SEISMIC PERFORMANCE OF FLOATING ROOF STEEL STORAGE TANKS WITH CONSIDERATION OF ENERGY DISSIPATION SYSTEM

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Abstract

Liquid storage tanks are widely used in the industry and can contain not only harmless substances, but also various ones that can be explosive and toxic or pollutant. For this reason, engineers must ensure that both the structure and the content remain safe and operational in different types of loading. The importance of the latter became more prominent following the 2003 Tokachi-oki Earthquake (Mw=8.0). Although the structural shell has not been damaged under such long-period strong ground motion, as a consequence of sloshing phenomena severe damage has been observed in oil tanks, igniting fires and sinking floating roof. The subject of this paper is to investigate the seismic performance of floating roof steel liquid storage tanks with and without consideration of the energy dissipation system proposed herein. The energy dissipation unit consists of floating roof, external dampers and connector structural members that can be designed according to capacity design principles. Due to these supplemental devices, which can be either hysteretic or viscous ones, the liquid vibration can be controlled and the level of damping can be substantially augmented. The dissipation system mainly targets the large capacity tanks, nonetheless, the ease of implementation makes it a good candidate for improving the performance of any type of liquid storage tank. The research focuses on the case of above ground cylindrical steel storage tanks fully anchored at their base, filled partially with water, incorporating floating roof and linear viscous dampers. In the absence of experiment, numerical methods are very useful tools for assessing the seismic response of such structures that may show highly nonlinear dynamic behaviour. In this study, the Arbitrary Lagrangian-Eulerian (ALE) formulation is used to represent nonlinear fluid structure interaction (FSI). Navier-Stokes equations are assumed to simulate the motion of the fluid, and geometric nonlinearities, together with material ones, are considered in the wall of the tank to determine stress, strain and pressure distributions. Discrete elements have instead been used to represent the external supplemental devices. The numerical model proposed herein has been validated using a past experimental test. For both cases, namely floating roof tanks with and without supplemental devices, a good fit has been obtained between experimental and numerical estimates. A series of explicit nonlinear dynamic analyses have been performed to evaluate the performance of a case study tank using the FE code LS-DYNA. The change in seismic response because of seismic input (i.e. far field and near field earthquakes) have also been quantified for the tank in question.

Keywords: liquid storage tank; energy dissipation system; seismic performance; fluid-structure interaction

1. Introduction

Liquid storage tanks are vital infrastructures that need to operate safely after a major earthquake event due to the importance of the contents beyond their economic value. After the 1906 San Francisco earthquake, the major problem was the lack of water supply as a consequence of the collapse of many water tanks that resulted in serious fire damage than the event itself [1]. Likewise, the past events such as 1964 Niigata and 1964 Alaska earthquakes proved that the failure of industrial liquid storage tanks which contain inflammable and toxic contents such as oil and naphtha may cause serious environmental problems and uncontrolled fires. Nowadays, tanks with floating roof are among the most common storage structure types used in the oil industries all over the world. Throughout the years, extensive damages have been surveyed and reported for such tanks that were not properly designed or detailed against earthquake-induced actions, thus leading to the development of code regulations [2-4]. These guidelines recommend the use of low behaviour factors since such thin-walled structures have lack of redundancy and provide very limited ductility due to the shell instability. Moreover, due to the damage consequences observed in past events, the importance factors assumed for the design of liquid storage tanks is usually considerably high. Therefore, relatively higher lateral seismic design forces are used, compared to the ordinary building structures. However, a recent event show that further reinforcement is necessary to improve robustness in liquid storage tanks. After the 2003 Tokachi-oki Earthquake (Mw=8.0) conspicuous fires and sinking of floating roofs have been observed in the partially filled large oil tanks located in the Yufutsu sedimentary basin, even though no significant damage in the structural shells of such tanks was reported as a consequence of the earthquake itself. In JST failure knowledge database [5] it is reported that description of the direct cause of the fire was unknown however, the cause of the first fire was considered to be a spark caused by an impact and friction from sloshing. Hatayama [6] demonstrated that tanks experienced large-amplitude long period motion and particularly for tanks characterised by predominant fundamental mode between 5-12 sec, the sloshing wave height exceeded 3 m. It is well understood that the susceptibility of large oil storage tanks with floating roofs to these types of damage can be associated with the convective component of motion and in particular with the maximum sloshing height experienced during an earthquake.

In order to prevent the occurrence of disproportionate damage and to have better performance in such strategic infrastructures, the stricter regulations on the capacity of the tanks can be enforced or modern and innovative strategies can be used to limit the sloshing response of the liquid. Two major sources amplify the sloshing response of a liquid-tank system: when the hydrodynamic fluid-tank motion exerted by seismic excitation has a period close to the convective period, or if the damping associated with the fluid is rather low. With regards to the above, it is noteworthy that base isolation is frequently adopted as retrofitting strategy to improve performance of liquid storage tanks. Nonetheless, although base-isolated liquid storage tanks usually have smaller base shear and overturning moments, they may have greater sloshing wave height since the period associated with the convective component of motion is usually high as well. Moreover, retrofitting existing steel tanks with such systems might not be practical and cost-effective. An energy dissipation system illustrated Fig. 1 is thus proposed to implement both for the retrofit of existing floating roofed steel tanks as well as for the design of new storage systems, especially the squat ones which are mainly preferred in oil industries. It enhances the damping of the liquid vibration, thus reduces the sloshing wave height, resulting in better seismic performance of the tank; in particular, fire caused by spillage of containment, as well as potential damage and sink of floating roofs can be prevented. The dissipation system consists of a floating roof with the addition of external hysteretic or viscous dampers. The floating roof is much stiffer than water, it prevents wave breaking, hence making the response linear and smoother. Thanks to the supplemental devices, the level of damping of the liquid vibration can be increased substantially. In such a system, the force induced by sloshing phenomena is first transferred to viscous dampers through the floating roof, then passed to rigidly connected beams, and finally resisted by the stiffening ring layer that is located at the top of tank walls. The axial forces induced in the tank walls may cause local buckling. In order to avoid stress concentration, it is very important to provide uniform force distribution over the wall.

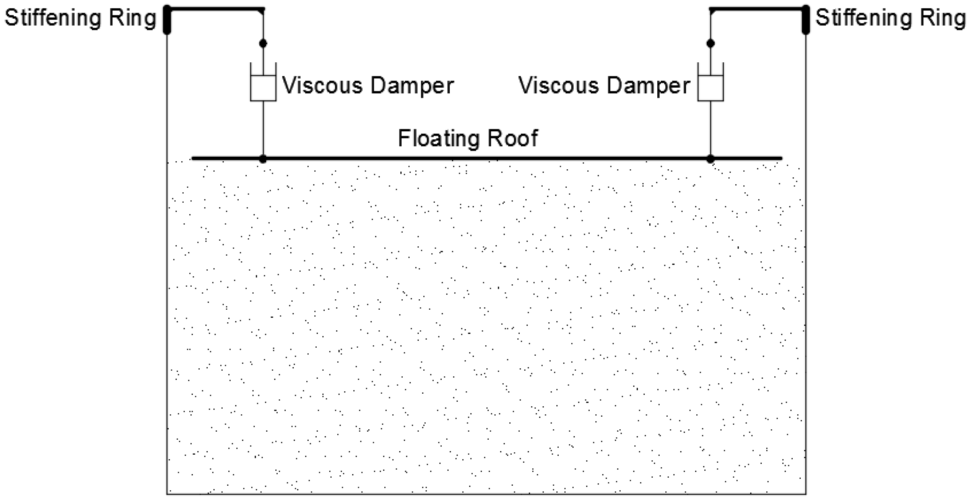

Fig. 1 – Proposed energy dissipation system for storage tanks

The main objective of the study is to investigate the seismic performance of liquid storage tanks with and without the proposed dissipation system by comparing the base shear, overturning moment, sloshing height, Von Mises stresses and hydrodynamic pressures exerted by the fluid on the tank walls as a result of the seismic excitation, for a case study tank. In particular, the research focuses on the case of above ground cylindrical steel storage tanks with external floating roof, fully anchored at their base, filled partially with water, with and without consideration of the viscous dampers. In order to understand the effectiveness of the system, different type of seismic inputs were used (near-field and far-field ground motions). Performing experimental tests would be the first choice to obtain accurate results, however, they are rather costly and take a lot of time to be undertaken. In the absence of experiments, numerical simulations can be used after they are validated. Some researchers (among others see [7-9]) developed simple mechanical models to simulate the tank-liquid system response. In this model, the contained fluid is assumed to be incompressible, inviscid and irrotational, and is subdivided into two masses, one of which is rigidly attached to the tank wall representing the impulsive behaviour and the other is connected to the tank wall by springs simulating the convective response of the fluid. The method includes the effects of tank wall-liquid interaction, and the parameters of this type of models depend on the geometry and flexibility of the tank wall. This concept constitutes the basis for the many international seismic provisions. Further, the method of analysis is extended to account for the coupling between the liquid sloshing modes and shell vibrations. Modification of the simplified model for rigid tanks has been proposed by Haroun [10] and Veletsos [11] to account for the flexibility of the tank walls. These authors proposed to add to the earlier model one single degree of freedom system to reproduce the effect of the tank wall flexibility. Malhotra [12] have further simplified the models for flexible tanks combining the effects of the higher impulsive and convective modes with those corresponding to the first modes. However, these mechanical models, which are also provided by the different international regulations, allow calculating only global response parameters such as the shear and overturning moment at the base of the tank. Global response parameters, such as base shear and overturning moment, can be used to compute both vertical and shear stresses in the steel shells, but these are not very meaningful without combining them with circumferential stresses. It must be noted that the cylindrical tanks are usually employed rather than rectangular ones because of their ability in sustaining large circumferential stresses due to geometry. Moreover, the equivalent damping ratio for the energy dissipation system have to be determined to implement in equivalent mechanical models. For this purpose, a rigorous finite element model is used to investigate the precise three-dimensional behaviour of cylindrical tanks involving sloshing behaviour of the contained liquid rather than using simplified mechanical models. Yet, before assessing seismic response of these tanks, the numerical techniques used were validated by experimental results.

2. Numerical Modeling and Validation

2.1 Numerical model

The numerical problem described herein can be categorized as fluid-structure interaction (FSI) problem in which the flow field for the fluid is dependent on the deformation of the solid and the deformation of the solid depends on the pressure applied by the fluid. In such problem, in general, the tank shell undergoes relatively small deformations whereas the fluid body undergoes large deformations and strong nonlinearity is present in the overall response. Therefore, the adopted finite element formulation has a great impact on the accuracy of the solution. Instead of two classical formulations (i.e. Lagrangian and Eulerian ones), the Arbitrary Lagrangian-Eulerian (ALE) approach, which combines the advantages both (see e.g. [13]), is often adopted to simulate the liquid sloshing in tank structures (see for instance [14-17]) since it yields more accurate solutions. Likewise, the Smooth Particle Hydrodynamics (SPH) is another formulation that could be used to express the fluid motion accurately, as shown by different researchers (among others see [18-20]). For instance, Xu [21] demonstrated that both SPH and ALE method are quite accurate and lead to similar results. However, unlike FEM methodologies, SPH method is a particle method and requires a very large number of particles to obtain accurate results; therefore, it is much more demanding in terms of memory and computational time with respect to the ALE method. For this reason, the fluid was modelled by using solid elements with one-point ALE formulation. The proper bulk modulus of the water was defined as K=2.25GPa. The tank walls, base plate and floating roofs were modelled by means of four node shell elements with the Belytschko-Tsay [22] formulation (with two integration points). The beam elements, floating roof and the stiffening ring are assumed to be rigid, and the base nodes are restrained in all degrees of freedom. The viscous dampers were defined by discrete 1-D elements with proper damping coefficients. As it is reported by Nishi [23], the damping ratio of sloshing with floating roof is around 0.5% except very low sloshing heights that are out of engineering interest. Hence, damping ratio of 0.5% is assigned to water and 2% to the steel elements. The penalty method is adopted for FSI and a contact algorithm is used to implement the adopted framework. The contact algorithm generates the coupling forces only when the fluid impacts against the wall. The gravity loads are applied to the model in dynamic fashion by means of a ramp function that reproduces the gravitational acceleration, and the seismic input is applied at the base plate. In order to perform dynamic analysis FE code LSTC/LS-DYNA is used [24]. An explicit solution strategy is adopted to perform the non-linear dynamic simulations, with an automatic mesh dependent integration time step of the order of 10^{-6}.

2.2 Selected experimental test

The experimental test was originally performed by Ruiz [25], with a view to validate the modelling of a new type of liquid damper which is introduced by the same authors. As depicted in Fig. 2, the tuned liquid damper was constructed using rectangular base glass (0.8 x 0.4 x 0.6 m). The water depth is 0.16 m and the floating roof consists of a 1.5 in (38 mm) thick expanded polystyrene foam board. Two external viscous dampers with approximately 15 N.s/m damping coefficient are installed between the top and the floating roof, at 0.2 m from mid-span. The test was carried out with (Tank B) and without (Tank A) the consideration of dampers.

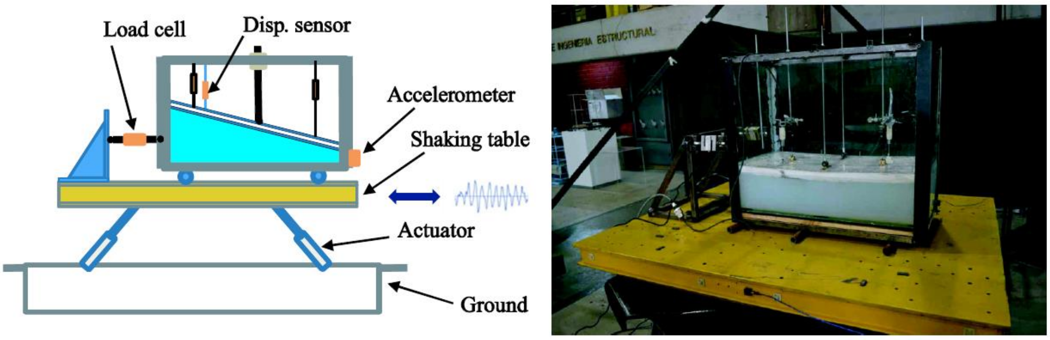

Fig. 2 - The scheme for experimental setup (adopted from [25])

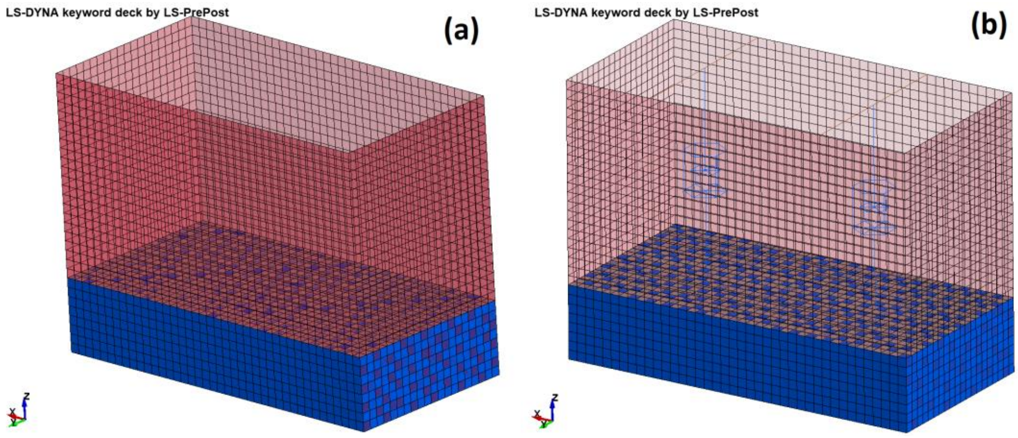

Fig. 3 – Finite element models used in LS-DYNA (a) Tank A; (b) Tank B

The characterization and validation are established by considering different dynamic tests: (i) response to harmonic excitations and (ii) response to earthquake excitations. The simulation results under harmonic excitations with amplitude $|\ddot{u}_b(t)|_{max}=0.01g$ for several excitation periods were expressed in terms of normalized ratio $g/|\ddot{u}_b(t)|_{max}$ times the non-dimensional parameter *AR*. The amplitude ratio can be expressed as reported by Eq. (1):

$$AR = \frac{|\eta(t)|_{max} \times 100}{H} \quad (1)$$

where $\eta(t)$ is the time variation of the oscillation of the floating roof and *H* corresponds to the water depth. *AR* relates the maximum amplitude of the oscillation of the floating roof to the water depth. The dynamic analysis was carried out with the FE models illustrated in Fig. 3. The analysis results for both tanks, together with the response obtained using SSM-FR, simplified sloshing method with floating roof [25] and experimental values are compared in Fig. 4. Since the experimental data was digitized the level of accuracy could be relatively low and minor errors are inevitable. Nonetheless, the overall behaviour is well-predicted with very small errors varying between 1-8% except two points T=1.2 and T=1.4sec and the trend can be clearly seen. The oscillation of floating roof significantly amplifies as the period of harmonic excitation approaches to the fundamental sloshing period 1.35 sec.

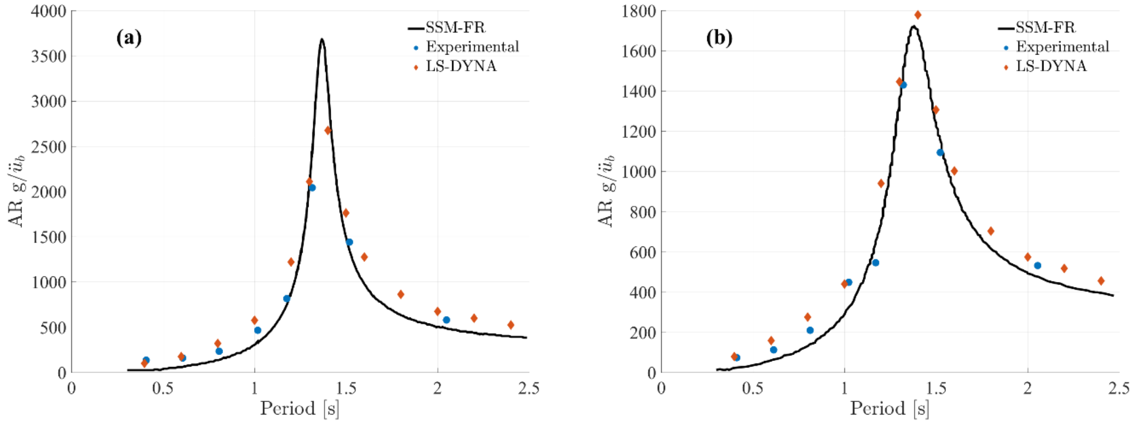

Fig. 4 - Comparison of peak floating roof oscillations under harmonic excitations (a) Tank A; (b) Tank B

The ground motion used in the experiment, recorded at Melipilla station during the 1985 Chile earthquake, had a peak ground acceleration (PGA) of 0.137 g; the excitation was introduced to the shaking table in the direction of longer dimension. Fig. 5 and Fig. 6 compares results of dynamic analysis with the test results in terms of AR and the transmitted force or the base shear.

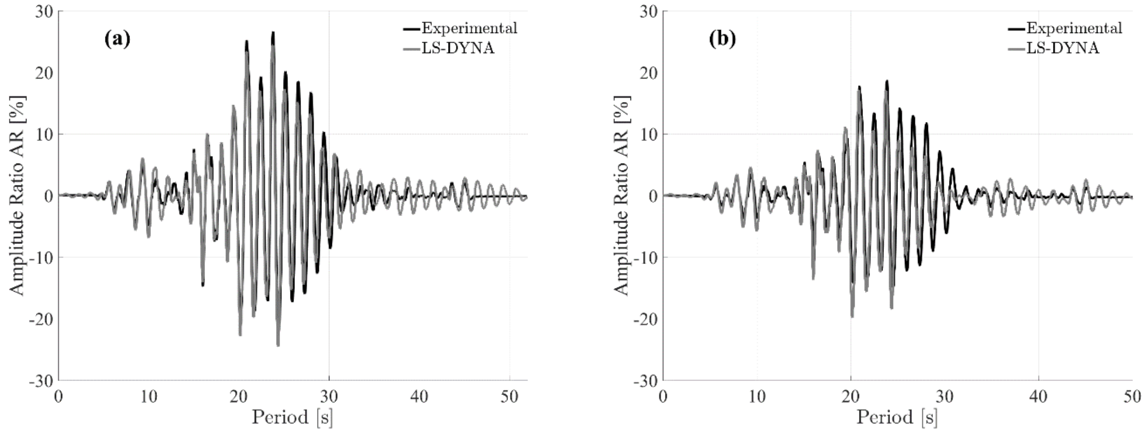

Fig. 5 - Floating roof oscillation amplitude for (a) Tank A; (b) Tank B under seismic excitation

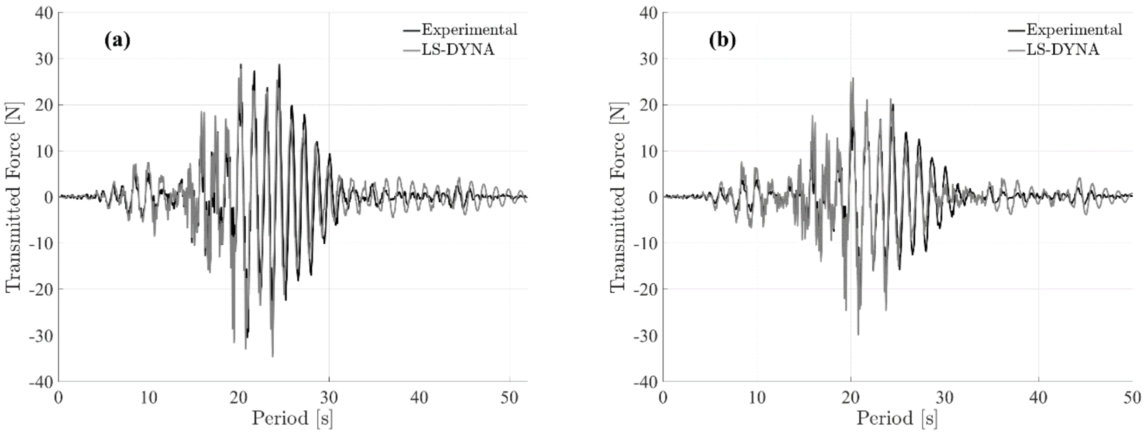

Fig. 6 - Transmitted force for (a) Tank A; (b) Tank B under seismic excitation

In general, the numerical results are in very good agreement with the experimental data with differences between peak responses being less than 9%. Some differences between the response histories are observed after t=25 sec. This might be due to the fact that the inherent damping of the floating roofed tank (0.5%) is assumed to be linear which might not be correct for low level of sloshing as explained before. Moreover, the dampers are most likely non-linear, but they were assumed linear and the damping coefficients were calculated with numerical procedure by Ruiz [25].

3. Performance Evaluation of Dissipation System

Performance of the energy dissipation system proposed in this study is evaluated by comparing the base shear, the overturning moment just above the base, the maximum pressure distribution along the height of tank, the sloshing wave height and the Von Mises stresses or the effective stresses. A squat tank was selected with water depth to radius ratio, H/R=0.5; the tank was designed in accordance with [2] by considering response spectrum type 1, solid type C and design ground acceleration of 0.4g. In the Table 1, the main dimensions of for the considered tank is given.

Table 1 – The dimensions for the case study tank

Water Depth (m)	Radius (m)	Shell Thickness (mm)	Height (m)	Height of Stiffening Ring (m)
10	20	30	13	0.5

The FE model depicted in Fig. 7a is generated in accordance with the modelling assumptions provided in the previous section. Since the tank is cylindrical and the mesh size is different, the accuracy of model is further verified by comparing the hydrostatic pressure distribution obtained under gravity loads with theoretical values (Fig. 8). The six dampers are placed as depicted in Fig. 7b with red color, nevertheless, the number of dampers can be changed depending on the limitations of the selected device and required damping level. In this case, the value of damping coefficient of for the device is chosen such that 13% damping ratio obtained under free vibration response.

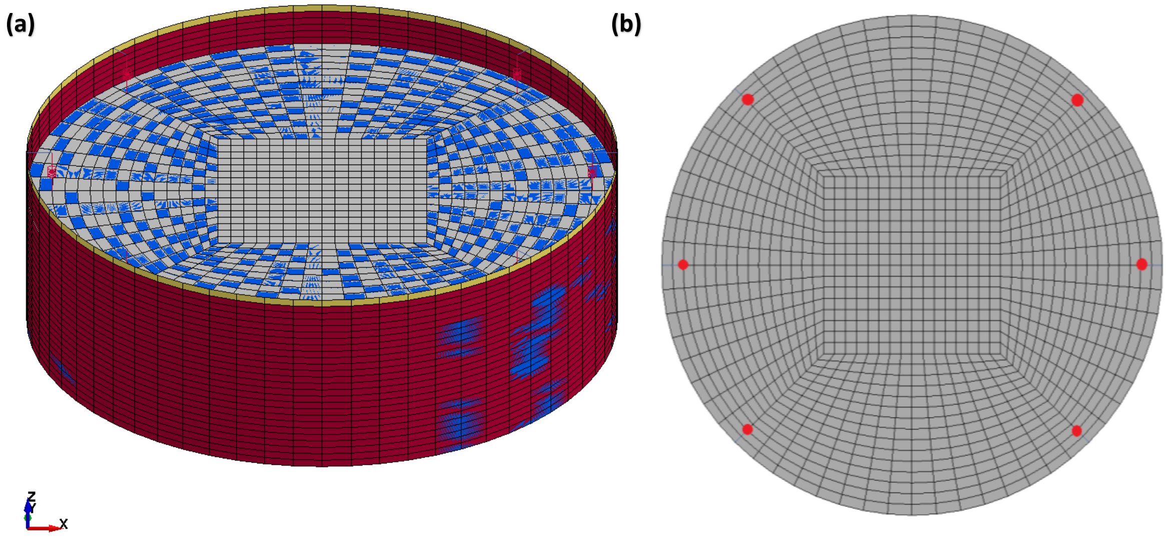

Fig. 7 – LS-DYNA FE model of (a) the case study tank; (b) floating roof with viscous dampers

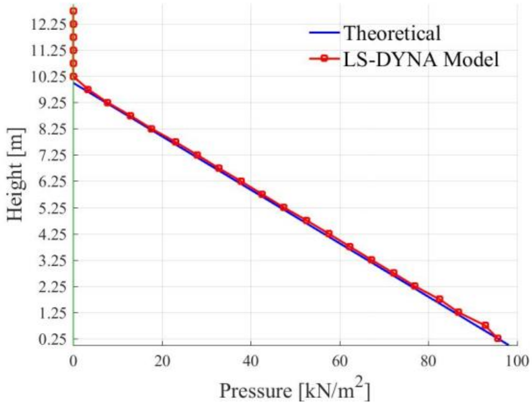

Fig. 8 – Comparison of theoretical hydrostatic wall pressure profile with analysis results

Two different record sets, which are provided in [26], are selected and used for performance evaluation of the dissipation system. The record subsets consist of ground motions with different characteristics. The first set contains 15 records (ID: 1-15), which are recorded at far field, while the second set involves 10 records, which all are recorded at near field. Near field record set is divided into two subsets which are no pulse-like record subset (ID: 16-20) and pulse-like record subset (ID: 21-25) where each contains 5 different ground motions. In many cases, near field record sets are not scaled whereas far field record sets are scaled so that the ground motions are target spectrum compatible. Although there are many recommendations to scale ground motions in case of buildings, there is not much guidance in the case of liquid storage tanks. One should consider both impulsive period and convective period of the tank since both are important for the response of the structure. Since the two usually differ a lot from each other, scaling the ground motion set by considering single period value or a period range close to only one of the structural periods might not be the best approach.

Intuitively, the convective and impulsive periods are calculated as 0.14 sec and 7.78 sec according to [2]. Therefore, in this work the scaling factors for far field record set is found by matching the target spectrum within the period range of 0 to 8 seconds. The matching is done by using minimization of mean squared error (MMSE) method within the estimated period range, and corresponding scale factors are changing between 0.82 and 2.07.

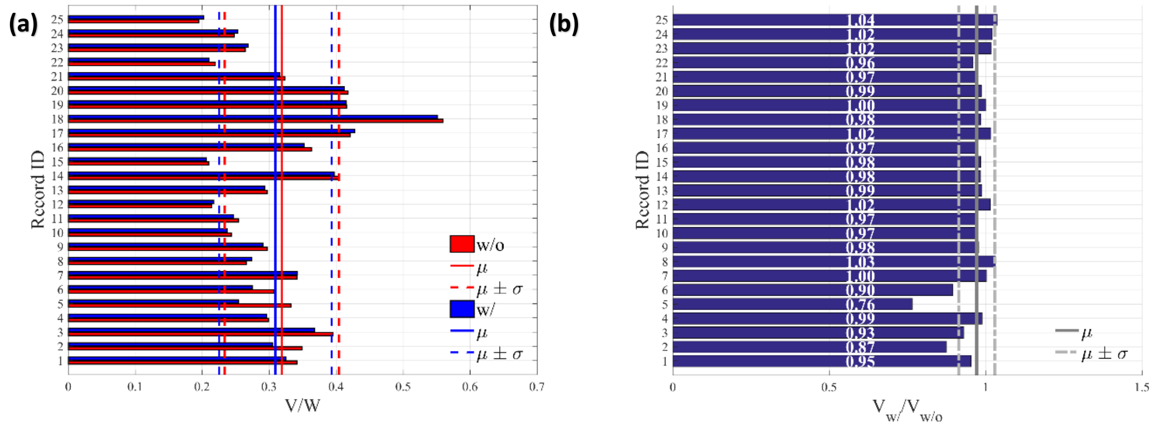

Fig. 9 - (a) Weight normalized maximum base shear; (b) base shear ratio for record

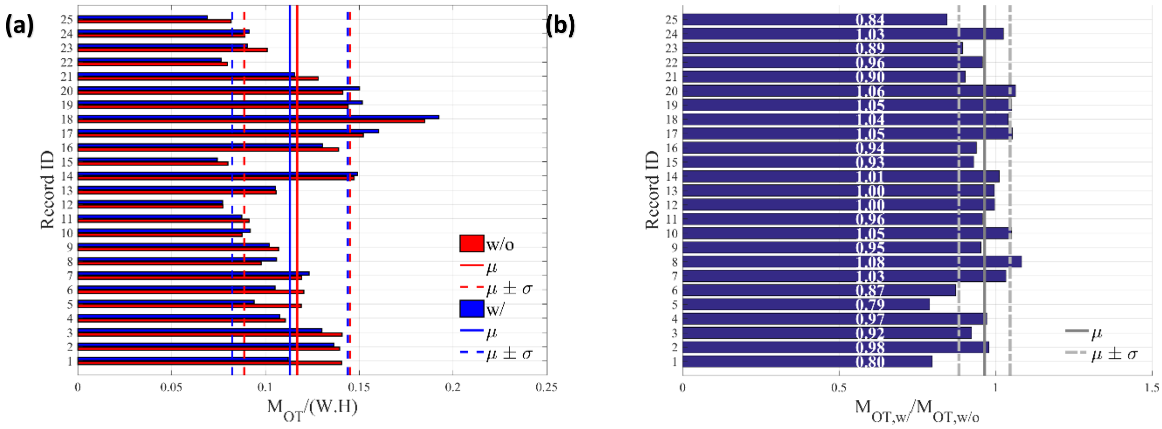

Fig. 10 - (a) H x W normalized maximum overturning moment just above the base; (b) overturning moment ratio for each record

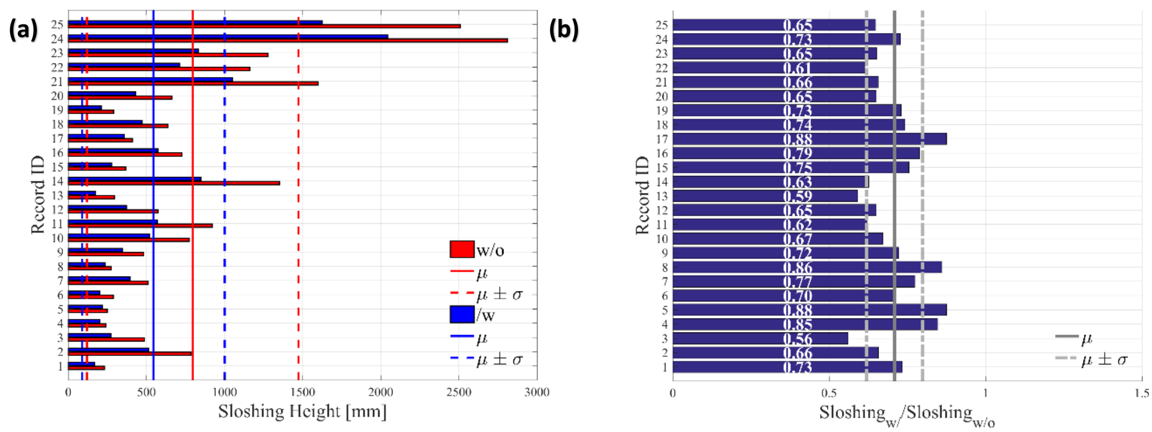

Fig. 11 - (a) Maximum sloshing height; (b) maximum sloshing height ratio for each record

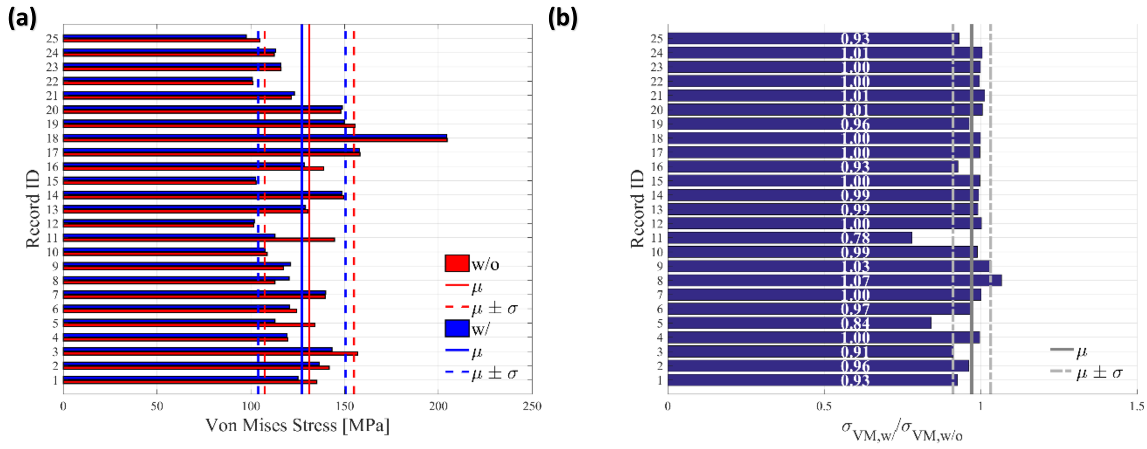

Fig. 12 - (a) Maximum von mises stress; (b) maximum von mises stress ratio for each record

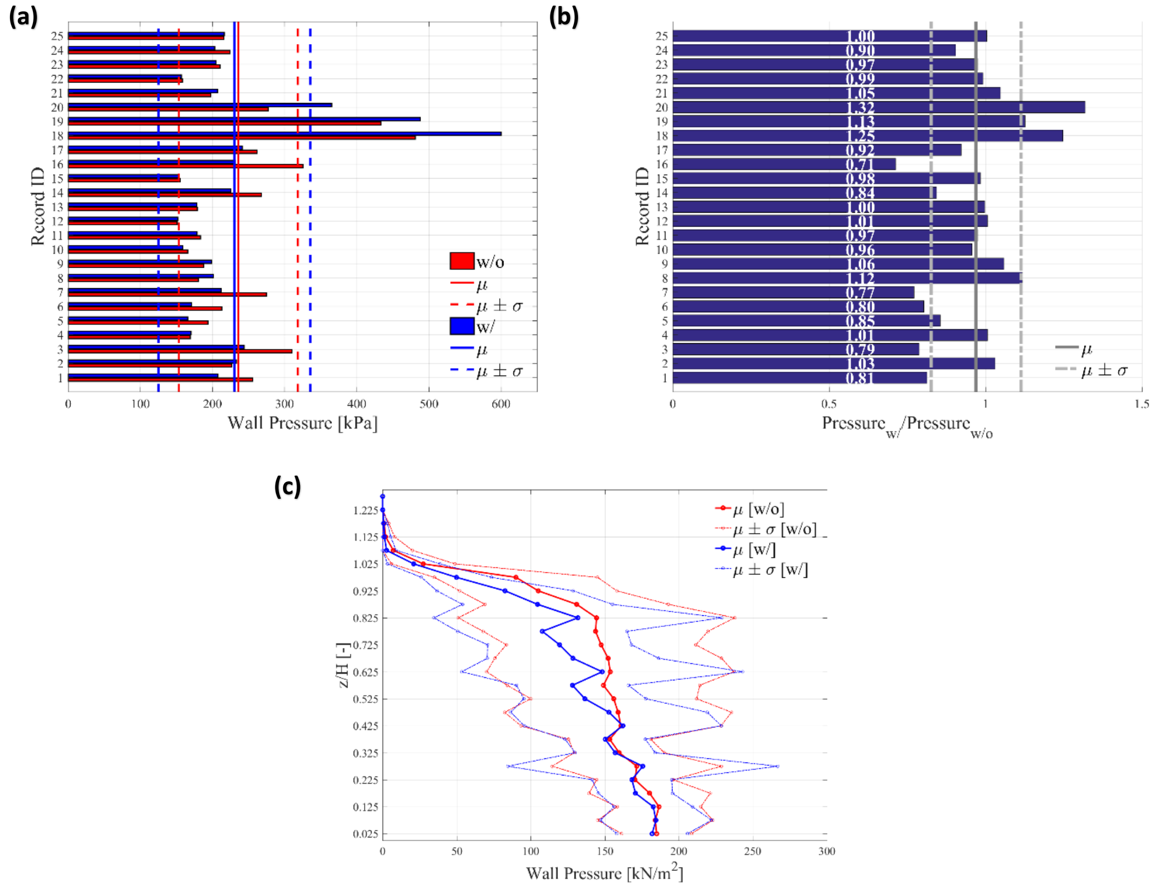

Fig. 13 - (a) Maximum wall pressure; (b) maximum wall pressure ratio for each scenario; (c) mean of maximum wall pressure distributions obtained from analysis

In total 50 transient explicit analyses were performed for two cases, namely for a tank with (w/) and without (w/o) viscous dampers. Performance of the dissipation system is evaluated by comparing the maximum of the selected parameters (see Fig.9-13); more in detail, analysis results have been processed to compute (i) the weight normalized total base shear force, (ii) the overturning moment (just above the base) normalized to the weight times the height of the free water surface, (iii) the hydrodynamic pressure acting on the tank walls, (iv) the sloshing wave height, and (v) the Von Mises stress (or effective stress) for each record. Moreover, the results obtained for the tank with dampers are normalized to the counterparts without dampers and accompany each plot, thus illustrating comparative trends for each record. Furthermore, the mean maximum pressure distribution over the height of the tank obtained from all the analyses is also presented and compared together with the mean plus and minus standard deviation (Fig. 13c). Although, in general there is a slight decrease in the maximum base shear, the overturning moment and Von Mises stresses when the dampers are included, the changes are negligible from engineering point of view. The mean ratio of (w/)/(w/o) is almost one for these three parameters, and the corresponding variation is usually low. Overall, the steel wall elements remain elastic and the stresses are much lower than yielding criterion except record 18 where σ_{VM}/f_y=0.70. Likewise, on average the wall pressures are slightly dropped for the (w/) case, but the change is negligible. However, the deviation is significant, which is mainly caused by the variability in the seismic input. In terms of pressure distribution there seems to be slight improvement at upper levels of the wall whereas the wall pressures remain nearly the same at lower levels. It is important to state that maximum stresses are obtained from elements located at 0.15H-0.2H from ground level where usually elephant buckling, or diamond buckling is expected. Unlike other parameters, the dampers have considerable impact upon the tank in terms of sloshing height, especially in the case of pulse-like ground motions, on average, a 30% drop is observed in peak sloshing height with relatively low variability.

4. Conclusions

The aim of the research was to investigate the performance of proposed dissipation system and to validate the modelling assumptions with regards to above ground storage tanks with floating roof under seismic excitations. In order to evaluate performance of the proposed dissipation system in this study, the influence on five different performance parameters is investigated. In particular, the seismic response of floating roofed steel tanks with deformable walls and fully anchored at the base is studied. The main advantage of the proposed dissipation system is that it controls the sloshing of the liquid and reduces the wave height. Hence, possible fires due to loss of liquid, potential damage and sink of floating roofs can be prevented/minimized. Applying such damping control devices may influence other parameters like base shear, overturning moment, wall pressures and von mises stresses of the wall as well. Therefore, after implementing the viscous dampers, these parameters have been also investigated to determine the performance of proposed dissipation system. Once the modelling assumptions are verified using an experimental test available in the literature, transient explicit analyses have been performed to obtain the envelopes of performance parameters for the squat tank with H/R=0.5 slenderness ratio. The following conclusions can be stated based on the results obtained:

- The FSI problem herein is treated by using Arbitrary Lagrangian Eulerian (ALE) formulation and contact algorithm. The modelling approach considered has been verified comparing the results of a shake table test performed by other authors with the numerical results of a model developed in this study. The modelling approach considered provides a sufficiently accurate prediction of the response.

- It is observed that ground excitations with certain characteristics such as the pulse like ones (ID:21-25) causes greater sloshing motion. Even if structural elements do not fail under such ground motions, the freeboard might be insufficient. In such scenarios sloshing motion of tank can be controlled via proposed dissipation system.

- Overall, the dissipation system improves significantly the seismic performance of the tanks with low H/R ratio (squat tanks), in terms of sloshing wave height, regardless of the ground motion characteristics. It is predicted that this retrofitting strategy can be more beneficial for squat tanks since the convective contribution is far greater in squat tanks compared to those in slender ones. Yet, the performance of slender tanks can also be enhanced.

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