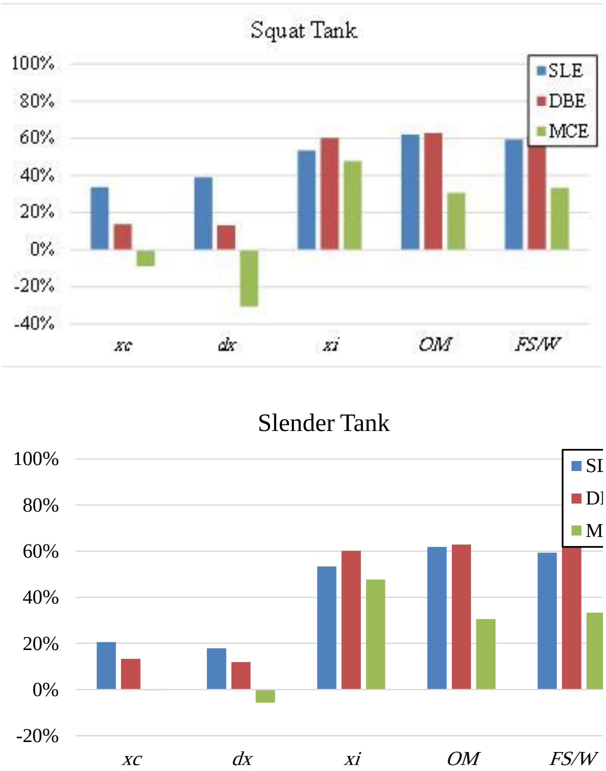

Fig. 8. Average of seismic responses reduction in selected tanks.

4.2 Effect of Impact

The influence of impact on the seismic responses of considered steel storage tanks is examined in this section. For required analysis, the distance of slider to restrainer is contemplated to be $d = 0.1\ m$, as described in previous sections, in this condition the base isolation displacement comes to contact with the side restrainers. With the aim of examining the impact of stiffness of side restrainers on the seismic responses of selected steel storage tanks, the stiffness of side restrainers are considered as various ratios of impulsive displacement. The results reveal that as the hazard level of ground motion increases the probability of impact increases. For the SLE ground motions, no impact was observed except when the liquid storage tank, both squat and slender, is excited under RT59 ground motion. It was also observed for the DBE ground motions, the impact was observed for only RT14, RT16 and RT18. On the other hand, when the steel storage tank is excited by MCE ground motions, for all ground motions, the impact was observed. Figure 9 indicates the effect of side restrainer stiffness on the some response factors of selected steel tank subjected to RT40 which is representative of MCE ground motions.

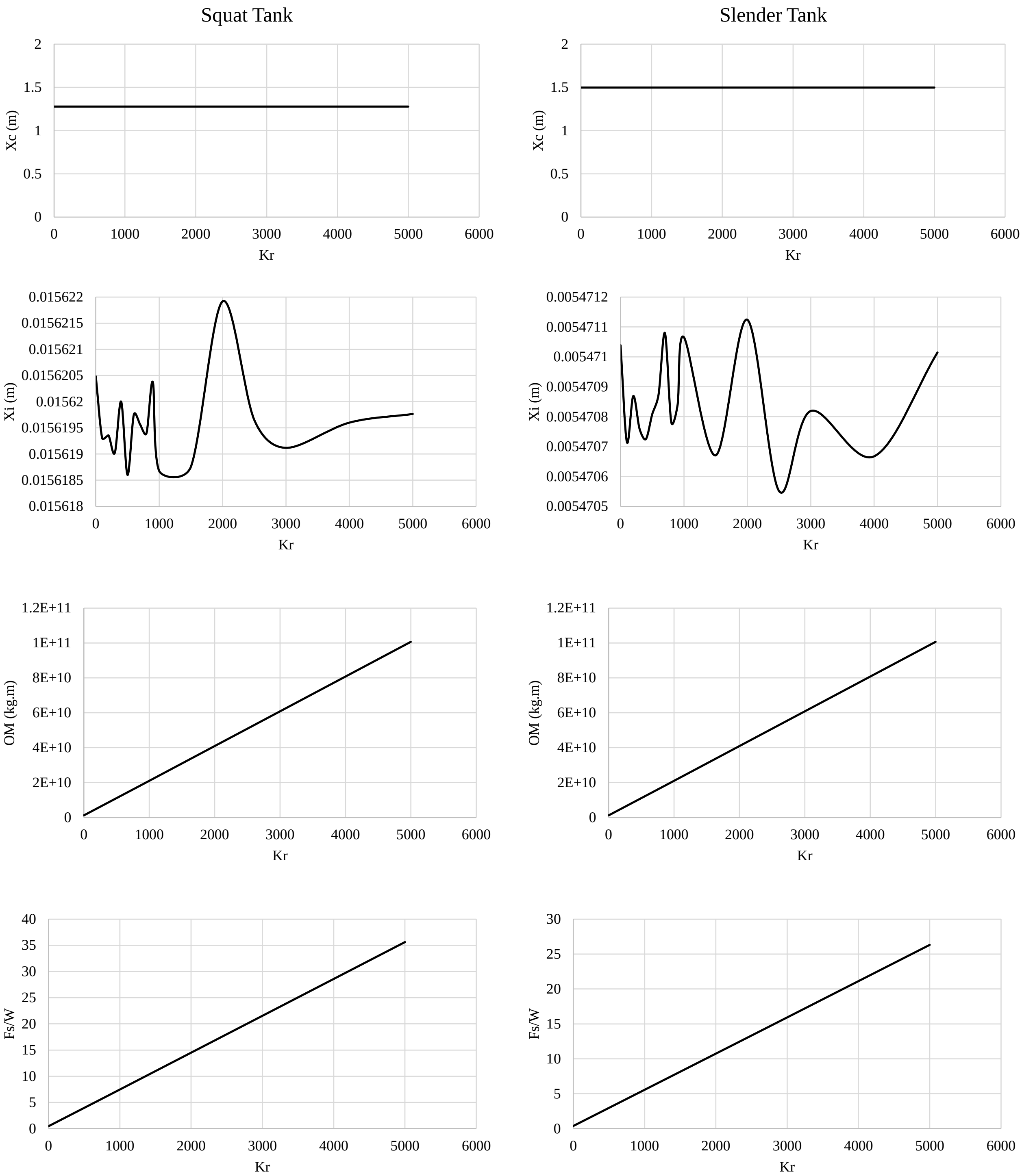

Fig. 9. Effect of stiffness of side restrainers on peak responses of squat and slender tank.

It is detected that the responses are the same when $k_r = 0$ and the impact is ignored. It is also observed that, the impact causes to increase the normalized overturning moment and base shear. It also affects the impulsive displacement and cause to increase the impulsive mass displacement. This is due to that when the slider came to contact with side restrainers, the structure's behavior is similar to fixed ones. It causes to transform the ground motion's acceleration to the structure and causes to increase the seismic responses.

On the other hand, the acquired responses exhibit that the convective mass displacement is not affected by the stiffness of side restrainers, as a result to its long period.

5. Conclusion

In this paper the effect of single concave friction isolators was studied on the seismic behavior and performance of some selected steel storage tanks under the long period ground motion records. Besides, the effects of impact were also considered in the analysis. It was observed that the friction isolator has improved performance under SLE ground motions in both slender and squat tanks. Displacements of impulsive mass, moment of overturning and normalized base shear were decreased in all tanks as a result of isolation. A significant increase of overturning moment and normalized base shear was also observed as a result of impact. For the SLE ground motions, no impact was observed except when the steel storage tanks were excited under RT59 ground motion. It was also observed when the steel storage tank is excited by MCE ground motions, the impact occur for all ground motions. In other words, the convective displacement did not affected noticeably by either isolation and/or impact.

REFERENCES

[1] Cooper, T.W. and T.P. Wachholz. *Optimizing post-earthquake lifeline system reliability*. 1999. 5th US conference on lifeline earthquake engineering: ASCE.

[2] Housner, G.W., *The dynamic behavior of water tanks.* Bulletin of the seismological society of America, 1963. **53**(2): p. 381-387.

[3] Rosenblueth, E. and N.M. Newmark, *Fundamentals for Earthquake Engineering*. 1971: Prentice Hall.

[4] Haroun, M.A., *Vibration studies and tests of liquid storage tanks.* Earthquake Engineering and Structural Dynamics, 1983. **11**(2): p. 179-206.

[5] Chalhoub, M.S. and J.M. Kelly, *Theoretical and experimental studies of cylindrical water tanks in base isolated structures*. 1988: Earthquake Engineering Research Center, University of California at Berkeley.

[6] Zayas, V.A. and S.S. Low, *Application of seismic isolation to industrial tanks*. 1995: American Society of Mechanical Engineers, New York.

[7] Malhotra, P.K., *New method for seismic isolation of liquid‐storage tanks.* Earthquake engineering and structural dynamics, 1997. **26**(8): p. 839-847.

[8] Malhotra, P.K., *Method for seismic base isolation of liquid-storage tanks.* Journal of Structural Engineering, 1997. **123**(1): p. 113-116.

[9] Shrimali, M. and R. Jangid, *A comparative study of performance of various isolation systems for liquid storage tanks.* International Journal of Structural Stability and Dynamics, 2002. **2**(04): p. 573-591.

[10] Shrimali, M. and R. Jangid, *Non-linear seismic response of base-isolated liquid storage tanks to bi-directional excitation.* Nuclear Engineering and design, 2002. **217**(1): p. 1-20.

[11] Bagheri, S. and M. Farajian, *The effects of input earthquake characteristics on the nonlinear dynamic behavior of FPS isolated liquid storage tanks.* Journal of Vibration and Control, 2016: p. 1077546316655914.

[12] Abalı, E. and E. Uçkan, *Parametric analysis of liquid storage tanks base isolated by curved surface sliding bearings.* Soil Dynamics and Earthquake Engineering, 2010. **30**(1): p. 21-31.

[13] Virella, J.C., L.A. Godoy, and L.E. Suárez, *Dynamic buckling of anchored steel tanks subjected to horizontal earthquake excitation.* Journal of Constructional Steel Research, 2006. **62**(6): p. 521-531.

[14] Alembagheri, M. and H.E. Estekanchi, *Nonlinear analysis of abovground anchored steel tanks using endurance time method.* Asian Journal of Civil Engineering, 2011. **12**(6): p. 731-750.

[15] Yong-Chul, K., et al., *Seismic isolation analysis of FPS bearings in spatial lattice shell structures.* Earthquake Engineering and Engineering Vibration, 2010. **9**(1): p. 93-102.

16. [16] Jia, G. and Z. Shi, *A new seismic isolation system and its feasibility study.* Earthquake Engineering and Engineering Vibration, 2010. **9**(1): p. 75-82.

[17] Haroun, M.A., *Vibration studies and tests of liquid storage tanks.* Earthquake Engineering & Structural Dynamics, 1983. **11**(2): p. 179-206.

[18] Mokha, A., et al., *Experimental study of friction-pendulum isolation system.* Journal of Structural Engineering, 1991. **117**(4): p. 1201-1217.

[19] Kim, Y.-S. and C.-B. Yun, *Seismic response characteristics of bridges using double concave friction pendulum bearings with tri-linear behavior.* Engineering Structures, 2007. **29**(11): p. 3082-3093.

[20] Fenz, D.M., *Development, implementation and verification of dynamic analysis models for multi-spherical sliding bearings*. 2008: ProQuest.

[21] Simulink, M. and M. Natick, *The MathWorks.* Inc., Natick, MA, 1993.

[22] Shrimali, M. and R. Jangid, *Seismic response of liquid storage tanks isolated by sliding bearings.* Engineering structures, 2002. **24**(7): p. 909-921.

[23] Koketsu, K. and H. Miyake, *A seismological overview of long-period ground motion.* Journal of Seismology, 2008. **12**(2): p. 133-143.

[24] Malekzadeh, M. and T. Taghikhany, *Adaptive behavior of double concave friction pendulum bearing and its advantages over friction pendulum systems.* Scientia Iranica. Transaction A, Civil Engineering, 2010. **17**(2): p. 81.

[25] Mortezaei, A. and H.R. Ronagh, *Effectiveness of modified pushover analysis procedure for the estimation of seismic demands of buildings subjected to near-fault ground motions having fling step.* Nat. Hazards Earth Syst. Sci., 2013. **13**(6): p. 1579-1593.

[26] Colombo, J.I., Almazán, J.L. *Seismic reliability of legged wine storage tanks retrofitted by means of a seismic isolation device*. Engineering Structures. 2017, 134:303-16.

[27] Hashemi, S., Aghashiri, M.H. *Seismic responses of base-isolated flexible rectangular fluid containers under horizontal ground motion*. Soil Dynamics and Earthquake Engineering. 2017, 100:159-68.