Earthquakes and Structures, *Vol. 16, No. 5 (2019) 523-532*
DOI: https://doi.org/10.12989/eas.2019.16.5.523

Seismic protection of LNG tanks with reliability based optimally designed combined rubber isolator and friction damper

Ali Khansefid*, Ali Maghsoudi-Barmi[a] and Alireza Khaloo[b]

Civil Engineering Department, Sharif University of Technology, Azadi Ave., Tehran, Iran

(Received October 10, 2018, Revised February 9, 2019, Accepted March 24, 2019)

Abstract. Different types of gas reservoir such as Liquid Natural Gas (LNG) are among the strategic infrastructures, and have great importance for any government or their private owners. To keep the tank and its contents safe during earthquakes especially if the contents are of hazardous or flammable materials; using seismic protection systems such as base isolator can be considered as an effective solution. However, the major deficiency of this system can be the large deformation in the isolation level which may lead to the failure of bearing system. In this paper, as a solution, the efficacy of an optimally designed combined vibration control system, the combined laminated rubber isolator and rotational friction damper, is investigated to evaluate the enhancement of an existing metal tank response under both far- and near-field earthquakes. Responses like impulsive and convective accelerations, base shear, and sloshing height are studied herein. The probabilistic framework is used to consider the uncertainties in the structural modeling, as well as record-to-record variability. Due to the high calculation cost of probabilistic methods, a simplified structural model is used. By using the Mont-Carlo simulation approach, it is revealed that this combined isolation system is a highly reliable system which provides considerable enhancement in the performance of reservoir, not only leads to the reduction of probability of catastrophic failure of the tank but also decrease the reservoir damage during the earthquake. Moreover, the relative displacement of the isolation level is controlled very well by this combined system.

Keywords: combined isolation system; rotational friction damper; rubber; optimization; probabilistic framework; LNG tank

1. Introduction

Reservoirs are one of the most applicable types of infrastructures. By considering this fact, and the day to day development of new technologies in building construction industry, obviously design codes are not exceptional and changed a lot during the recent decades. Accordingly, if the seismic performance of existing tanks were assessed, it might be declared that many of them cannot satisfy the new seismic requirements. This can be mainly due to the changes in design codes, structural damages during the operation, changes in the imposed loads on the structure during its life-time, and etc. The common types of tank damages are elephant-foot buckling, local buckling of upper part of tank due to sloshing and fracture in the joint connections (Malhotra *et al*. 2000). Nowadays, with the great development in the field of seismic protection systems, it is very convenient to rehabilitate the existing structure by passive vibration control systems such as rubber isolator, friction isolator, viscous dampers, friction dampers, tuned mass dampers and etc. (Christopoulos *et al*. 2006, Khansefid and Ahmadizadeh 2016). The application of these devices, especially seismic isolation systems, is rapidly growing during the recent decades in order to improve the performance of tanks as it is done in Incheon, South Korea (STRABAG 2017); island of Revithoussa, Greece (EPS 2017); and Pampa Melchoritam, Peru (EPS 2017).

Beside the practical implementation of isolators in retrofitting of tanks which mentioned above, there are many theoretical researches in this field. Housner’s (1982) work is one of the earliest one which deals with the water tank behavior. Veletsos (1984), Veletsos and Tang (1990), Veletsos *et al*. (1990), in several researches assessed the behavior of the anchored and non-anchored tanks. In another study, Malhotra (1997, 1998) investigated the seismic behavior of the reservoirs by considering the effect of soil interaction. In further researches (Malhotra 1997, 1998), he also evaluated the effectiveness of energy dissipating devices as well as seismic isolation systems on the performance of reservoirs. Shirmali and Jangid (2002) modeled the behavior of isolated tank in two horizontal directions. Calugaru and Mahin (2009) studied the performance of seismically isolated tank by triple pendulum friction isolators both theoretically and experimentally. Panchal and Jangid (2008) presented a comparative study about the efficacy of different friction isolators on the response of tanks. Later they (Panchal and Jangrid 2011) tested the efficiency of variable frequency friction isolator on the reservoir behavior. In another study (Panchal and Jangid 2012), they investigated earthquake response of slender and broad liquid storage steel tanks isolated with

*Corresponding author, Ph.D.
E-mail: khansefidali@gmail.com
[a]Ph.D. Candidate
E-mail: ali.maghsoudi@student.sharif.edu
[b]Distinguished Professor
E-mail: khaloo@sharif.edu

http://www.techno-press.com/journals/eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

Fig. 1 Application of RFD and isolation system in the 5-story laboratory building in Osaka, Japan (Nielsen *et al*. 2004)

variable curvature friction pendulum systems (VCFPSs) under near-fault motions. Shekari *et al*. (2009) investigated the ability of seismic isolation system to enhance the response of liquid storage tank in the presence of fluid-structure interaction. The seismic performance of tanks equipped with the multiple friction pendulum system is studied by Zhang *et al*. (2011). Uckan *et al*. (2015) comparatively studied the effectiveness of high damping rubber bearing and friction pendulum system to isolate the elevated tank, and Razzaghi and Eshghi (2014) worked in a probabilistic domain, to develop the fragility curves for the fixed base cylindrical oil tank.

As it is seen in the mentioned works, the great number of research works are carried on the behavior of the seismically isolated reservoir using deterministic approaches. However, little attention has been devoted on the probabilistic evaluation of a special type of isolated tank. Intrinsic uncertain characteristics of a natural phenomenon like earthquake besides the uncertainty in mechanical properties of the system thoroughly show the importance of using a strong probabilistic evaluation framework. This topic has attracted many researchers in recent years, especially for infrastructures in other fields (Marano 2005, Sistani *et al*. 2013, Khansefid and Vaezzadeh 2015, Li *et al*. 2017, Beheshti *et al*. 2017, Castaldo *et al*. 2017, 2018, Khansefid and Bakhshi 2019).

In this paper, an attempt is made to assess the performance of LNG tanks equipped with the combined vibration control system, namely, laminated rubber and rotational friction damper (RFD), which were first introduced by Barmo *et al*. (2015) and has been used in several practical projects (Fig. 1) in Japan (Nielsen *et al*. 2004). The main privilege of this system is reducing the huge lateral deformation of the rubber isolation system which can cause serious damages to the structures as it is reported for the multiple bridges experienced the rupture in their isolation bearing system during the Tohoku earthquake in Japan in 2011 (Takahashi 2011). Additionally, less sensitivity to the environmental temperature, no dependency of the base isolation system hysteresis behavior to the level of fluid in tank, and convenient repair and maintenance are some of the other advantages of this system which show its superiority to other common vibration control systems, like lead rubber bearing or friction pendulum system. However, the characteristics of this combined system may cause some residual deformation in the device after the intensive earthquakes which needs some additional site work to release the pre-stressing forces on the friction pads and consequently re-centering of the structure by its internal elastic forces (Shrestha *et al*. 2016).

In order to achieve a comprehensive inference about the performance of the considered vibration control system, the probabilistic approach is used in this paper, i.e., a Mont-Carlo simulation method. Due to the very large calculation cost of probabilistic methods, the simple structural model is used to model the whole system. In other words, the tank liquid content mass is divided into the impulsive and convective part, and the whole system is considered as a mass-spring model.

By developing the cumulative density functions of LNG tank responses, it is revealed that this combined isolation system is greatly capable of enhancing the tank behavior. The convective and impulsive acceleration and displacement responses of system are decreased in most cases as well as the base shear. However, the sloshing height of tank content does not improve significantly. Besides, the isolation device displacement is remained in a low level due to the existence of supplemental damping system.

2. Modeling

The best method to model tanks with the fluid contents is the nonlinear finite element methods by considering appropriate fluid and structure interaction (Shekari *et al*. 2009, Cho *et al*. 2002, Kim *et al*. 2002). Performing nonlinear time history analysis for such a model will confront convergence difficulty throughout the analysis and take too much time. Therefore, for the probabilistic modeling with a large number of analyses, it is impractical to use the fully detailed model. Hence, in this work, the simplified model of reservoir presented by Malhotra (Malhotra *et al*. 2000) is used. The important point of this procedure is the accuracy of the method which is studied by Goudarzi and Sabbagh-Yazdi (2009). Their research showed an acceptable agreement between the results of nonlinear dynamic time history analysis of finite element model and simple mass-spring method.

In the research, it is attempted to consider all the possible sources of uncertainties. In this regard, two different categories are considered: record-to-record variability; and structural modeling uncertainties such as mass, stiffness, damper parameter and etc.

2.1 Ground motion modeling

The most important source of uncertainty in estimation of the response of any structure by dynamic time history method is the earthquake input accelerograms. In order to take this uncertainty into account, a method presented by Khansefid and Vaezzadeh (2015) is used, based on which, an earthquake record with a random peak ground acceleration (PGA) is generated. Steps of this method are as follow:

a. Selecting a set of earthquake records (180 suggested earthquake records by SAC (http://nisee.berkeley.edu)

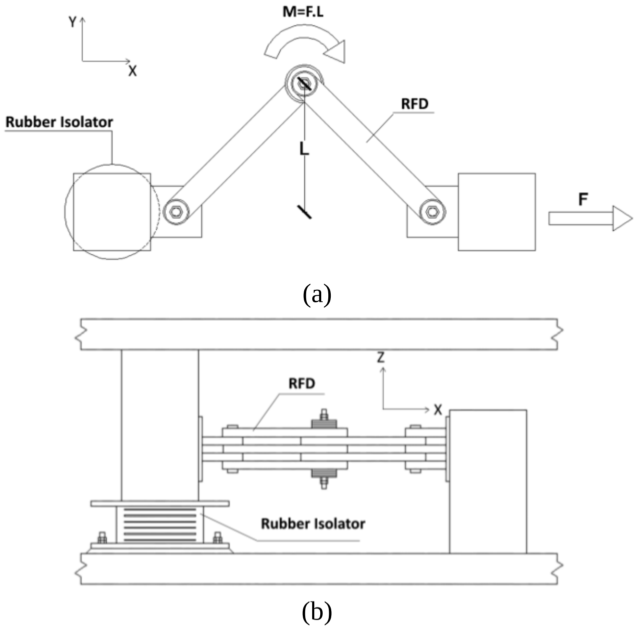


Fig. 2 The schematic of combined rubber isolator and friction damper: (a) Plan, (b) View

project for Los-Angeles (LA), Boston (BO), and Seattle (SE) are used, which are all for soil type S_d of ASCE7-16 (2016) and containing both far- and near-field events.
b. Categorizing the accelerograms based on their PGA in five separate bins (0 to 0.4 g, 0.4 g to 0.8 g, 0.8 g to 1.2 g, 1.2 g to 1.6 g, and 1.6 g to 2.0 g).
c. Producing random PGA from the Los-Angeles hazard curve (Peteren *et al*. 1996) (the lower bound of the curve is scaled to 0.3 g).
d. Selecting a record randomly from the bin of records that the generated random PGA of step c locates between its boundary.
e. Scaling the selected record to the obtained PGA of step c.

2.2 Combined control system, laminated rubber isolator and rotational friction damper

In this research, the combined vibration control system including rubber isolator and rotational friction damper is used to improve the performance of LNG tanks. The laminated rubber bearing stiffness is much lower than the superstructure, thus it can practically separate the structure from the ground at the isolation level. However, as a main disadvantage, these bearings provide a low level of energy absorption which may causes large lateral displacement in severe earthquakes. This problem can be solved by adding the RFD parallel to the rubber unit. RFD has great capability to absorb the seismic energy. Therefore, it can keep the lateral displacement of the isolation level in the desired range. The schematic view of this combined control system is presented in Fig. 2.

The schematic of force-displacement behavior of this combined system is illustrated in Fig. 3. As it is seen, adding the RFD to the rubber bearing leads to a great energy absorption capacity. During the earthquake, this system is not activated while the lateral force in the vibration control system is less than the sliding force of friction pad surfaces of RFD. Afterward, and right at the moment that lateral force in the system reaches to the sliding force, the friction damper is activated and the whole system will experience lateral deflection which then is controlled by the lateral stiffness of rubber.

2.3 Reservoir simple modeling and equation of motion

In order to obtain the equation of motion of a fluid tank equipped with the combined isolation system for the nonlinear dynamic time history analysis, the simplified procedure introduced by Malhotra *et al*. (2000) is used. This procedure considerably helps to reduce the calculation cost of probabilistic modeling. Accordingly, the whole reservoir and its content are modeled by a 4 degree of freedoms system which is shown in Fig. 4. These DOFs include relative displacements of combined isolation system, tank wall, and inner fluid content divided to the impulsive and convective part. The impulsive mass is a part of fluid which will excites with the rhythm of the tank structure, and the convective one is the upper level of the fluid, near its surface, which causes a sloshing motion. Therefore, in this figure, m_t, m_i, m_c, and m_b are mass of tank wall, impulsive mass, convective mass, and base isolation level mass, respectively. u_t, u_i, u_c, u_b, and u_g are the relative displacement of tank wall, impulsive mass, convective mass, combined isolation level and input ground motion excitation, respectively.

The equation of motion of this model is written as below:

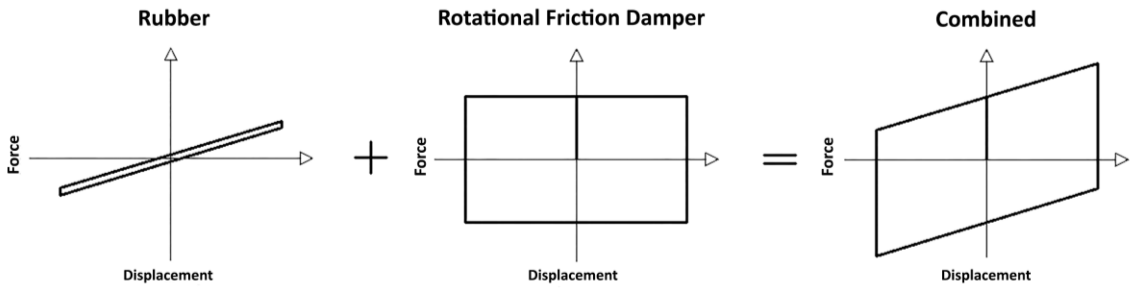
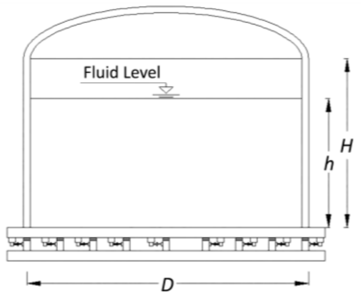
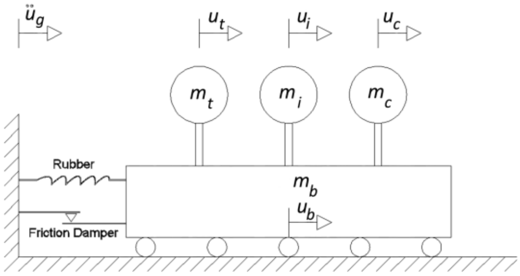


Fig. 3 Hysteretic behavior of the combined rubber isolator and rotational friction damper using for the non-linear dynamic time history analysis



(a)



(b)

Fig. 4 Isolated tank with combined rubber plus rotational friction damper: (a) Schematic of Isolated tank, (b) Analytical model

$$\begin{bmatrix} m_b & & & \\ & m_i & & \\ & & m_c & \\ & & & m_t \end{bmatrix}\begin{bmatrix} \ddot{u}_b \\ \ddot{u}_i \\ \ddot{u}_c \\ \ddot{u}_t \end{bmatrix}+\begin{bmatrix} c_i+c_c+c_t & -c_i & -c_c & -c_t \\ -c_i & c_i & & \\ -c_c & & c_c & \\ -c_t & & & c_t \end{bmatrix}\begin{bmatrix} \dot{u}_b \\ \dot{u}_i \\ \dot{u}_c \\ \dot{u}_t \end{bmatrix}+\begin{bmatrix} k_i+k_c+k_t & -k_i & -k_c & -k_t \\ -k_i & k_i & & \\ -k_c & & k_c & \\ -k_t & & & k_t \end{bmatrix}\begin{bmatrix} u_b \\ u_i \\ u_c \\ u_t \end{bmatrix}+\begin{bmatrix} F_{iso} \\ 0 \\ 0 \\ 0 \end{bmatrix}=\begin{bmatrix} m_b & & & \\ & m_i & & \\ & & m_c & \\ & & & m_t \end{bmatrix}\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}\ddot{u}_g \tag{1}$$

where indices b, i, c, and t correspond to the four DOFs of the system, namely, isolation level, impulsive mass, convective mass, and the tank structure degree of freedom. In addition, parameters m, c, and k are the mass, damping, and stiffness, respectively, and $\ddot{u}_g$ is the ground motion acceleration. The inherent damping matrix of this equation of motion is calculated using the Rayleigh method (Chopra, 2011) by assuming the first and third modes damping values equal to 2% (Malhotra *et al*. 2000) for steel tanks.

To calculate the impulsive and convective masses, stiffness, periods and heights the Malhotra *et al*. (2000) method is considered. According to this method, these parameters are calculated based on the height to radius ratio of the fluid content of tank. In other words, for different ratios of fluid total height to its radius, the ratio for impulsive and convective masses and heights to the total fluid mass and height are presented by the abovementioned research. Additionally, impulsive and convective periods of the fluid content of tank are obtained by Eqs. (2) and (3) using the geometry properties of tank and its content as below:

$$T_{imp}=C_i\frac{H\sqrt{\rho}}{\sqrt{t/r}\sqrt{E}} \tag{2}$$

$$T_{con}=C_c\sqrt{r} \tag{3}$$

where H, r, t, E, ρ are the fluid height, tank radius, tank wall thickness, tank wall module of elasticity, and fluid density, respectively. C_i and C_c are coefficients represented by Malhotra *et al*. (2000).

The impulsive and convective stiffness of the fluid are also calculated by the principle definition of the period of vibration (Chopra 2011)

$$k_i=4\pi^2\frac{m_i}{T_{imp}^2} \tag{4}$$

$$k_c=4\pi^2\frac{m_c}{T_{con}^2} \tag{5}$$

After determining values of fluid properties, the tank mechanical properties (stiffness and mass) are divided into two parts; the first one is the mass of tank roof and its body; and the second one is the mass of isolation level which are clearly shown in Fig. 4.

At this step, in order to consider uncertainties in tank properties such as fluid mass (convective and impulsive), tank mass, isolation level mass, fluid density, tank dimensions, material properties, and isolation system properties, the Log-normal distribution is adopted to produce random input values for the model parameters. The mean value and the coefficient of variation of each random variable is assumed and reported in Table 1 based on the values suggested by Joint Committee of Structural Safety

Table 1 Mean value and the coefficient of variation of the model parameters

Parameter	Mean Value	Coefficient of Variation
Tank fluid height (m)	20	0.2
Tank radius (m)	25	0.02
k_t (kN/m)	75,000,000	0.03
m_t (kg)	5,000,000	0.1
m_b (kg)	4,000,000	0.1
m_i+m_c (kg)	31,500,000	0.1
Tank wall thickness (m)	0.02	0.02
Tank wall modulus of elasticity (GPa)	200	0.02
Fluid density (kg/m3)	800	0.02
Rubber isolator stiffness* (kN/m)	1000	0.02
Rotational friction damper capacity** (kN)	Variable	0.02
T_{imp} (s)	0.97	___
T_{con} (s)	7.85	___
C_i	6.77	___
C_c	1.57	___

* The value is for each rubber isolator unit, 100 units exist.

** Damper capacity is reported for all isolator units; 100 units exist.

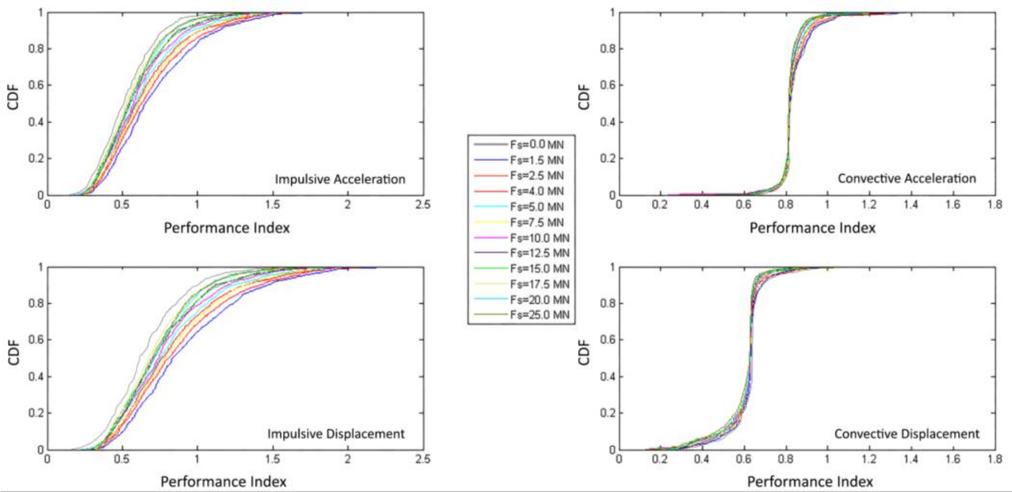


Fig. 5 CDF of the response of LNG tank for all introduced performance indices, for all slip loads

[JCSS] (2001) for the material uncertainty modeling with some minor modifications. The JCSS is a guideline for the probabilistic analysis procedure.

2.4 Fundamentals of probabilistic method

To pace through a more real modeling, the probabilistic framework is considered. There are many simulation methods (Robert and Casella 2004, Mackay 1998) such as Mont-Carlo sampling, importance sampling, rejection sampling, Metropolis sampling, slice sampling, histogram sampling and etc. Here in this research, the first one is adopted. The most important point of Mont-Carlo simulation method is the minimum number of required samples to reach to the desired accuracy level in the results. Accordingly, the minimum number of samples required to achieve a target coefficient of variation for the specified probability level is obtained by the following formula

$$N_{\min} = \frac{1}{\delta^2} \frac{P}{1-P} \tag{6}$$

where δ is the coefficient of variation of sampling and P is any arbitrary point of probability density function (PDF) diagram calculated from Eq. (7)

$$P = P(R < R_0) \tag{7}$$

in which R is the system response and R_0 is the desired limit state.

3. Analysis and results

The combined isolation system properties are going to be obtained via an optimization process. The mean value of the activation load of RFD is considered as a decision variable of optimization. Sweeping optimization method is used to obtain the best value for slip force. In this regard, firstly, a wide practical range of activation forces for each device is used including 15, 25, 40, 50, 75, 100, 125, 150, 175, 200, and 250 kN. Additionally, a case in which the RFD does not exist (sliding force equal to zero) and only rubber bearing works is considered beside the abovementioned values. However, this case is not participated in the optimization process. Afterward, it is necessary to define a desired performance index (*PI*) to find the optimal design. In this work, four separate indices are taken into account and for each one, an optimization process is done and results are obtained separately. These indices are as following

$$PI_{A-\text{cov}} = \left(\frac{A_{Isolated}}{A_{Non-Isolated}} \right)_{Convective} \tag{8}$$

$$PI_{A-imp} = \left(\frac{A_{Isolated}}{A_{Non-Isolated}} \right)_{impulsive} \tag{9}$$

$$PI_{D-\text{cov}} = \left(\frac{D_{Isolated}}{D_{Non-Isolated}} \right)_{Convective} \tag{10}$$

$$PI_{D-imp} = \left(\frac{D_{Isolated}}{D_{Non-Isolated}} \right)_{impulsive} \tag{11}$$

where A is the maximum absolute value of acceleration response, and D is the maximum value of relative displacement response to the top of isolation level. As it is seen, each *PI* is calculated by dividing the response of isolated tank to the non-isolated one. Hence, for each case, two separate analyses are done, one for the non-isolated system and another for the isolated tank.

As mentioned before, eleven different alternative values are considered in the sweeping optimization process for acquiring the sliding force capacity of the friction isolator as a decision variable. To obtain the whole cumulative density function (CDF) of the performance indices of system, 1000 analyses are done for each RFD alternative, which is determined based on the Mont-Carlo sampling method (Eq. (6)) to achieve the calculation precision of 10% (COV=0.1) in the probability level of the 90% (P=0.9). Therefore, totally, 11000 nonlinear dynamic time history analysis are carried out in this research to evaluate the behavior of the LNG tank equipped with the

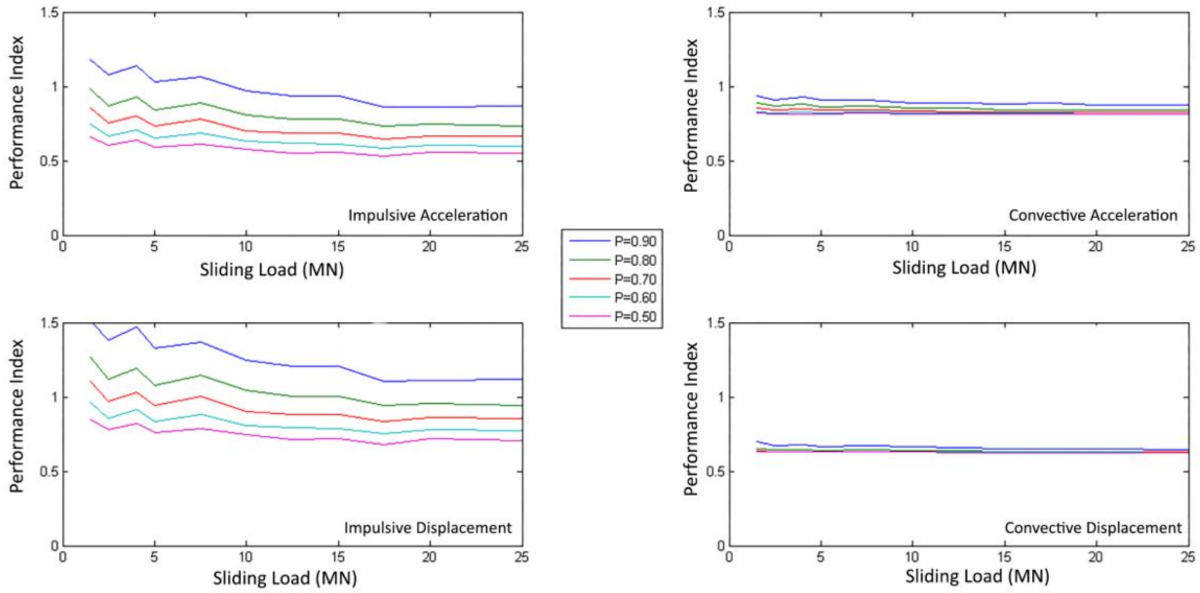


Fig. 6 Optimization diagram of the isolated tank for all performance indices and reliability level

combination of rubber isolation and rotational friction damper.

3.1 Optimal design

By using the large database of system responses created in this work, it is possible to build a CDF of different desired responses of LNG tank mounted on the combined rubber isolator and rotational friction damper. Accordingly, the CDF of previously introduced performance indices are illustrated in Fig. 5.

The most important observation in Fig. 5 is the great capability of the combined isolation system to enhance the tank content responses. The probability level of achieving improvement (*PI*<1) by using this combined isolation system under any desired earthquake excitation is almost more than 80% for impulsive acceleration; 65% for impulsive displacement; 95% for convective acceleration; and almost 99% for convective displacement. Moreover, by decreasing the sliding load of the friction damper, the content responses (both displacement and acceleration) do not improve necessarily. In other words, for some probability levels, it is possible to face the performance index with the value of higher than one. This can be due to the closeness of effective period of isolation system (about 0.6 to 0.8) to tank's content one (T_{imp} equal to 0.97), which may cause a limited resonance in the responses. Additionally, it is seen that when the damping system is removed, the impulsive responses improve. However, the convective responses do not experience this enhancement. In this case, by considering the resonance phenomena in the response of system, the natural period of isolation system is equal to 4.0 second which means that the natural period of isolation system is getting away from the impulsive period and getting close to the convective one in compare to the case of using RFD. Another interesting observation is the less sensitivity of convective responses to the sliding force of the damping system than the impulsive one.

To find the optimal solution, different specific probability levels are selected, namely, 90%, 80%, 70%, 60%, and 50%; and the optimization is performed for each reliability level. By this method, the risk level is taken into account in the optimization process. The results of this optimization method are illustrated in Fig. 6.

In optimization diagrams, each curve shows the result for specific reliability level, i.e., the excepted probability of facing results equal to or less than the illustrated one. As an example, level *P* equal to 0.90 means by a probability of 90% the system will experience the response equal or better than the ones illustrated in the Fig. 6. Accordingly, it is inferred from this figure that by the probability of 80% for all damping properties alternatives the impulsive acceleration response of the whole system is improved (*PI*<1). This probability level for the impulsive displacement, convective acceleration and convective displacement responses are 60%, 90%, and 90% respectively. In general, these diagrams confirm that the combined isolation system is a highly reliable system capable of enhancing the convective responses more than the impulsive one.

The optimal sliding force for all probability level, in Fig. 6, is almost the same, which implies that the risk level does not affect the final optimal design significantly. Therefore, as it is seen, generally by considering all performance indices simultaneously, increase of the sliding force beyond the 17.5 MN, has no tangible effects on the optimal result. Thus, the optimal design value for sliding force is selected equal to be 17.5 MN.

3.2 Optimal design results

In this part, some important responses of optimally designed isolated LNG tank (with the slip force of 17.5 MN) including impulsive and convective accelerations, impulsive and convective displacements, isolation level displacement, base shear force, and sloshing height of the

Table 2 Impulsive and convective acceleration responses of optimally isolated and fixed LNG tank

Probability level (CDF)	Impulsive acceleration (m/s^2)			Convective acceleration (m/s^2)		
	Fixed	Isolated	Improvement (%)	Fixed	Isolated	Improvement (%)
0.90	18.23	17.13	6.3	1.75	1.52	13.0
0.80	14.42	10.78	25.2	0.72	0.59	18.0
0.70	12.11	7.91	34.7	0.34	0.28	18.0
0.60	10.37	6.50	37.3	0.19	0.15	16.0
0.50	9.04	4.91	45.7	0.12	0.10	17.0

Table 3 Impulsive and convective displacement responses of optimally isolated and fixed LNG tank

Probability level (CDF)	Impulsive displacement (m)			Convective displacement (m)		
	Fixed	Isolated	Improvement (%)	Fixed	Isolated	Improvement (%)
0.90	1.05	1.33	-26.0	2.60	1.70	34.0
0.80	0.90	0.97	-8.0	1.08	0.68	37.0
0.70	0.61	0.55	10.0	0.50	0.32	36.0
0.60	0.42	0.34	19.0	0.29	0.18	37.0
0.50	0.26	0.19	27.0	0.17	0.11	37.0

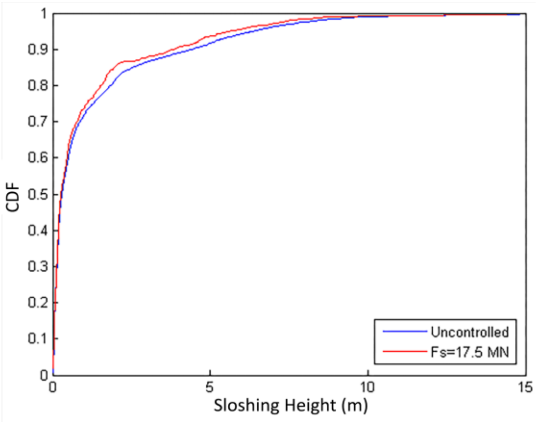


Fig. 7 Sloshing height of the LNG content

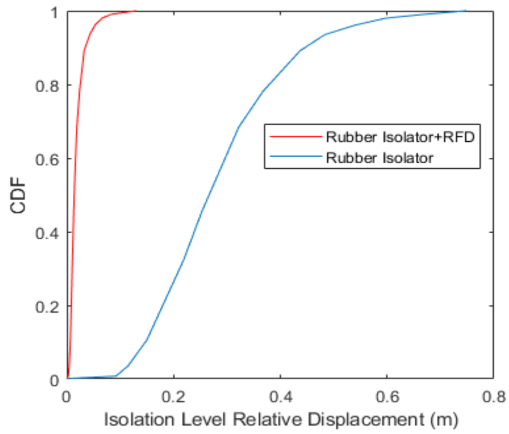


Fig. 8 Isolation level lateral relative displacement for F_s equal to 17.5 MN and F_s equal to zero

liquid content are evaluated.

The acceleration and displacement responses of optimal design are presented in Tables 2 and 3 for various probability level. It is indicated that by using combined rubber isolation system and RFD, the acceleration response of LNG tank content is decreased considerably, especially for the lower target probability level. As another fact, on average, the impulsive acceleration is much higher than the convective one in both fixed base and isolated tank.

As it is seen in Tables 2, and 3, convective displacement response of tank content is enhanced by using the combined isolation system. However, the impulsive one in higher probability level is not improved. In other words, using base isolation leads to a closer natural period of isolated system (about 0.6 to 0.8 in intensive earthquakes) to the tank content (T_{imp} equal to 0.97). Therefore, the improvement of the impulsive displacement for higher risk level or more severe seismic events is not guaranteed. Also it should be kept in mind that the effective period of the whole system is affected by both rubber bearing stiffness, which is assumed equal to 1000 kN/m in this study, and the effective stiffness of the RFD.

As another important response, sloshing height of the LNG tank content is assessed. To calculate the sloshing height of the content, proposed method by Malhotra (2006) is adopted. Accordingly, sloshing height of the LNG content is calculated by the following formula

$$SH = R\left(\frac{(A_{convective})_{max}}{g}\right) \quad (12)$$

where R is the radius of tank, $A_{convective}$ is the convective acceleration response of the content, and g is the gravity acceleration. In this study, it is assumed that there is no restriction for the sloshing height, even if the sloshing height is in the range of 15 m. The results of isolated and non-isolated tank are illustrated in Fig. 7.

It is observed that the combined isolation system slightly reduces the sloshing height of LNG tank content. In different probability levels of 0.90, 0.80, 0.70, 0.60, and 0.50 the sloshing height is decreased by 13.6%, 17.9%, 17.8%, 16.0%, and 17.0%, respectively. It implies that the capability of combined isolation system in reducing the sloshing height of tank content is independent of the risk level of the analysis.

One of the most important advantages of using RFD in the isolation system is its capability of controlling the relative displacement in the isolation level. The maximum value obtained for the isolation level displacement with RFD, illustrated in Fig. 8, is equal to 0.10 m, while without the RFD it increases up to 0.80 m. Moreover, in the case of existence of RFD, the isolation level relative displacement for the probability levels of 0.90, 0.80, 0.70, 0.60, and 0.50 is 0.032 m, 0.024 m, 0.019 m, 0.016 m, and 0.014 m, respectively. However, by removing the RFD from the isolation levels these values increase significantly to 0.442 m, 0.382 m, 0.332 m, and 0.282 m. These results show the acceptable performance for the RFD in order to control the isolation level displacement which is one of the major concerns in rubber bearings and other types of isolation systems.

Another main response parameter, is the base shear

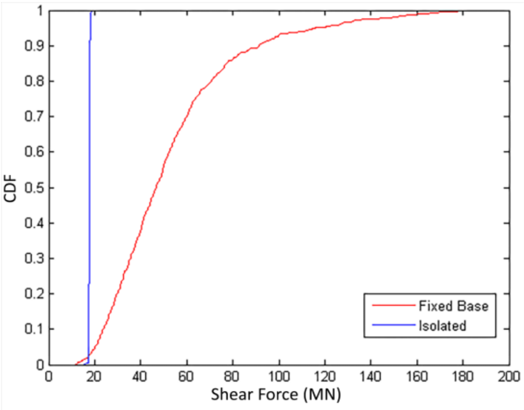


Fig. 9 Maximum base shear of the tank with and without optimal combined isolation system

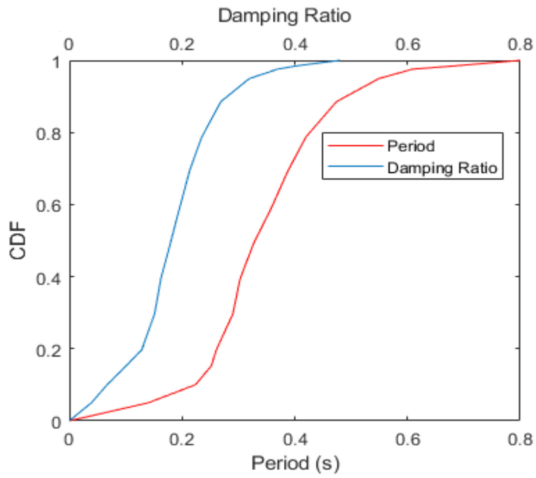


Fig. 10 CDF of the effective period, and effective damping ratio of optimal combined isolation system

response of tank. By using the RFD in the isolation level beside the laminated rubber, the base shear level is limited to the sliding capacity of the RFD, as it is clearly seen in Fig. 9. In the probability level of the 0.90, 0.80, 0.70, 0.60, and 0.50, application of combined isolation system leads to great reduction in base shear which is equal to 80.8%, 75.2%, 71.0%, 66.6%, and 62.4%, respectively, and show the highly reliable performance of this system.

At the end, to have an overall perspective, the effective damping ratio and effective period of the whole tank and isolation system is calculated based on the procedure of ASCE7-16 (2016) and illustrated in Fig. 10. It is shown that the effective period of isolated tank varies between 0.1 to 0.8 second in the different risk (or seismic intensity) level with the mean value of 0.57 second. While the equivalent damping ratio varies between 0.06 to 0.47 with the mean value of 0.18. This almost low level of effective period, as well as relatively high value of damping ratio may be interpreted as a result of application of the rotational friction dampers which causes less desired deformation in the isolation level by increasing the energy absorption capability of base isolation system, especially in the more severe earthquake.

4. Conclusions

Performance of a new combined isolation system including rubber isolation and RFD is evaluated in the probabilistic domain. 11000 nonlinear dynamic time history analyses are performed to find the optimal design by the specified risk level. In general, using combined isolation system improves the response of tank. However, in some rare cases the responses of isolated tank may increase in comparison with the non-isolated tank. It is observed that, for all the reliability levels, in the presence of combined control system, the acceleration response of tank content is increased by decreasing the sliding force capacity of rotational friction damper, since the natural period of whole system is getting closer to the natural period of contents, especially convective period while the sloshing height of tank content decreases slightly. In addition, it is seen that for either acceleration responses or displacement responses of the tank content, selected as an optimization target, the risk level of optimization does not affect the optimal value of the sliding force capacity of RFD. Moreover, the system base shear is significantly reduced by using combined isolation, and finally the isolation level displacement is observed to be very low. All of these results prove that the combined isolation system with rotational friction damper is a highly reliable solution for improving the existing tanks as an important infrastructure. However, it is needed to keep in mind that an accurate design procedure should be followed to improve the performance of both structural and tank fluid contents simultaneously.

Reference

American Society of Civil Engineering (ASCE) (2016), ASCE7: Minimum Design Loads for Buildings and Other Structures, SEI, Reston, Virginia.

Barmo, A., Mualla, I.H. and Hasan, H.T. (2015), “The behavior of multi-story buildings seismically isolated hybrid isolation (Friction, rubber and with the additional rotational friction damper)”, *J. Earthq. Res.*, **4**, 1-13. http://dx.doi.org/10.4236/ojer.2015.41001.

Beheshti Aval, S.B., Farrokhi, A., Fallah, A. and Tsouvalas, A. (2017), “The seismic reliability of two connected SMRF structures”, *Earthq. Struct.*, **13**(2), 151-164. https://doi.org/10.12989/eas.2017.13.2.151.

Calugaru, V. and Mahin, S.A. (2009), “Experimental and analytical studies of fixed-base and seismically isolated liquid storage tank”, *Proceedings of the 3rd International Conference on Advances in Experimental Structural Engineering*, San-Francisco, USA.

Castaldo, P., Palazzo, B. and Della Vecchia, P. (2015), “Seismic reliability of base-isolated structures with friction pendulum bearings”, *Eng. Struct.*, **95**, 80-93. https://doi.org/10.1016/j.engstruct.2015.03.053.

Castaldo, P., Palazzo, B. and Ferrentino, T. (2017), “Seismic reliability-based ductility demand evaluation for inelastic base-isolated structures with friction pendulum devices”, *Earthq. Eng. Struct. Dyn.*, **46**(8), 1245-1266. https://doi.org/10.1002/eqe.2854.

Cho, H.H., Kim, M.K., Lim, Y.M. and Cho, S.Y. (2004), “Seismic response of base isolated liquid storage tanks considering fluid-structure-soil interaction in time domain", *Soil Dyn. Earthq. Eng.*, **24**, 839-852. https://doi.org/10.1016/j.soildyn.2004.05.003.

Chopra, A. (2011), *Dynamics of Structures- Theory and Applications to Earthquake Engineering*, Prentice Hall, India.

Christopoulos, C., Filiatrault, A. and Bertero, V.V. (2006), *Principle of Passive Supplemental Damping and Seismic Isolation*, IUSS Press, Italy.

EPS. Earthquake Protection Systems Inc. (2016), http://www.earthquakeprotection.com/industrial_liquefied_natural_gas_storage_tanks.html.

Goudarzi, M.A. and Sabagh Yazdi, S.R. (2009), "Numerical investigation on accuracy of mass spring models for cylandrical tanks under seismic excitation", *Int. J. Civil Eng.*, **7**(3), 190-202.

Housner, G.W. (1982), "Dynamic analysis of fluids in containers subject to acceleration", ASCE Technical Seminar, Los-Angeles, USA.

Joint Committee of Structural Safety (2001), Probabilistic Model Code: Part III-Resistance Models, Denmark Technical University, Denmark.

Khansefid, A. and Ahmadizadeh, M. (2016), "An investigation of the effects of structural nonlinearity on the seismic performance degradation of active and passive control systems used for supplemental energy dissipation", *J. Vib. Control*, **22**(16), 3544-3554. https://doi.org/10.1177/1077546314563969.

Khansefid, A. and Bakhshi, A. (2019), "Advanced two-step integrated optimization of actively controlled nonlinear structure under mainshock-aftershock sequences", *J. Vib. Control*, **22**(4), 748-762. https://doi.org/10.1177/1077546318795533.

Khansefid, A. and Vaezzadeh, A. (2015), "Probabilistic optimization of viscous dampers in non-linear structure", *Proceedings of the 5th International Conference on Acoustics and Vibration*, Tehran, Iran.

Kim, M.K., Lim, Y.M., Cho, S.Y., Cho, K.H. and Lee, K.W. (2002), "Seismic analysis of base-isolated liquid storage tanks using the BE-FE-BE coupling technique", *Soil Dyn. Earthq. Eng.*, **22**(9-12), 1151-1158. https://doi.org/10.1016/S0267-7261(02)00142-2.

Li, Z., He, M., Lam, F., Zhou, R. and Li, M. (2017), "Seismic reliability evaluation of steel-timber hybrid shear wall systems", *Earthq. Struct.*, **13**(3), 289-297. https://doi.org/10.12989/eas.2017.13.3.289.

Mackay, D.J.C. (1998), *Introduction to Monte Carlo Methods, in Learning in Graphical Models*, MIT Press, Cambridge, USA.

Malhotra, P.K. (1995), "Base uplift analysis of flexibly supported liquid storage tank", *J. Earthq. Eng. Struct. Dyn.*, **24**(12), 1591-1607. https://doi.org/10.1002/eqe.4290241204.

Malhotra, P.K. (1997a), "Seismic response of soil-supported unanchored liquid storage tank", *J. Struct. Eng.*, ASCE, **123**(4), 440-450. https://doi.org/10.1061/(ASCE)0733-9445(1997)123:4(440).

Malhotra, P.K. (1997b), "New method for seismic isolation of liquid-storage tanks", *J. Earthq. Eng. Struct. Dyn.*, **26**(8), 839-847. https://doi.org/10.1002/(SICI)1096-9845(199708)26:8<839::AID-EQE679>3.0.CO;2-Y.

Malhotra, P.K. (1998), "Seismic strengthening of liquid storage tanks with energy-dissipating anchors", *J. Struct. Eng.*, **124**(4), 405-414. https://doi.org/10.1061/(ASCE)0733-9445(1998)124:4(405).

Malhotra, P.K. (2006), "Earthquake induced sloshing in tanks with insufficient freeboard", *Struct. Eng. Int.*, **16**(3), 222-225.

Malhotra, P.K., Wenk, T. and Wieland, M. (2000), "Simple procedure for seismic analysis of liquid-storage tanks", *Struct. Eng. Int.*, **10**(3), 197-201.

Marano, G.C. (2005), "Probabilistic seismic response and reliability assessment of isolated bridges", *Earthq. Eng. Eng. Vib.*, **4**(1), 95-106. https://doi.org/10.1007/s11803-005-0028-5.

Nielsen, L.O., Mualla, I.H. and Iwai, Y. (2004). "Seismic Isolation with a new friction-viscoelastic damping system", *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

Panchal, V.R. and Jangid, R.S. (2008), "Variable friction pendulum system for seismic isolation of liquid storage tanks", *Nucl. Eng. Des.*, **238**(6), 1304-1315. https://doi.org/10.1016/j.nucengdes.2007.10.011.

Panchal, V.R. and Jangid, R.S. (2011), "Seismic response of liquid storage steel tanks with variable frequency pendulum isolator", *KSCE J. Civil Eng.*, **15**(6), 1041-1055. https://doi.org/10.1007/s12205-011-0945-y.

Panchal, V.R. and Jangid, R.S. (2012), "Behavior of liquid storage tanks with VCFPS under near-fault ground motions", *Struct. Infrastr. Eng.*, **8**(1), 71-88. https://doi.org/10.1080/15732470903300919.

Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A. and Schwartz, D.P. (1996), "Probabilistic seismic hazard assessment for the state of California", California Department of Conservation Division of Mines and Geology, California.

Razzaghi, M.S. and Eshghi, S. (2014), "Probabilistic seismic safety evaluation of precode cylandrical oil tank", *J. Perform. Constr. Facil.*, **29**(6), 04014170. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000669.

Robert, C.P. and Casella, G. (2004), *Monte Carlo Statistical Methods*, Springer.

SAC. Suites of Earthquake Ground Motions for Analysis of Steel Moment Frame Structures. (2010), http://nisee.berkeley.edu/data/strong_motion/sacsteel/ground_motions.html.

Shekari, M.R., Khaji, N. and Ahmadi, M.T. (2009), "A coupled BE-FE study for evaluation of seismically isolated cylandrical liquid storage tanks considering fluid-structure interaction", *J. Fluid Struct.*, **25**, 567-585. https://doi.org/10.1016/j.jfluidstructs.2008.07.005.

Shirmali, M.K. and Jangid, R.S. (2002), "Non-linear seismic response of base-isolated liquid storage tanks to bi-directional excitation", *Nucl. Eng. Des.*, **217**(1-2), 1-20. https://doi.org/10.1016/S0029-5493(02)00134-6.

Shrestha, B., Hao, H., Ibrahim, N.H.J. and Bi, K. (2016), "On the effectiveness of rotational friction hinge damper to control responses of multi-span simply supported bridge to non-uniform ground motions", *Adv. Struct. Eng.*, **19**(10), 1575-1591. https://doi.org/10.1177/1369433216645974.

Sistani, A., Asgarian, B. and Jalaeefar, A. (2013), "Reliability analysis of braced frames subjected to near field ground motions", *Earthq. Struct.*, **5**(6), 733-751. http://dx.doi.org/10.12989/eas.2013.5.6.733.

STRABAG. STRABAG International GmbH (2017), http://www.strabag-international.com/databases/internet/_public/content.nsf/web/EN-STRABAGINTERNAT.COM-lng.html#?men1=2&men2=1&sid=2328&h=15.

Uckan, E., Akbas, B., Paolacci, F., Shen, J. and Abali, E. (2015), "Earthquake protection of liquid storage tanks by sliding isolation bearings", *ASME 2015 Pressure Vessels and Piping Conference*, Boston, USA.

Veletsos, A.S. (1984), "Seismic response and design of liquid storage tanks", *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*, 255-370.

Veletsos, A.S. and Tang Y. (1990), "Soil-structure interaction effect for laterally excited liquid storage tank", *J. Earthq. Eng. Struct. Dyn.*, **19**(4), 473-496. https://doi.org/10.1002/eqe.4290190402.

Veletsos, A.S., Shivakumar, P., Tang, Y. and Tang, H.T. (1990), "Seismic response of anchored steel tank", *Proceedings of the Third Symposium on Current Issues Related to Muclear Power Plant Structures, Equipment and Piping,* North Carolina State University.

Zhang, R., Weng, D. and Ren, X. (2011), "Seismic analysis of a LNG storage tank isolated by a multiple friction pendulum system", *Earthq. Eng. Eng. Vib.*, **10**(2), 253-262. https://doi.org/10.1007/s11803-011-0063-3.

KT