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Seismic Control of LNG Storage Tanks using MR Damper

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Abstract
The paper aims to focus on the semi-active control behaviour of base-isolated liquified natural gas (LNG) Storage tanks under six artificial earthquake ground motions compatible with Operational Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE). The LNG storage tank is seismically isolated using High Damping Rubber Bearing (HDRB) Isolation system. The storage tank is analyzed for maximum operating level of LNG (full-level) to compute the seismic response under six artificial accelograms compatible to OBE and SSE earthquakes. In order to investigate the effective of semi-active control device in form of MR damper the seismic responses are compared with uncontrolled, base-isolated and controlled strategies. The seismic response quantities considered for the analysis included displacement at isolation level, total pile shear, base-overturning moment and sloshing wave height. The numerical results of the study demonstrated that controlled system in form of MR damper along with isolation system is significantly reducing the response of the LNG Storage tank specifically the displacement at isolation level without much modification in other responses.
Keywords: Base Isolation, LNG Storage Tanks, HDRB Isolation system, MR damper.

1. Introduction

The huge capacity storage tanks considered as lifeline projects are constructed in large numbers for the storage of liquefied natural gas (LNG). Liquified Natural gas being one of the most authentic source of energy is utilized globally to tackle the demands of energy. Over past years the usage of natural gas has been hiked up due to which LNG storage tanks have become most crucial component of urban infrastructure. These storage tanks have huge capacity and volume in range of 150,000 m^3 to 160,000 m^3. The schematic view of modern LNG tank is demonstrated in Fig. 1(a) consisting of internal tank storing LNG, external tank constructed of concrete that protects the inner tank with an insulation layer sandwiched between two layers. In comparision to traditional buildings or structures, LNG tanks have high risk of seismic failure since can lead to secondary disasters, such as explosions and environmental pollution resulting in considerable damage to the property and loss of life. Moreover these tanks are susceptible to earthquakes due to its less ductility and less energy-dissipation capacity comparison to typical structures. For example, the 1964 Japan earthquake caused failure of LNG tank due to explosions and fire. Another 1976 Tangshan earthquake buckled the bottom ring of a storage tank leading to liquid damage.

Natural gas is a fossil fuel with 90% or more methane content which is mostly transmitted from site of production to place of consumption in gaseous state through ducts or pipes. The cooling process occurs at a temperature of about -170 ºC in order to allow condensation to its liquid state. This phenomenon increases the density of the product approximately 600 times allowing to be shipped in unique designed containers and storing it in insulated thermal tanks. Through the process of re-evaporation the stored product can be piped to the consumption site. These facilities pertaining to unloading, storage and re-vaporisation of liquid natural gas is usually referred as the LNG terminal facility.

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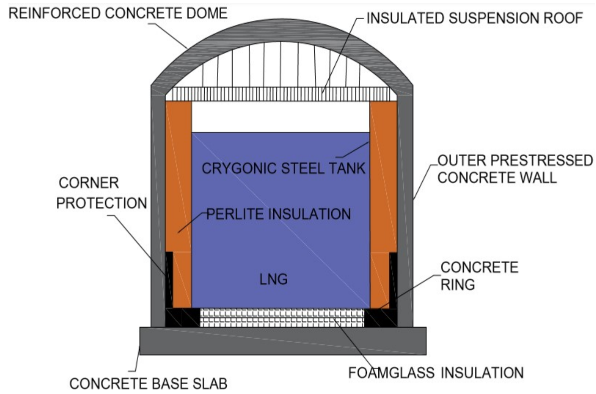
LNG storage tanks being critically important structures, seismic protection against severe earthquake excitations is merely required. The existing infrastructure may get disrupted causing fire or environmental contamination if the poisonous chemicals or flammable materials leaks leading to rupture of such storage tanks. Hence it is primarily necessary to protect effectively such structures from seismic excitations. Because of the multi-layer construction of the tank and hazardous nature of LNG, seismic analysis, design and construction of LNG storage facility requires highly advanced technology in comparison to the conventional structures.

(a)



(b)

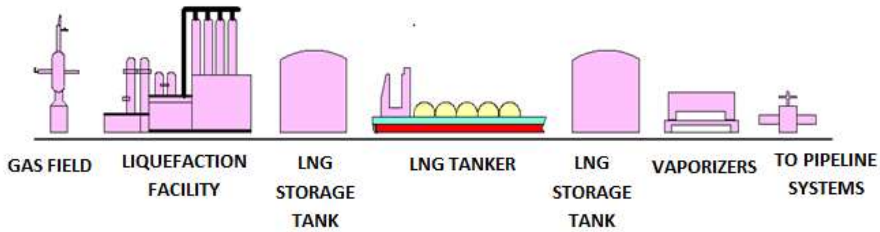


Fig.1 (a) View of modern LNG tank. (b) LNG chain: extraction, transportation and regasification

Owing to reduce the risk of earthquakes to the infrastructures, seismic engineers have evolved numerous solutions in form of vibration control devices, aseismic designs and base solation systems. One of the most challenging alternative for safeguarding liquid storage tanks against severe earthquake events can be the passive control approach in form of base-isolation technology. Numerous past investigations and research have been implemented to check the effectiveness of seismic isolation approach for safeguardment of liquid storage tanks. [Christovasilis and Whittaker, 2008; Malhotra et al., 2000; Panchal and Soni, 2014; Soni et al., 2011; Wang et al., 2001; Weng et al., 2012; Kim et al., 2015; Nick et al.,2017; Luo et al., 2021; Zhao et al., 2020a,b; Kim et al., 2019; Martí et al., 2010; Zhou et al., 2013]. Currently the use of passive technology along with smart control device has achieved greater attention owing to the advantages of both approaches. [Datta, 2003; Spencer and Nagarajaiah, 2003; Symans and Constantinou, 1999]. Implementation of this combined approach decreases the isolation level displacement as well as the response of the superstructure.

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2. Literature Survey

Many of the researchers have investigated in past studies the adaptability and efficacy of passive and semi-active control approaches for earthquake response mitigation of liquid as well as LNG storage tanks.

A variety of semi-active control strategies such as Lyapunov Control, Decentralized Bang-Bang Control, Modulated Homogeneous Friction and Clipped- Optimal Control have been evaluated by Dyke and Spencer (1997) for use with the MR damper through a numerical simulation. A 3-storey model was controlled by a single MR damper subjected to 1940 El Centro Earthquake under passive and semi-active strategies. The results of MATLAB analysis indicated the superior performance of semi-active strategies than passive ones. Symans and Constantinou (1999) explained and compared the qualitative behaviour of passive, active, and semi-active control systems for protection of structures focusing on the dynamic behavior of systems and the study directly represented that semi-active device has the capability to upgrade the behaviour against severe excitations. The theoretical aspects of cylindrical ground-supported tanks were evaluated by Malhotra et al. (2000) with impulsive and convective (sloshing) effects of the liquid. It was inspected that the performance of tank can be improved either by use of peculiar isolation bearings or energy dissipating devices. The experimental research of smart, base isolated system employed with magnetorheological (MR) dampers was implemented by Yoshioka et al. (2002) under near-field and far-field motions. From experimental range of series it was noted that acceleration response tremendously reduced for smart isolated structure. Chin-Hsiung et al. (2003) investigated the seismic response of an isolated structure using a 2kN MR damper and fuzzy logic control algorithm. The results of numerical simulation indicated that semi-active device in from of MR damper effectively reduced the displacement and acceleration responses of base-isolated structures. The external hazards of above ground full containment LNG storage tanks were addressed by Douglas et al. (2005) using High Damping Rubber Bearings (HDRB) and Spheric sliding isolators like Friction Pendulum Bearings (FPB). It was examined that earthquake force reduced and provided safety factor against earthquake damage using base-isolation system. Further a shift in fundamental natural period to about 2 seconds in HDRB and upto 5 seconds using Spheric sliding isolator was observed that prevented damage and uplift of inner tank due to buckling. Christovasilis and Whittaker (2008) computed the seismic response of a conventional and an isolated Liquefied Natural Gas (LNG) tank using a mechanical analog as suggested by Malhotra et al. (2000) and a finite element code ANSYS. Two levels of earthquake shaking, the Operating Basis Earthquake (OBE) and the Safe Shutdown Earthquake (SSE) were considered to carry out response history analysis. The results of two numerical models indicated that mechanical analog can be used confidently to determine the global response of both conventional and isolated tank and is most preferable for preliminary design. The effectiveness of MR damper was checked by Bharti et al. (2010) for earthquake response mitigation of adjacent multi-storey buildings using Lyapunov direct approach including passive-off, passive-on, and semi-active control strategies. The numerical study demonstrated that MR damper is effective control device for both the buildings for numerous range of ground motions. Bitaraf et al. (2010) controlled the performance of a structure equipped with MR dampers by proposing the Simple Adaptive Control (SAC) method and genetic-based fuzzy control method. The performance of the controllers developed by fuzzy theory was compared with semi-active control algorithms and the developed controllers significantly reduced maximum absolute acceleration, peak displacement and drift of the structure. Zhang et. al. (2011) analysed the seismic response of an isolated vertical, cylindrical, extra-large liquefied natural gas (LNG) tank by a Multiple Friction Pendulum System (MFPS). A simplified finite element model by Malhotra and Dunkerley was used to determine the usefulness of the isolation system. Data reported consisted of pile shear, wave height, impulsive acceleration, convective acceleration and outer tank acceleration. The analysis results shown that MFPS is very effective in controlling seismic responses and effectively decreased the pile shear, impulsive mass acceleration and outer tank acceleration. The seismic behaviour of broad and slender liquid storage tanks isolated by DVFPI

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were investigated by Soni et al.(2011). Four different combinations of the DVFPI design cases having different isolator geometry and coefficient friction at top and bottom sliding surfaces were studied. It was concluded from the study that the top sliding surface of DVFPI should be designed with high initial stiffness relative to the bottom one, the coefficient of friction should be same at both sliding surfaces for slender tank and both surfaces should be designed with equal initial stiffness and coefficient of friction for broad tank. The seismic control for an extra-large LNG storage tank using smart base isolation system consisting of laminated rubber bearing and MR damper were discussed by Dashrath et. al.(2019). The excessive displacement of tank system was controlled by Magneto-rheological (MR) dampers commended by state feedback controller designed using pole placement method. The effectiveness of derived control algorithm was compared with uncontrolled system for past three earthquake ground motion. The simulation results showed that the state feedback control strategy is more effective in reducing the structural responses as compared to uncontrolled system. The establishment of system for selection of optimum friction material to meet the seismic performance requirements of a liquefied natural gas tank with a friction pendulum system (FPS) was studied by Kim et. al. (2019). Seismic fragility analysis was implemented for determination of optimum frictional material and was applied to materials by varying frictional coefficients for FPS. Fragility curves were developed for two different limit states and methodology for combining fragility curves was proposed. The analysis results represented that a lower friction coefficient for FPS was more appropriate for preventing failure in FPS and the superstructure.

3. Modelling of Base-Isolated LNG Tank with Semi-active Control Device

The structural model of the liquified natural gas tank is constructed and modelled into two layers. Two appropriate models are implemented for the schematic construction of these two layers. First one is outer tank portion which is modelled based on Dunkerley's model and second is the inner portion which is designed by Malhotra's model. (Refer Fig. 2)

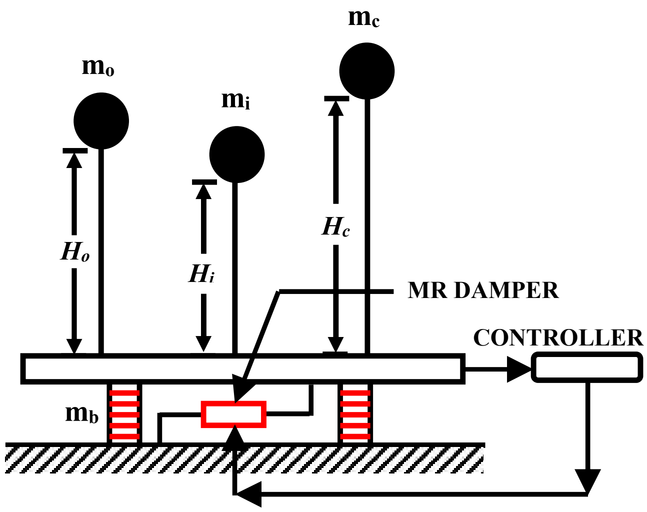

Fig.2 Simplified Model of LNG Storage tank

The structural model procedure recommended by Malhotra was dependant on Veletos work with some alterations that incorporated:

- The higher impulsive modal mass can be combined with the first impulsive mode while the higher convective modal mass can be combined with the first convective mode.

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- Alteration in the modal heights should be incorporated to enable the higher modes to contribute to the base overturning moment.
- Generalization of impulsive period formula in order to be applied to steel and concrete tanks of varying wall thickness.

It can be examined from Fig. 2 that the MR damper generates signal which is applied to the controller. This measured signal would be computed by controller and appropriate control actions would be generated to control the force in damper applied at the input side of the system force in the presence of matched uncertainty.

The governing equations of motion of the LNG tank is generated by considering the equilibrium of outer tank mass, impulsive mass, convective mass and base slab as shown in Fig. 2.

$$m_0\ddot{u}_0+c_0\dot{u}_0+k_0u_0=-m_0\left(\ddot{u}_g+\ddot{u}_b\right) \quad (1)$$

$$m_i\ddot{u}_i+c_i\dot{u}_i+k_iu_i=-m_i\left(\ddot{u}_g+\ddot{u}_b\right) \quad (2)$$

$$m_c\ddot{u}_c+c_c\dot{u}_c+k_cu_c=-m_c\left(\ddot{u}_g+\ddot{u}_b\right) \quad (3)$$

$$m_b\ddot{u}_b+c_b\dot{u}_b+k_bu_b-m_0\ddot{u}_{0a}-m_i\ddot{u}_{ia}-m_c\ddot{u}_{ca}+F_d=-m_b\ddot{u}_g \quad (4)$$

In the above represented equations, the displacements of convective mass, impulsive mass and outer tank mass
are shown as u_c, u_i and u_0 respectively with reference to the base of the tank placed on isolation system in horizontal direction; u_b is the bearing displacement with respect to the ground; the convective, impulsive and outer tank mass damping coefficient are expressed as c_c, c_i and c_o respectively; c_b is the equivalent damping of the isolation devices; the stiffness coefficient of convective, impulsive and outer tank mass are k_c, k_i and k_o while the equivalent stiffness of the isolation devices is k_b; F_d is the exerted MR damper force; m_o is the outer tank total mass; m_b is the bottom plate and foam glass mass.

The matrix form equation of equations (1) to (4) can be expressed in as,

$$[\mathcal{M}]\{\ddot{u}\}+[\mathcal{C}]\{\dot{u}\}+[\mathcal{K}]\{u\}+F_d\{\mathcal{L}\}=-[M]\{\iota\}\ddot{u}_g \quad (5)$$

where, $[\mathcal{M}]$, $[\mathcal{C}]$ and $[\mathcal{K}]$ are hybrid system mass, damping and stiffness matrices respectively; $\{\mathcal{L}\}$ is the location vector of control devices and $\{\iota\}$ is the influence coefficient vector. Equation (5) can be expressed in state space form as,

$$\begin{Bmatrix}\{\dot{u}\}\\\{\ddot{u}\}\end{Bmatrix}=\begin{bmatrix}[0] & [I]\\-[\mathcal{M}]^{-1}[\mathcal{K}] & -[\mathcal{M}]^{-1}[\mathcal{C}]\end{bmatrix}\begin{Bmatrix}\{u\}\\\{\dot{u}\}\end{Bmatrix}+\begin{Bmatrix}\{0\}\\-[\mathcal{M}]^{-1}\{\mathcal{L}\}\end{Bmatrix}F_d+\begin{Bmatrix}\{0\}\\-\{\iota\}\end{Bmatrix}\ddot{u}_g$$

$$\therefore\{\dot{X}(t)\}=[A]\{X(t)\}+\{B\}F_d(t)+\{E\}\ddot{u}_g(t) \quad (6)$$

Further, using Equation (5) and (6), the input-output equation can be expressed as,

$$\begin{Bmatrix}\{u\}\\\{\dot{u}\}\\\{\ddot{u}\}\end{Bmatrix}=\begin{bmatrix}[I] & [0]\\ [0] & [I]\\-[\mathcal{M}]^{-1}[\mathcal{K}] & -[\mathcal{M}]^{-1}[\mathcal{C}]\end{bmatrix}\begin{Bmatrix}\{u\}\\\{\dot{u}\}\end{Bmatrix}+\begin{Bmatrix}\{0\}\\\{0\}\\-[\mathcal{M}]^{-1}\{\mathcal{L}\}\end{Bmatrix}F_d+\begin{Bmatrix}\{0\}\\\{0\}\\-\{\iota\}\end{Bmatrix}\ddot{u}_g$$

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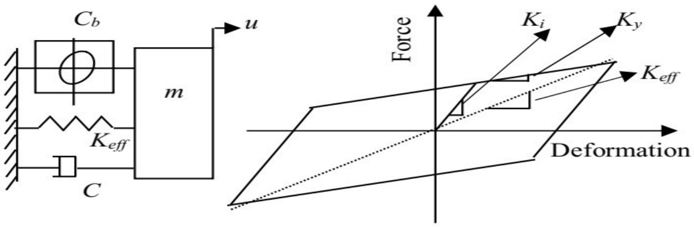
$$\therefore \{Y(t)\} = [C]\{X(t)\} + \{D\}F_d(t) + \{H\}\ddot{u}_g(t) \quad (7)$$

3.1. Base-isolation system

In order to have reduction in the superstructure response, a High damping Rubber bearing system is considered. The HDRB consists of special rubber having a good damping attribute together sandwiched with layers of steel without any lead plugs. These bearings have unique feature of decoupling the structure from horizontal earthquake ground motion components by interposition of layer of low horizontal stiffness between the structure and foundation. They can be designed to withstand the design earthquakes without significant damage.



(a) (b)

Fig.3 (a) Mathematical model (b) Force-deformation curve of HDRB

3.2. Semi-active Control device

In the present work, as a semi-active control device Magnetorheological Dampers (MR) is utilized for the seismic response mitigation of LNG tanks. These dampers composed of iron particles which remain in suspension in liquid carrier medium like oil. They require very less power and their damping and stiffness features varies in dynamic nature. In presence of magnetic field, the alignment of particles occurs resulting the fluid to convert to semi-solid by varying its stiffness and damping properties. The manufacturing cost of these dampers is very low and is stable, reliable and responds in milliseconds. They require less power in range of 20–50W. It is one of the most reliable device since it does not require any mechanical valve. The MR damper force, F_d, is determined by using the phenomenological model proposed by Spencer et al. [1997] shown in Fig. 4.

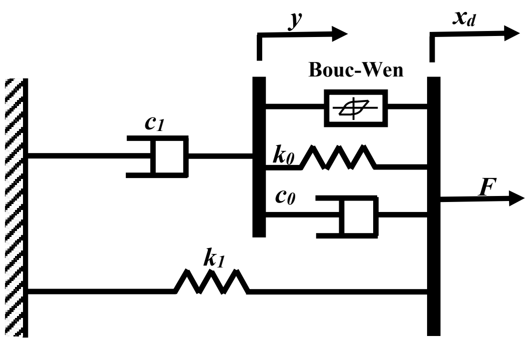


Fig.4 Phenomenological model of MR damper [Spencer et al., 1997].

The numerical problem considered for the present study is the LNG storage tank having capacity of about 150,000 m^3 (150 million liter) which is analyzed by Christovasilis and Whittaker [2008]. The thickness of inner wall linearly varies from 34 mm at the base to 8mm at top of the tank with the average thickness of outer tank portion as 900 mm. The outer tank is 45 m high with 1.86 m rise of dome. The height of steel inner tank is 40.6 m and LNG design height is 37.4 m. The internal and

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external radii are 37 m and 38 m, respectively. The peculiar dimensions of LNG tank considered are illustrated in Table 1. The mass density of LNG, ρ_l, is 480 kg/m^3; the elasticity modulus of steel, E_s, and concrete, E_c, is 2×10^{11} N/mm^2 and 3×10^{10} N/mm^2, respectively; the mass density of steel and concrete is 7.9×10^3 kg/m^3 and 2500 kg/m^3, respectively and the Poisson's ratio of concrete wall, μ_c, is 0.3.

Table 1 Dimensions of the Inner tank, Outer tank and the Contained fluid

Tank Dimension	Inner Steel Tank	Outer Concrete Tank
Height of Tank Wall (m)	40.6	45
Rise of dome of outer tank (m)	--	1.86
Radius (m)	37	38
Mean wall thickness (mm)	21	900
Design height of contained LNG (m)	37.4	--

The isolation period and damping ratio of the HDRB system considered are 2 sec and 5% respectively. The specifications of MR damper are: α_{0a}= 8.7 kN/m/V; γ = 496m^{-2}; α_{0b}= 6.40 kN/m/V; β = 496m^{-2}; c_{0a} = 50.30 kN s/m; η = 195 sec^{-1}; c_{0b} = 8.3 kN s/m/V; k_0 = 0.0054 kN/m; c_{1a} = 8106.2 kN s/m; k_1 = 0.0087 kN/m; c_{1b} = 7807.9 kN s/m/V; x_0 = 0.18 m; A_d = 810.50; and n = 2. The maximum voltage applied to MR damper, V_{max}, is 6 Volt.

4. Design Earthquake Ground Motions

The NFPA 59A[2001] standards suggests to design the LNG tanks for two earthquake levels of shaking viz. Operating Basis Earthquake (OBE) and the Safe Shutdown Earthquake (SSE). The OBE ground motions recorded at the site are defined as minimum value of ground motion with a 10% probability of exceedance within a 50 year period; or two-thirds of the ordinates of the Maximum Credible Earthquake (MCE) spectrum. The SSE ordinates of ground motions are considered as the minimum of ground motion with a probability of 1% of exceedance within a period of 50 years; or twice the value of OBE. The probability of exceedance of SSE, MCE and OBE ordinates can be specified by demand with a 1%, 2% and 10% probability of exceedance in 50 years, respectively.

In order to perform the non-linear time history analysis of LNG tank a total six artificial accelerograms are generated. Three of them are compatible to SSE spectrum and the other three are compatible to the OBE spectrum. The response quantities considered here are (i) Displacement at the isolation level, (ii) pile shear normalized by the total weight of the tank, W, (iii) global overturning moment, and (iv) sloshing wave height in the inner tank.

5. Results and Discussion

With the aim to examine the semi-active control behaviour of LNG storage tank , three different control strategies i.e. uncontrolled, base-isolated and controlled strategy were considered in the present study. The uncontrolled strategy refers to the absence of isolation system while the controlled system aims to include implementation of semi-active device in form of MR damper along with the base-isolation system in form of HDRB. According to the seismic design specifications, the LNG storage tank has been analyzed for design storage level (full storage level) of LNG in the tank.

The peak response parameters of the LNG storage tank determined under OBE and SSE earthquakes are tabulated in Table 2 and Table 3 respectively. The time variation behaviour of

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uncontrolled, base-isolated, and controlled system for the response parameters in terms of displacement at isolation level, total pile base shear normalized by total weight of the tank, W, base overturning moment and sloshing wave height of the tank with the maximum operating level of LNG underOBE1 earthquake is depicted in Fig. 5. The variation illustrates reduction of almost 80% for base overturning moment and 77% in total pile shear. Although this reduction in the behaviour is obtained by allowing large magnitude of isolator displacement which would demand huge size isolators and high cost connections for the pipeline system. Hence it is necessary to mitigate displacement at isolation level. For this purpose semi-active control strategy is employed along with base-isolation system. The efficacy of semi-active device combined with isolation system is examined in Fig. 5 wherein the isolation displacement is reduced by 66% without much modifying the other response parameters under the OBE earthquake.

Table 2 Peak Values of Response for LNG Tank evaluated in OBE

Earthquake	**Control Strategy**	**Isolator Displacement (mm)**	**Total Pile Shear (W)**	**Base Overturning Moment (KN-m)**	**Sloshing Wave Height (m)**
OBE1	Uncontrolled	-	0.2957	9.22×10^{6}	1.5838
	Base-Isolated	144.3	0.0690	1.88×10^{6}	1.7065
	Controlled	49.0	0.0591	1.82×10^{6}	1.4901
OBE2	Uncontrolled	-	0.3599	9.9×10^{6}	1.3517
	Base-Isolated	144.9	0.0714	1.92×10^{6}	1.4960
	Controlled	79.2	0.0566	1.87×10^{6}	1.1663
OBE3	Uncontrolled	-	0.3238	9.43×10^{6}	1.5097
	Base-Isolated	137.0	0.0671	1.75×10^{6}	1.5789
	Controlled	54.7	0.0618	1.49×10^{6}	1.3580

Table 3 Peak Values of Response for LNG Tank evaluated in SSE

Earthquake	**Control Strategy**	**Isolator Displacement (mm)**	**Total Pile Shear (W)**	**Base Overturning Moment (KN-m)**	**Sloshing Wave Height (m)**
SSE1	Uncontrolled	--	0.5796	18.1×10^{6}	3.0810
	Base-Isolated	280.1	0.1341	3.66×10^{6}	3.3230
	Controlled	120.5	0.1063	2.77×10^{6}	2.9673
SSE2	Uncontrolled	--	0.7129	19.6×10^{6}	2.6357
	Base-Isolated	285.6	0.1407	3.79×10^{6}	2.9176

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	Controlled	168.3	0.1034	3.31×10^6	2.4120
SSE3	Uncontrolled	--	0.5917	16.6×10^6	1.7857
	Base-Isolated	267.8	0.1294	3.43×10^6	1.8253
	Controlled	164.9	0.1051	3.22×10^6	1.9395

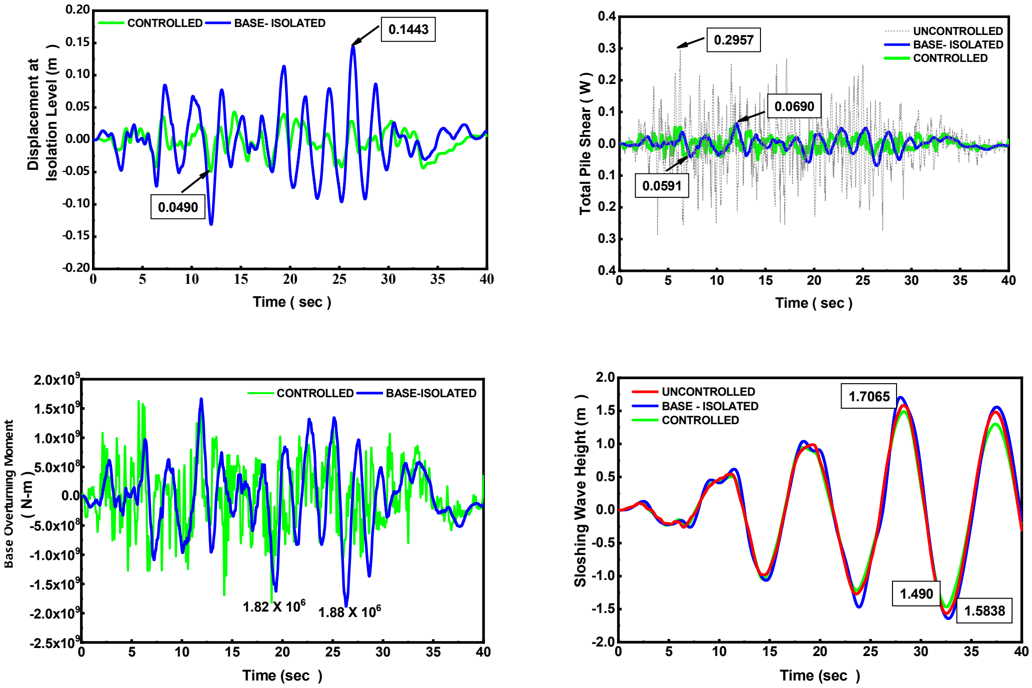
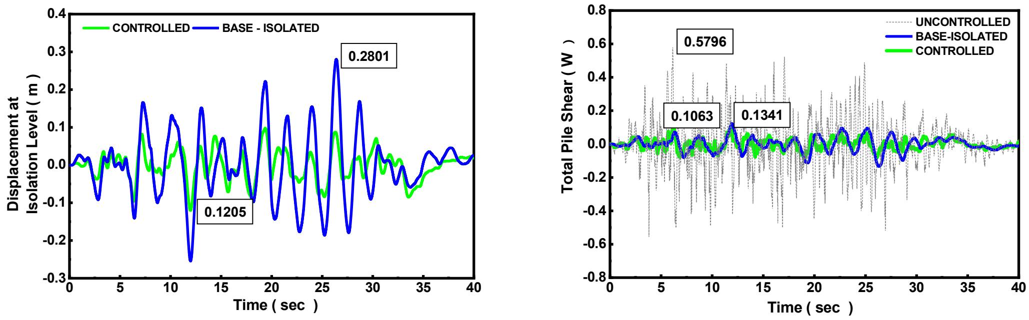


Fig.5 Time variation of isolator displacement, pile base-shear, base overturning moment and sloshing wave height under OBE1 earthquake.



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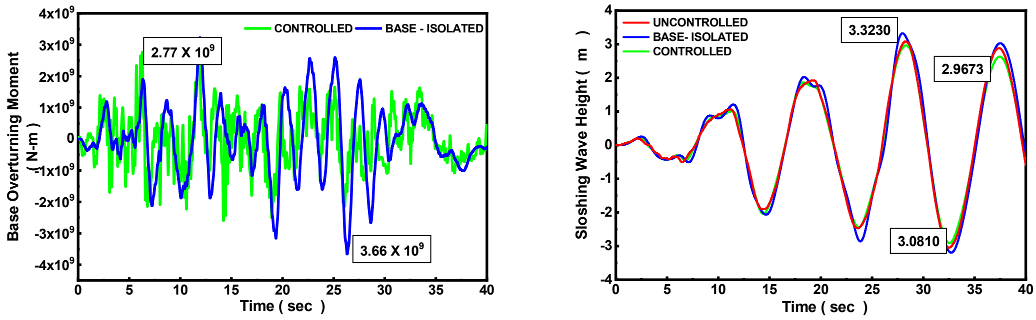

Fig.6 Time variation of isolator displacement, pile base-shear, base overturning moment and sloshing wave height under SSE1 earthquake.

6. Conclusions

The efficacy of base-isolated LNG storage tank using semiactive control in form of MR damper was studied for seismic response computation under six artificial earthquake ground motions compatible with Operational Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) for full level of LNG storage in the tank. The following conclusions may be drawn from the results:

1) The displacement at isolation level is reduced about 45 to 55% under the Controlled System as compared to the Base-Isolated system.
2) In comparision to the uncontrolled strategy, the base-isolated LNG tank has 70–85% reduction in pile base shear and base overturning moment response resulting in considerable large displacement at the isolation level. The semi-active control of isolated LNG tank is effectively found in reduction of isolator displacement in the range of 45–55% for both, OBE and SSE, levels of earthquakes without much altering other response quantities.
3) The reduction in total pile shear is almost found in range of 75-80% in case of Base-isolated system and Controlled system as compared to the uncontrolled system. Further the Controlled system results in 15-20% reduction of pile shear as compared to the Base-Isolated system.
4) There is almost 80% reduction in base overturning moment under the Base-Isolated and Controlled system in comparison to the uncontrolled system. Also, the Controlled system reduces the overturning moment about 6-15% as compared to the Base-Isolated system.
5) The sloshing wave height response is reduced under the Controlled system as compared to both uncontrolled and Base-Isolated system.

Hence there is overall reduction in dynamic response for the extra-large LNG storage tank under both OBE and SSE representing the effectiveness of MR damper in response mitigation of LNG Storage tanks.

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