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EFFECT OF FLUID VISCOUS DAMPERS IN FLEXIBLE BASE TANKS SUBJECTED TO SIESMIC LOADING

Ahmed Hafez
Senior Engineer, Dams and Structures, Ontario Power Generation, Toronto, Ontario
ahafez@ryerson.ca

M. Reza Kianoush
Professor, Department of Civil Engineering, Ryerson University, Toronto, Ontario, Canada
kianoush@ryerson.ca

Saeid Haji ghasemali
Research Associate, Department of Civil Engineering, Ryerson University, Toronto, Ontario, Canada
shajighasemali@ryerson.ca

ABSTRACT: Liquid containing structures (LCS) are important components in the commercial and industrial applications. The improving of nonlinear behavior of LCS under seismic loads has a significant role in analysis and design. The results of the nonlinear finite element (FE) analysis of circular tanks under dynamic time- history analysis show that the flexible base tanks with seismic cables are not capable of dissipating the seismic forces as expected. So in this study, a new design approach is proposed for anchored flexible base tanks, using external fluid viscous dampers (FVD) to improve the tank response under seismic loads. The response of open top ground supported flexible base circular tanks under time- history analysis is considered in this study with different aspect ratios. Furthermore, the effect of the FVD damping constant (C) on the results is also investigated. In addition, the results of the study are also compared with those of current practice. It is found that, the behavior of flexible base tanks under seismic loads can be improved by adding FVD. Accordingly, using FVD can improve the tank serviceability by reducing the concrete cracking and displacement.

1. Introduction

During strong motions, such as earthquakes, conventional structures usually deform well beyond their elastic limits and eventually fail or collapse. Therefore, most of the energy dissipated is absorbed by the structure itself through localized damage as it fails. The concept of supplemental dampers added to a structure assumes that much of the energy input to the structure from a transient load will be absorbed, not by the structure itself, but rather by supplemental damping elements.

Many research studies have been conducted on the effects of dampers on seismic behavior of structures. As a result of the previous studies, in order to avoid damage due to earthquakes, an alternate source of energy dissipation, such as fluid viscous dampers, should be provided. An experimental study on a cable-damper system was conducted by Fournier and Cheng (2014) to investigate the individual and the combined effects of damper stiffness and damper support stiffness on the performance of a linear viscous damper. A finite-element (FE) model of the corresponding cable-damper system was developed to verify the experimental results. This study showed that higher damper stiffness and/or lower damper support stiffness would have an adverse impact on damper performance. Increasing the stiffness of a damper and/or its support would result in a larger optimum damper size. Another research study was conducted by Martinez et al. (2010) to deal with the application of Passive Control techniques to mitigate the excessive vibrations that short simply supported railway bridges may undergo under the circulation of

High-Speed trains. They found that the inadmissible levels of deck vertical acceleration was reduced based on retrofitting the bridge with fluid viscous dampers connected to the slab and to an auxiliary structure. Museros et al. (2007) researched on a new alternative for reducing the resonant vibration of simply supported beams under moving loads. The strategy proposed was based on the use of linear fluid viscous dampers that connect the beam carrying the loads (main beam) and an auxiliary beam placed underneath the main one. Their research showed that the resonant response of the main beam can be drastically reduced with this type of device. The results were then applied to real bridges subjected to railway traffic. The methodology proposed had potential applications for the reduction of the response of railway bridges subjected to the transit of high-speed trains.

Although much research has been conducted on the effect of fluid viscous damper (FVD) on dynamic response of structures, there is no significant investigation on the effect of such dampers on the flexible base tank behavior. In this research, a new design technique is presented to reduce the dynamic response of anchored flexible base tanks to the desired level. The main focus of this study is to investigate the effect of fluid viscous dampers in flexible base tanks subjected to ground accelerations. For this purpose, FE technique is used to study the linear and nonlinear response of the tanks under seismic loads using time-history analysis. The results of the FE dynamic analysis are also compared with current practice. In this study, the effect of damping constant (C) on the tank response is also investigated. Furthermore, for the sake of comparison, the effect of FVD on the tank response for flexible supports without seismic cables is also investigated.

2. Flexible base tank

The flexible base supports can be used for prestressed circular tanks (ACI 350.3-06, 2006). For anchored, flexible-base tanks, it is assumed that the entire base shear is transmitted by membrane (tangential) shear. The anchored, flexible-base support consists of seismic cables connecting the wall and the footing, as well as elastomeric bearing pads. The main mechanism for transferring the base shear from the wall to the foundation is the tangential resistance offered by a system of seismic cables connecting the wall to the perimeter footing (Fig. 1). Due to expected linear behavior of seismic cables, the flexible base tanks with seismic cables are not capable of dissipating the seismic forces. The seismic cables are made of prestressing cables with high yield strength; therefore, the flexible supports are unable to yield. In addition, the restraints provided by seismic cables in the tangential direction restrict the wall movement to dissipate the seismic energy. Therefore, other mechanisms such as applying FVD, which can dissipate the seismic energy, could be used.

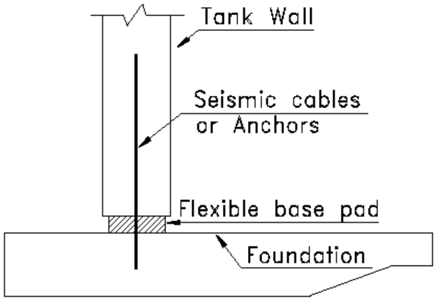


Fig. 1 – Flexible base Ground-supported tank support connections

3. Fluid viscous damper

As shown in Fig. 2, a FVD consists of a hollow cylinder filled with a fluid. As the damper piston rod and piston head are stroked, fluid is forced to flow through orifices either around or through the piston head. The fluid flows at high velocities, resulting in the development of friction and thus heat. The heat is dissipated harmlessly to the environment. Interestingly, although the damper is called a viscous fluid damper, the fluid typically has a relatively low viscosity. The term viscous fluid damper comes from the macroscopic behavior of the damper which is essentially the same as an ideal viscous dashpot (i.e., the force output is directly related to the velocity).

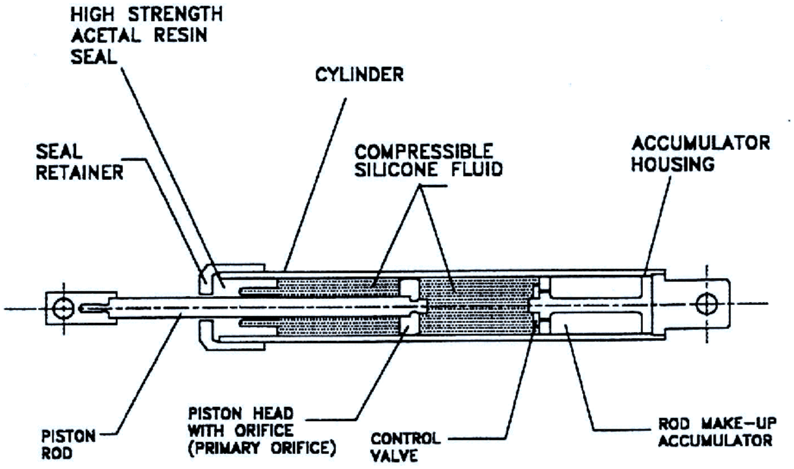


Fig. 2 – Typical cross section of fluid viscous damper

Generally, a simple dashpot can be used to model dampers that exhibit viscosity and little or no elasticity. In a viscous damping model, the output of the damper is calculated using Equation (1) as follows:

$$F_{damper} = C\,V^{\alpha} \tag{1}$$

Where,

C = damping constant

V= Velocity

$\alpha =$ Velocity exponent

The effect of the damping velocity exponent has been investigated by Hwang et al. (2005) where linear and nonlinear dampers have been examined. Fig. 3 shows the efficiency of the nonlinear damper in minimizing the high velocity shocks. However, for the purpose of this study, only first iteration for linear dampers with α equal to one is considered in the analysis.

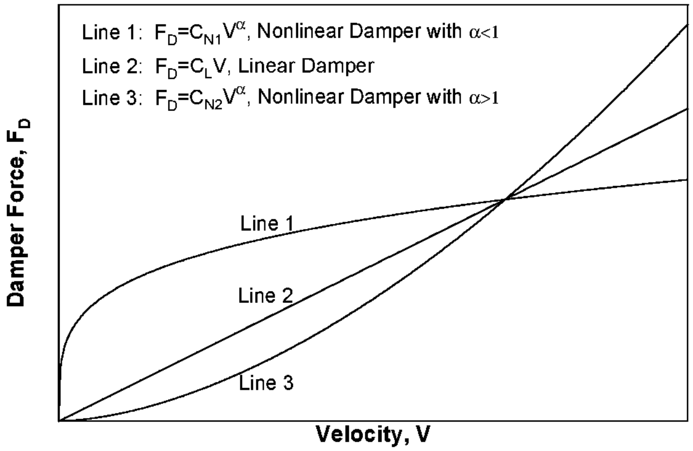
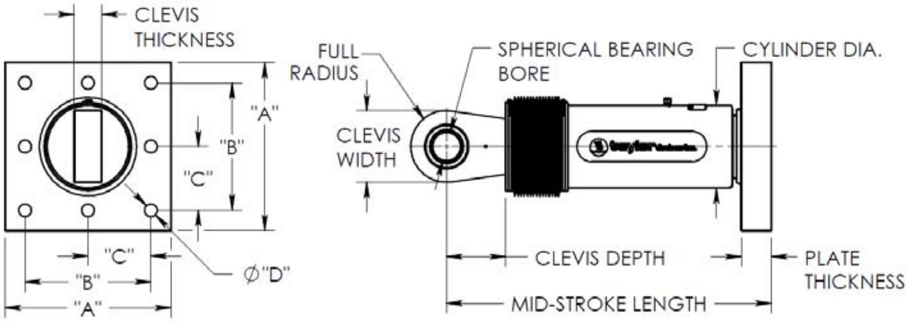


Fig. 3 – Force-velocity relationship of viscous dampers (Hwang et al. , 2005)

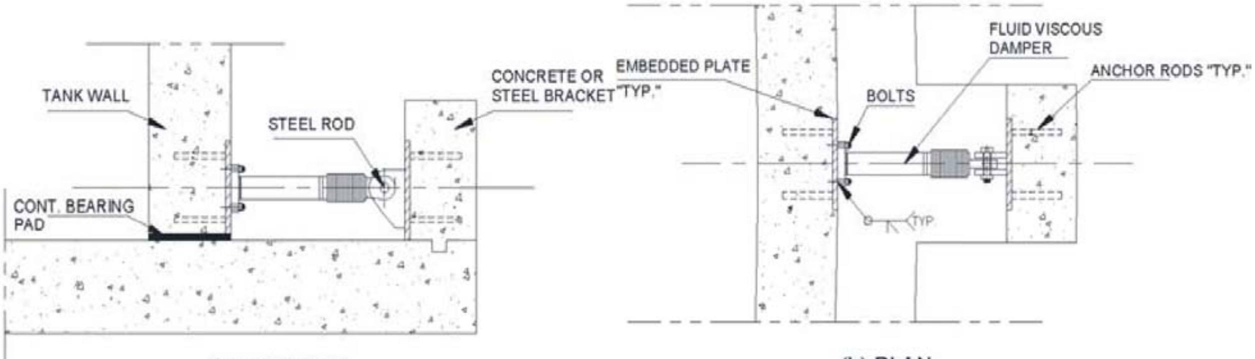
Moreover, the forces in the dampers are calculated from the time-history analyses for different damping constants, and then, the suitable dampers are selected from the manufacturer datasheets. The FVD detail and dimensions are shown in Fig. 4.



(a) (b)

Fig. 4 – Fluid viscous damper detail and dimensions; (a) Front view, (b) Side view

The fluid viscous damper connection detail is shown in Fig. 5. The dampers are connected to the bottom of the tank wall in the radial direction. Embedded steel plates are anchored to concrete wall using steel anchors at damper locations. These steel plates, accordingly, can be welded or bolted to damper end plates on the side of the damper near the tank wall. On the other side of the damper, the damper clevis is connected to fixed steel or concrete bracket that is connected to the tank foundation. The damper supporting brackets are considered to be rigid similar to the tank foundation. For the purpose of this study, a total of thirty two dampers are used for each tank; thus, the polar angle θ between every consecutive damper is 11.25^{o} as shown in Fig. 6. The total number of FVD (32 dampers) is found to be reasonable since the damper maximum reaction (245 kN) is found appropriate for designing the end plates and anchoring system. The dampers are installed horizontally for anchored flexible-base tanks in order to compensate for the lack of ductility and to dissipate the seismic energy especially for prestressed tanks.



(a) SECTION (b) PLAN

Fig. 5 – Fluid viscous damper connection detail; (a) Section, (b) Plan

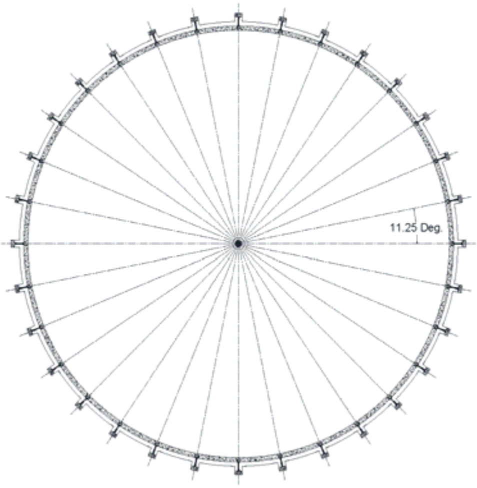


Fig. 6 – Fluid viscous dampers layout – Plan view

4. Time- History Analysis

4.1. Tank configuration and design parameters

Three models referred to as tanks 1, 2 and 3 with anchored flexible base condition and horizontal prestressing, are used in this study. These Tanks are corresponding to different D/H_L ratios of 13.33, 6.67 and 4.44, respectively. Furthermore, in order to investigate the behaviour of the tanks with FVD and without seismic cables, another model referred to as without seismic cables (W/O SC) is also considered for tanks. Wall reinforcement, prestressing strands, and seismic cable details are shown in Table 1. The tank diameter (D) is equal to 40m. H_L, H_W and t_W are water depths, wall heights and wall thickness respectively.

Table 1 – Tank details

Tank type	H_L (m)	H_W (m)	t_W mm	Vertical bar EF		Horizontal Prestressing Seven Wire Strands – Size 15		Base seismic cables	
				Bar size	Spacing (mm)	No. of Strands	Spacing (mm)	Strand Size (mm)	Spacing (m)
1	3	3.25	250	15M	300	3	400	15	5.0
2	6	6.5	300	15M	225	3	200	15	2.0
3	9	9.6	400	20M	250	5	270	15	0.9

In this study, FE time-history analysis is conducted on the tank model in order to investigate the nonlinear behavior of such structures under seismic loads. The hydrodynamic forces are calculated based on ACI 350.3-06 (2006), and the design is according to ACI 373R (1997), AWWA D110 (1995) and Chapter 18 of ACI 350-06 (2006). The tanks are designed representing high seismic zone having S_s= 150% and S_1= 60%, corresponding to 1940 El-Centero earthquake record. S_s is the mapped maximum considered earthquake 5% damped spectral response acceleration parameter at short periods, expressed as a fraction of acceleration due to gravity g. S_1 is the mapped maximum considered earthquake 5% damped spectral response acceleration; parameter at a period of 1 second, expressed as a fraction of acceleration due to gravity g. Furthermore, for time-history FE analysis, the El-Centro record, as shown in Fig. 7, is scaled in such way that its peak ground acceleration (PGA) in the horizontal direction reaches 0.4g from its original value of 0.32g, where (g) is the acceleration due to gravity (9.807 m/s2). Only P_i (impulsive forces) and P_W (lateral inertial forces of the accelerating wall) combined are considered. Since the convective component has a negligible effect on the overall seismic response, it is ignored in this study.

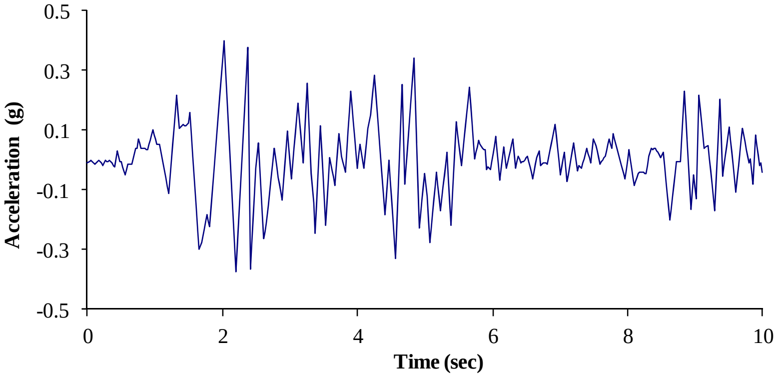


Fig. 7 – Scaled El- Centro earthquake record (horizontal component)

The design forces and bending moments for tanks with flexible base are calculated based on the results of linear static FE analysis. Moreover, for flexible supports, seismic cables in the tangential directions of the tank wall resist the seismic forces at the tank base. Also, the stiffness of the bearing pads in both tangential and radial directions is considered in the analysis and design of such tanks. The crack control and liquid-tightness is achieved by the circumferential prestressing together with non-prestressed vertical reinforcement near each face of the wall. The minimum thickness of the core wall is maintained as 250mm for cast-in-place concrete walls with internal circumferential tendons and vertical conventional reinforcement according to ACI 373R (1997). It should be noted that, the circumferential prestressing tendons are bonded according to ACI 350-06 (2006).

4.2. Constituent Materials

For linear elastic analysis, the material properties are specified as follows; the specified compression strength of concrete (f'_c) and yield strength of reinforcement (f_y) are 30 MPa and 400 MPa, respectively, where the modulus of elasticity of concrete (E_c) and reinforcement (E_s) are taken as 26000 MPa and 200000 MPa respectively. The concrete section is considered as uncracked section. For nonlinear analysis, the concrete damaged plasticity (CDP) model is used since it is a suitable concrete model for dynamic analysis. As the stresses in concrete shell of the circular tanks are bending and bending plus axial stresses, the Modified Hognestad method (1997) is used as analytical approximation for the compressive stress-strain curve for concrete. The steel reinforcement is considered elastic perfectly plastic material. The design requirements for prestressing tendons are specified in CSA Standards A23.3 (2004) and A23.1 (2010) including the minimum specified yield strength, and the minimum ultimate tensile strength. In this study, seven-wire strands grade CSA G279 are used for prestressing steel. It should be noted that, the steel grades for tendons depend on the minimum tensile strength (f_{pu}) which is 1860 MPa for grade CSA G279, and the yield strength (f_y) is 1581 MPa. The elastic modulus of non-prestressed tendons (Es) is taken as 200,000 MPa in this study. For both linear and nonlinear FE analysis, the following material proprieties are considered:

Thermal expansion coefficient of prestressing tendons (α_{pt}) = $1x10^{-5}$

Poisson's ratio of concrete (v_c) = 0.18

Poisson's ratio of reinforcement (v_s) and prestressing tendons (v_{pt}) = 0.0

The most common type of elastomeric pads is 40H which was used for the flexible based tank bearing pads. The shear module of elastomeric bearing pad (G_p) is taken 0.345 MPa (50 psi) for type 40H.

4.3. Computer model and FE Analysis

In this study, the FE analysis is conducted using ABAQUS/CAE Version 6.8.3 (Dassault Systèmes Simulia Corp., 2008). Linear and nonlinear FE time-history analyses are carried out on the circular tanks in order to investigate the effect of using FVD on the response. In summary, the entire tank is modeled using four-node quadrilateral shell element to model the wall where the number of elements along the wall height is four, seven, and ten elements for Tanks 1, 2 and 3 respectively. Both linear and nonlinear time-history analyses are performed. Also, the concrete tensile strength is not considered in the FE analysis. The seismic cables and bearing pads are modeled as spring elements. The viscous dampers are also modeled as dashpots in the radial direction as shown in Fig. 8. For the case without seismic cables, referred to as W/O SC, only bearing pads are modeled as spring elements where the stiffness of seismic cables are not included in the FE model. The dashpots are used to model relative velocity-dependent force resistance. The DASHPOTA element (ABAQUS/CAE, 2008) is also used to connect two nodes with its line of action being the line joining the two nodes. Each dashpot element is defined by connecting two nodes, in which one end of each dashpot is selected to be one of the tank nodes at the base, where the other end of the dashpot is modeled as fixed support.

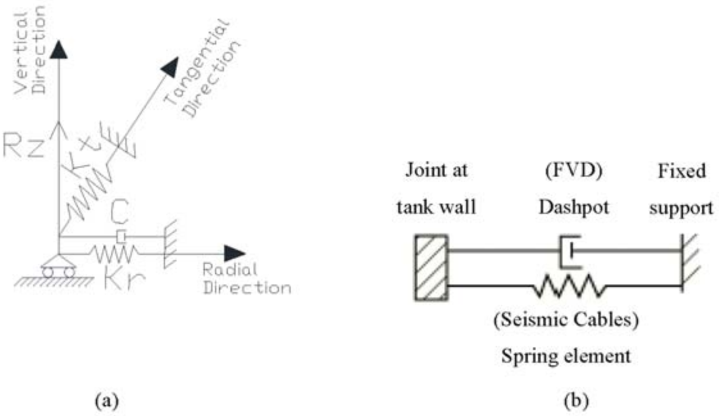


Fig. 8 – Flexible support and damper model; (a) 3-D view, (b) Radial direction

The stiffness of the anchored flexible support in the tangential direction (K_t) is the summation of K of seismic cables and K of bearing pads (ACI 350-06, 2006). In the radial direction, the stiffness of the bearing pads is also considered as the stiffness of the anchored flexible support (K_r) (ACI 350-06, 2006). As shown in Figure 8, the flexible base is modeled using two spring elements at each node of the tank base in the tangential and radial directions. Each spring is defined by connecting two points, where one end of each spring is selected to be one of the tank joints at the base, where the other end of the spring is modeled as fixed support. The prestressing force is applied in the form of thermal contraction that is applied only to the prestressing tendons which are assumed to be fully bonded to concrete. Therefore, the thermal expansion coefficient of concrete and reinforcement is assumed to be zero. Reinforcement is modeled in concrete walls by means of rebars. Rebars are one-dimensional strain theory elements (rods); which are defined as embedded elements in oriented surfaces. Since the tendons are fully bonded, the prestressing tendons are modeled using the same technique as the reinforcement. In FE analysis, only the masses associated with impulsive component, which was modeled as the nonstructural mass and the tank wall are included since the effect of the convective component is negligible. Also, both gravity load and hydrostatic loads are included in the FE model.

5. Results and Discussion

In this study, a wide range of C values are considered in FE analysis in order to determine the optimal value for C. The values of damping constant in units of kN.sec/m are included alongside the letter C, where C refers to damping constant for each FVD. For example, C100 refers to damping constant equals to 100 kN.sec/m and C0 indicates that dampers are not used. The following abbreviations are used in this study:

ACI 350.3 (R_i =1): Tank response for seismic force calculated based on ACI 350.3 (2006) with R_i = 1.0

FE: Tank response from FE time-history analysis due to scaled El-Centro horizontal record

$V_{El\text{-}Centro}$: Absolute maximum value of peak base shear from time-history analysis due to scaled El-Centro horizontal record

$V_{ACI\ (Ri\ =1)}$: Base shear based on ACI 350.3 (2006) with R_i = 1.0

R_i: Response modification factor for the impulsive component

FL: Flexible base

W/O SC: Without seismic cables

Fig. 9 shows the ratios between the maximum dynamic base shear ($V_{El\text{-}Centro}$) and the equivalent static elastic base shear based on ACI 350.3 (2006) ($V_{ACI\ (Ri\ =\ 1)}$) for various D/H_L ratios. It can be seen from Figure 9 that the flexible base tanks with seismic cables and without FVD (C0) cannot dissipate as much energy and the dynamic base shear is further reduced due to introducing FVD. However, the reduction in base shear is much greater when nonlinear material properties are included in the FE model which indicates that, nonlinear analysis may be required in order to predict a reasonable estimation of force reduction factor. Also, the results presented in this Figure show that the values of dynamic base shear for supports with FVD and without seismic cables (W/O SC) are similar to those for supports with FVD and seismic cables.

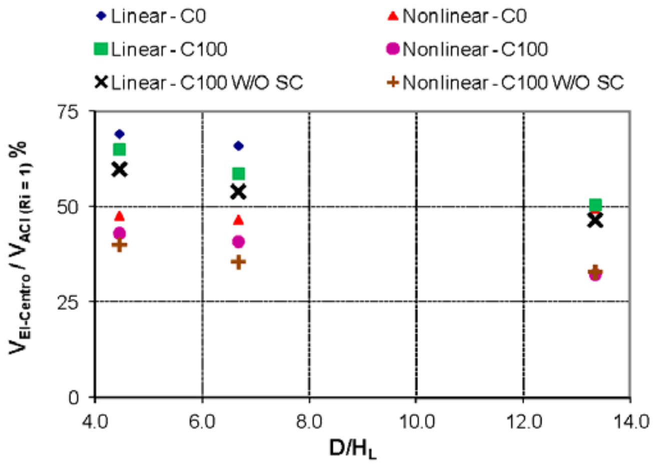


Fig. 9 – Effect of tank dimensions and damping coefficient on base shear

In this study, the ductility factor is considered as a ratio of V_{Linear} to $V_{Nonlinear}$ (ATC-19, 1995), and the overstrength factor is considered to be equal to 1.4 (FEMA 450, BSSC, NEHRP, 2003). The R_i-values are calculated as the product of the ductility factor and the overstrength factor (Newmark and Hall, 1982). Therefore, R_i-values are calculated for tanks with different D/H_L ratios and, also, for various values of damping constant. It should be noted that, for the purpose of comparison, V_{Linear} is always considered for C0. As shown in Figs. 10 and 11, R_i is directly proportional with damping constant, thus, the tank behavior under seismic loads can be improved by using FVD system. Fig. 10 shows that, for tank 2, in order to achieve R_i value recommended by current practice (ACI 350-06, 2006), R_i = 3.25, a damping constant of 490 kN.sec/m (interpolated from Ri-values for C100 and C500) should be provided for the used FVD configuration. Fig. 11 also shows that, for FVD system, the effect of D/H_L ratios on the response modification is relatively small. R_i-values are less than 2 for tanks without FVD for all D/H_L ratios, thus, using R_i-value recommended by current practice (R_i = 3.25) may underestimate the seismic load. Fig. 12 shows the deflection at tank base for Tank 2. As shown in this Figure, using FVD system with seismic cables reduces the tank deflection. However, the deflection for supports with FVD and W/O SC is around 85% more than the case for those with FVD and seismic cables. It should be also noted that, the deflection at tank base decreases as the damping constant increases.

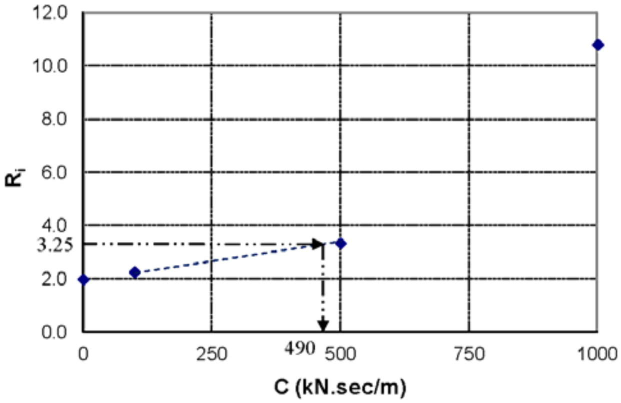


Fig. 10 – Effect of damping constant on response modification factor – Tank 2

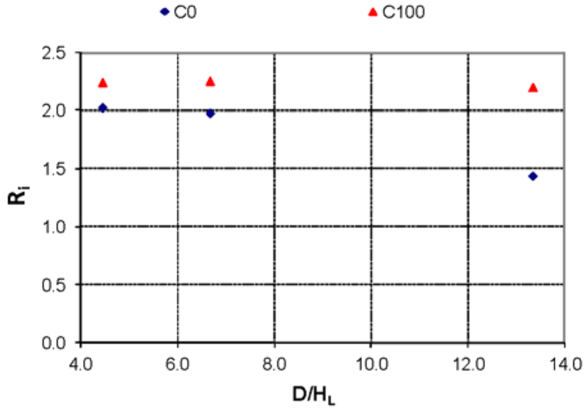


Fig. 11 – Effect of tank dimensions and damping constant on response modification factor

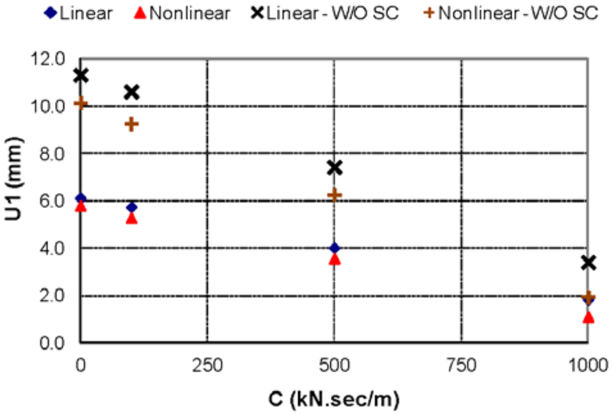


Fig. 12 – Effect of damping coefficient on base deflection –Tank 2

6. Conclusion

Based on the results of the FE analysis, it is found that, the behavior of flexible base tanks under seismic loads can be improved by adding fluid viscous dampers (FVD). In addition, the dynamic response of the tanks can be further improved by increasing the damping constant or nonlinear material properties are included in the FE model. It is also found that the R_i-values are less than 2 for tanks without FVD, so, applying R_i-value recommended by current practice [10] ($R_i = 3.25$) may underestimate the seismic load. Accordingly, using FVD can improve the tank serviceability by reducing the concrete cracking and displacements. Also, FVD can be used as a replacement for seismic cable as the values of base shear are similar for supports with and without seismic cables. However, deflections for supports with FVD and W/O SC are much higher than those for supports with FVD and seismic cables.

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