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Analysis and seismic buckling strength evaluation of liquid-filled stiffened steel cylindrical tanks

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Abstract

This study aims to investigate the buckling strength of unstiffened and stiffened liquid-filled steel cylindrical tanks under different earthquake excitations. Finite element models of liquid-filled steel cylindrical tanks with various diameter-to-thickness (D/t) and the height-to-diameter (H/D) ratios are generated to investigate the buckling behaviors of various sizes of the steel cylindrical tanks under different earthquake excitations. Vertical stiffeners around the circumference are included for stiffened steel cylindrical tanks. The transient analyses are carried out using a commercial finite element program ANSYS. Pseudo-Equilibrium path criterion is used to evaluate the seismic buckling strength. According to the results of both unstiffened and stiffened liquid-filled steel cylindrical tanks, the seismic buckling strength decreases significantly as the diameter-to-thickness (D/t) ratio increases. However, it decreases slightly as the height-to-diameter (H/D) ratio increases. The results show that the vertical stiffeners considerably improve the seismic buckling strength of the liquid-filled steel cylindrical tanks. Based on the extensive parametric study, the interaction effects of D/t ratio, H/D ratio, and vertical stiffeners on seismic buckling strengths for the steel cylindrical tanks of various geometries subjected to three different earthquakes are presented and discussed.

1. Introduction

Seismic buckling plays an important role in the design of liquid-filled steel cylindrical tanks because of the small thicknesses of the walls. The steel cylindrical tanks are susceptible to local buckling when they are subjected to horizontal earthquake accelerations. The damages of petroleum storage tanks were reported due to the Long Beach earthquake of 1933, the Kern County earthquake of 1952, the Alaska earthquake of 1964, the San Fernando earthquake of 1971, the Imperial Valley earthquake of 1979, the Coalinga earthquake of 1983, the Loma Prieta earthquake of 1989, the Landers earthquake of 1992, the Northridge earthquake of 1994, and the Kobe earthquake of 1995 (Cooper and Wachholz 1999). From recently published reports, the seismic buckling of steel cylindrical tank walls was observed after the Emilia earthquake of 2012 and the South Napa earthquake of 2014 (Buratti and Tavano 2014, Fisher et al. 2016). The American Lifelines Alliance (2001) reported the failure modes of steel storage tanks subjected to past earthquakes, which are roof damage, foundation failure, manhole failure, hydrodynamic pressure failure, piping failure, anchorage failure, and shell buckling. The main objective of this study is to

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investigate the local shell buckling of the liquid-filled steel cylindrical tanks when they are subjected to the horizontal earthquake accelerations.

Previous research was conducted in the area of seismic local buckling of unstiffened steel cylindrical tanks using experimental study and finite element method (FEM). The buckling of tall steel cylindrical wine storage tanks was investigated using a shaking table to generate the characteristics of the 1980 Livermore earthquake (Niwa and Clough 1982). Housner and Haroun (1979) conducted the force vibration tests to study the dynamic response of full-scale liquid-filled steel cylindrical tanks. Seismic buckling strengths of different sizes of steel cylindrical tanks under earthquake loads were studied using FEM (Virella et al. 2006, Djermane et al. 2014, Roopkumdee et al. 2018, Roopkumdee and Mamaghani 2018). Virella et al. (2006) used a commercial finite element program ABAQUS to study dynamic buckling of the anchored steel tanks with the height-to-diameter ratio (H/D) less than 1.0, finding that the seismic buckling occurred at peak ground acceleration (PGA) between 0.25g to 0.35g. Djermane et al. (2014) evaluated the PGA values that caused the instability state of the steel cylindrical tanks using FEM. Sobhan et al. (2017) used nonlinear static pushover to investigate the buckling behavior of the anchored steel tanks, finding that bi-directional excitation obtained from static pushover analysis is similar to that obtained from dynamic buckling analysis.

Steel cylindrical tanks are more susceptible to local shell buckling if the high strength steel materials are used for the walls of the cylindrical tanks (Blackler 1986). Sun et al. (2018) studied the design sizes of top and intermediate stiffener rings of the cylindrical tanks when they were subjected to wind loading. Blackler (1986) used FEM to propose an expression for the design of the top stiffener ring using curve fitting by relating the moment of inertia with the height and wall thickness of the tanks.

Based on previous studies in the literature, there are two questions that still need answers: first, can vertical stiffeners improve the seismic buckling strength of the liquid-filled steel cylindrical tanks?; second, what are the interaction effects of diameter-to-thickness (D/t) and height-to-diameter (H/D) ratios on seismic local buckling strength of the steel cylindrical tanks? Therefore, the aim of this study is twofold: first, to investigate if vertical stiffeners can improve the seismic buckling strength of the steel cylindrical tanks; second, to evaluate the interaction effects of H/D and D/t ratios on the seismic buckling strengths of liquid-filled steel cylindrical tanks.

2. Finite Element Models

2.1 Unstiffened cylindrical tanks

Different geometrical configurations of the liquid-filled steel cylindrical tanks are analyzed with height-to-diameter (H/D) ratios of 0.43, 0.67, 1.00, 1.46, and 2.41 and the diameter-to-thickness (D/t) ratios of 910, 1013, 1216, 1612, and 2130 to investigate the seismic local buckling behavior of various sizes of the cylindrical tanks. The geometries of the analyzed cylindrical tanks are listed in Table 1. As an example, a configuration of the analyzed steel cylindrical tanks is illustrated in Fig. 1. The unstiffened steel cylindrical tanks are represented as tanks A, B, C, D, and E, and the steel cylindrical tanks with vertical stiffeners are represented as tanks AS, BS, CS, DS, and ES, respectively.

Table 1: Geometries of the analyzed cylindrical tanks

Tank	H (m)	D (m)	t (mm)	H_r (m)	H/D	D/t	b_s (m)	t_s (mm)
A	6.1	9.1	10.0	0.85	0.67	910	-	-
AS	6.1	9.1	10.0	0.85	0.67	910	0.15	10.0
B	18.3	7.6	7.5	0.71	2.41	1013	-	-
BS	18.3	7.6	7.5	0.71	2.41	1013	0.15	7.5
C	15.2	15.2	12.5	1.43	1.00	1216	-	-
CS	15.2	15.2	12.5	1.43	1.00	1216	0.15	12.5
D	20.0	13.7	8.5	1.28	1.46	1612	-	-
DS	20.0	13.7	8.5	1.28	1.46	1612	0.15	8.5
E	9.1	21.3	10.0	2.00	0.43	2130	-	-
ES	9.1	21.3	10.0	2.00	0.43	2130	0.15	10.0

*H = height: D = diameter: t = wall thickness: H_r = roof height: b_s = width of stiffeners: t_s = thickness of stiffener

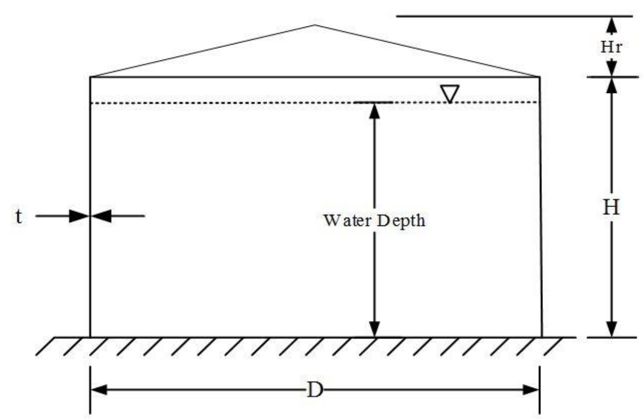


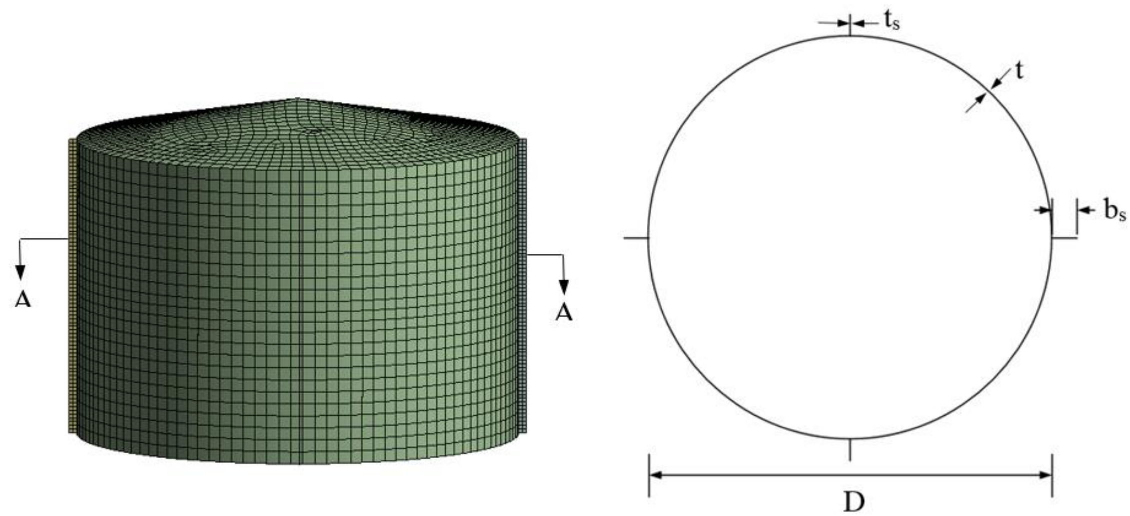
Fig. 1: Steel cylindrical tank geometry

The material, for all cylindrical storage tanks, is ASTM A572 structural steel with yield stress (σ_y) of 345 MPa, a modulus of elasticity (E) of 200 GPa, Poisson's ratio (ν) of 0.3, and the mass density (ρ) of 7,850 kg/m^3. The liquid inside the cylindrical tanks is water with the bulk modulus of 2,068.4 MPa, and the mass density of 1,000 kg/m^3. All cylindrical tanks are filled with water up to 90% of their heights.

The commercial finite element program ANSYS is used for all computations. SHELL181 element is used for the steel cylindrical tanks. SOLID186 element is used for the water-filled inside the cylindrical tanks. SHELL181 is a four-node element with six degrees of freedom at each node (three translations in x, y, and z directions, and three rotations about x, y, and z axes). SOLID186 is a higher order 3-D twenty-node solid element having three degrees of freedom per node that exhibits quadratic displacement behavior (ANSYS 2009).

2.2 Stiffened cylindrical tanks

The steel cylindrical tanks with four outer vertical stiffeners around the circumference are included in this study to investigate the pattern of buckling and seismic buckling strengths of the liquid-filled steel cylindrical tanks, see Fig. 2(b). The thicknesses of stiffeners are equal to the wall thicknesses of the cylindrical tanks. The widths of stiffeners are equal to 15 cm. The lengths of stiffeners are equal to the heights of the cylindrical tanks. SHELL 181 is also used to model the stiffeners. The material properties of stiffeners are the same as the unstiffened cylindrical tanks. cylindrical tanks AS, BS, CS, DS, and ES are modeled with SHELL181 elements. Fig. 2 represents the finite element meshing of tank AS.



(a) Side view (b) Section A-A

Fig. 2. Finite element meshing of the steel cylindrical tank AS

3. Nonlinear Seismic Analysis

Nonlinear seismic buckling analysis is carried to investigate the responses of the structures when they are subjected to time-dependent loads such as earthquake accelerograms (Rao 2011). Inertia and damping effects are considered in transient dynamic analysis. The equation of motion is expressed by Eq. 1. This equation is solved by the transient structure simulation in ANSYS. It uses the Newmark time integration method to solve the equation of motion at a discrete-time point.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F_{(t)}\} \tag{1}$$

where $[M]$ is mass matrix, $[C]$ is damping matrix, $[K]$ is stiffness matrix, $\{\ddot{u}\}$ is nodal acceleration vector, $\{\dot{u}\}$ is nodal velocity vector, $\{u\}$ is nodal displacement, $\{F_{(t)}\}$ is load vector, and t is time.

2.1 Damping

Rayleigh damping is a procedure of classical damping, which is adopted in this study. For simplicity and numerical efficiency, the damping is assumed as Rayleigh mass proportional damping as expressed in Eq. 2.

$$[C] = a_0[M] \tag{2}$$

where a_0 is the mass coefficient, $a_0 = 2\omega_n\zeta_n$, which based on natural frequency and fundamental mode (Cook 1995), ζ_n is a critical damping ratio, and ω_n is the first natural circular frequency (rad/s).

For the steel structure, the critical damping ratio (ζ_n) is generally between 2% and 3% (Djermane et al. 2014). In this study, the conservative value of 2% is adopted. Table 2 shows the calculated mass coefficients (a_0) for the unstiffened and stiffened liquid-filled steel cylindrical tanks.

Table 2: First natural frequencies and mass coefficients

Tank	f^* **(Hz)**	ω^* **(rad/s)**	a_0^*
A	4.26	26.77	1.07
AS	4.92	30.91	1.24
B	1.99	12.50	0.50
BS	3.67	23.06	0.92
C	2.29	14.39	0.58
CS	2.53	15.90	0.64
D	1.82	11.44	0.46
DS	2.75	17.28	0.69
E	2.07	13.01	0.52
ES	2.43	15.27	0.61

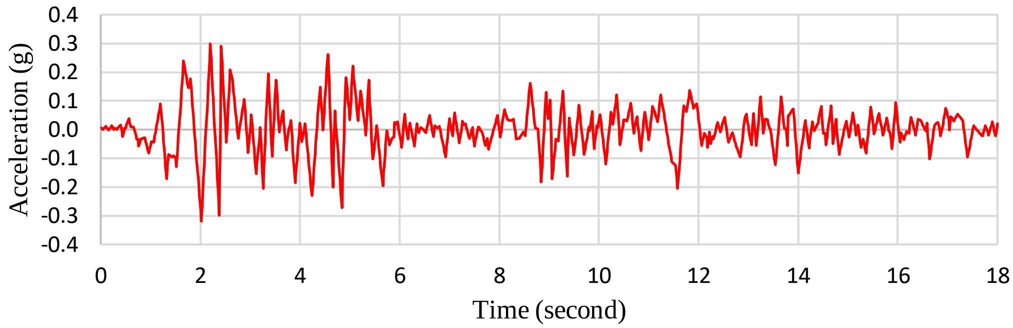
$*f$ is the first natural frequency (Hz): ω is the first natural circular frequency (rad/s):
ζ_n is critical damping ratio: a_0 is the mass coefficient:
$\omega = 2\pi f$: $\zeta_n = 0.02$: $a_0 = 2\omega_n\zeta_n$

2.2 Buckling criterion

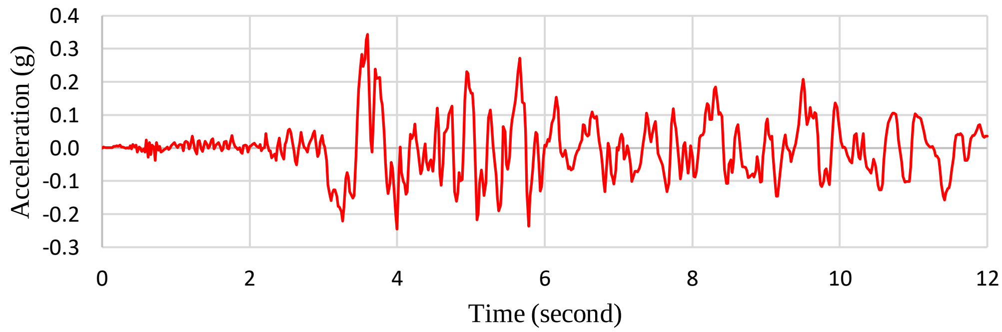
The Budiansky and Roth buckling criterion and phase plane buckling criterion are used to estimate the seismic buckling strengths of the stiffened liquid-filled steel cylindrical tanks. The Budiansky and Roth buckling criterion (1962) is employed in this study, as it has been broadly used as a technique to determine the seismic buckling strengths of structures. This criterion is based on a significant jump in displacement corresponding to an increase in load; therefore, several analyses need to be conducted using different loads. The plots of the peak displacements corresponding to the applied loads are obtained according to Budiansky and Roth buckling criterion, which is mentioned as "pseudo-equilibrium path" in this study

2.3 Earthquake excitations

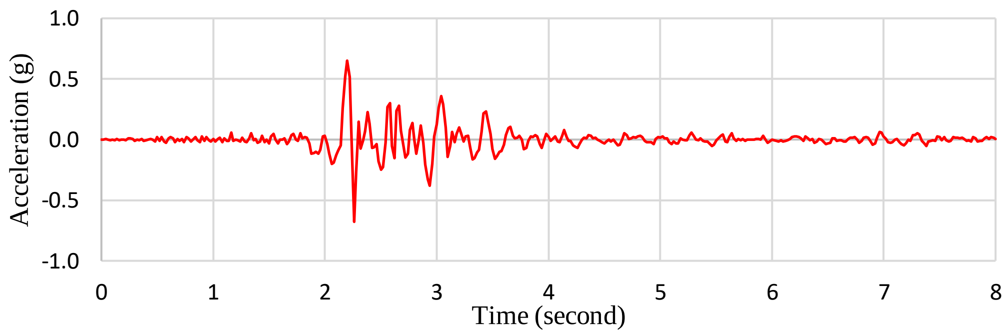
In this study, three different earthquake excitations are imposed on the liquid-filled steel cylindrical tanks as time-history accelerations corresponding to the El Centro earthquake of 1940, Northridge earthquake of 1994, and Parkfield earthquake of 2004, as shown in Fig. 3. All earthquake excitations are corrected from CESMD (2019).



(a) El Centro, 1940



(a) Northridge, 1994



(c) Parkfield, 2004

Fig. 3: Earthquake accelerograms

3. Seismic Buckling Results

3.1 Unstiffened cylindrical tanks

The nonlinear transient analyses of unstiffened liquid-filled cylindrical tanks are performed to investigate the seismic buckling strength and the interaction effects between D/t and H/D ratios. The location of elements where the maximum radial displacement occurs is tracked. The tracked elements are used to find the significant jump of the radial displacement when the PGA is increased. Fig. 4(a) and 4(b) show the deformation shapes of tank C when it is subjected to the El Centro earthquake of 0.3g and 0.6g, respectively.

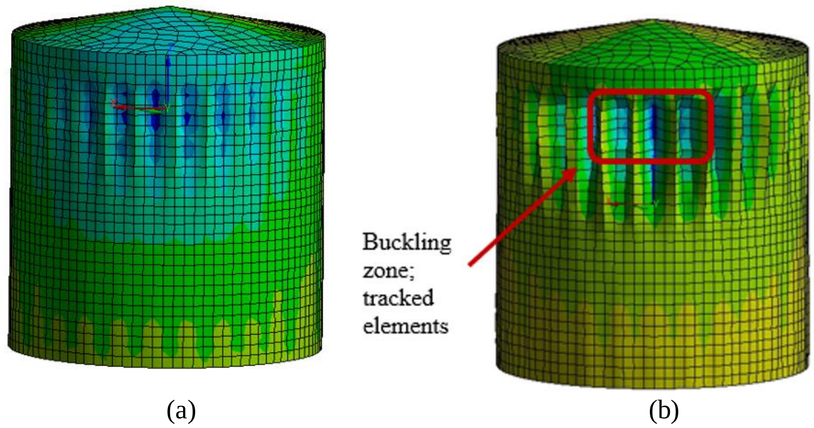


Fig. 4: Radial displacement: (a) pre-buckling tank C at 0.3g, scale 50:1; (b) post-buckling tank C at 0.6g, scale 50:1

Fig. 5 shows the example of the pseudo-equilibrium paths and the significant jumps of unstiffened liquid-filled steel cylindrical tanks under the El Centro earthquake. The seismic buckling strengths can be observed from a change in the slope of curves as shown in Fig. 5. The seismic buckling strengths for tanks A, B, C, D, and E under the El Centro earthquake are equal to 0.72g, 0.55g, 0.56g, 0.15g, and 0.075g, respectively. The seismic buckling strengths for tanks A, B, C, D, and E under the Northridge earthquake are equal to 1.34g, 0.63g, 0.70g, 0.21g, and 0.20g, respectively. The seismic buckling strengths for tanks A, B, C, D, and E under the Parkfield earthquake are equal to 1.30g, 1.20g, 0.88g, 0.40g, and 0.33g, respectively.

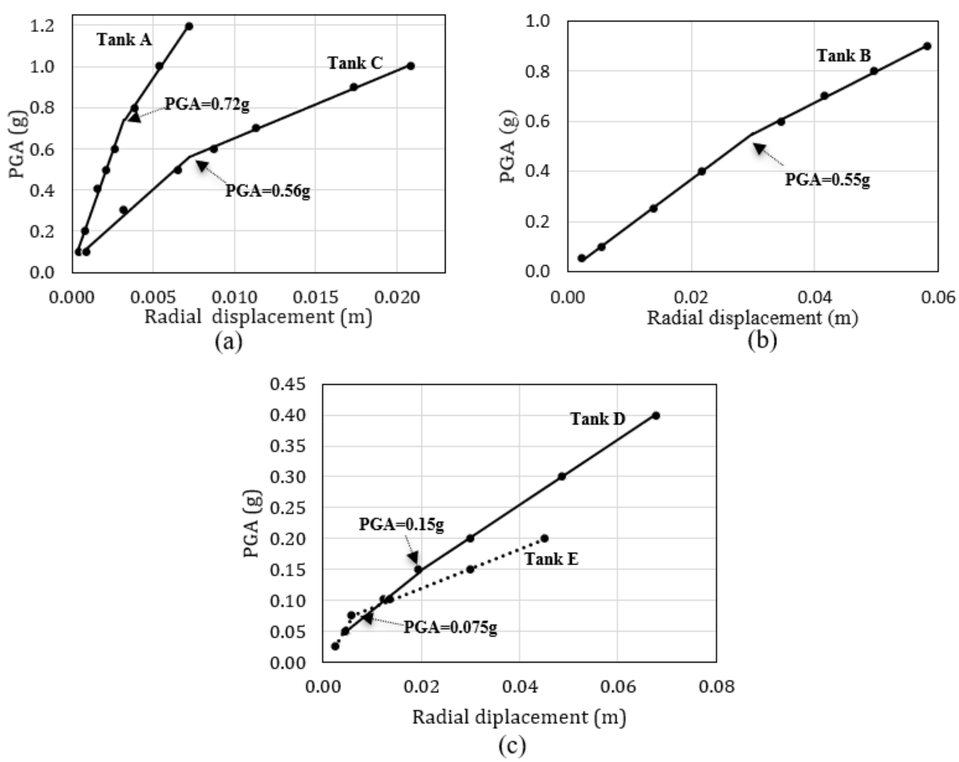
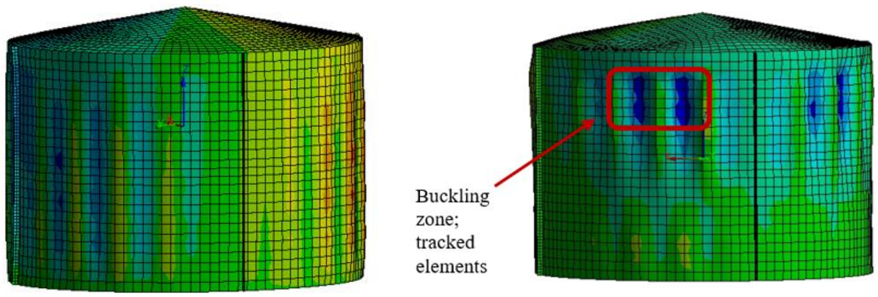


Fig. 5: Pseudo-equilibrium paths of unstiffened cylindrical tanks under El Centro earthquake: (a) tanks A and C; (b) tank B; (c) tanks D and E.

3.2 Stiffened cylindrical tanks

This study investigates the development of seismic buckling strength due to vertical stiffeners. The material properties and geometries of the stiffeners are discussed in section 2.2. Figs. 6(a) and 6(b) show the example of the deformation shapes of tank AS when it is subjected to the El Centro earthquake of 0.65g and 0.95g, respectively. The buckling zones occur slightly below the top of tank AS. It should be noted that, for the purpose of visualization, the radial displacements are magnified with the scale of 50:1 (listed in Fig. 6).



(a) (b)

Fig. 6: Radial displacement: (a) pre-buckling tank AS at 0.65g, scale 50:1; (b) post-buckling tank AS at 0.95g, scale 50:1

Fig. 7 shows the example of the pseudo-equilibrium paths of stiffened liquid-filled steel cylindrical tanks under Parkfield earthquake. Based on the seismic buckling corresponding to the point of change in the slope of pseudo-equilibrium path, the seismic buckling strengths for tanks AS, BS, CS, DS, and ES under the El Centro earthquake are equal to 0.85g, 0.61g, 0.63g, 0.23g, and 0.18g, respectively. The seismic buckling strengths for tanks AS, BS, CS, DS, and ES under the Northridge earthquake are equal to 1.47g, 0.68g, 0.81g, 0.35g, and 0.31g, respectively. The seismic buckling strengths for tanks AS, BS, CS, DS, and ES under the Parkfield earthquake are equal to 1.40g, 1.33g, 1.04g, 0.52g, and 0.46g, respectively.

Table 3: Seismic buckling Strength

	Seismic Buckling Strength (g)		
Tank	**El Centro earthquake**	**Northridge earthquake**	**Parkfield earthquake**
A	0.72	1.34	1.30
AS	0.85	1.47	1.40
B	0.55	0.63	1.20
BS	0.61	0.68	1.33
C	0.56	0.70	0.88
CS	0.63	0.81	1.04
D	0.15	0.21	0.40
DS	0.23	0.35	0.52
E	0.075	0.20	0.33
ES	0.18	0.31	0.46

The seismic buckling strengths for all analyzed liquid-filled steel cylindrical tanks are listed in Table 3. The seismic buckling strengths of stiffened liquid-filled steel cylindrical tanks are higher than the seismic buckling strengths of unstiffened liquid-filled steel cylindrical tanks. The results indicate that the improvement of the seismic buckling strength of the liquid-filled steel cylindrical tank due to the vertical stiffeners is more significant when the D/t ratio is high, as listed in Table 3. For example, the seismic buckling strength of tank AS with D/t = 910 is 8% higher than the seismic buckling strength of tank A. Whereas, the seismic buckling strength of tanks DS with D/t = 1612 is 30% higher than the seismic buckling strength of tank D.

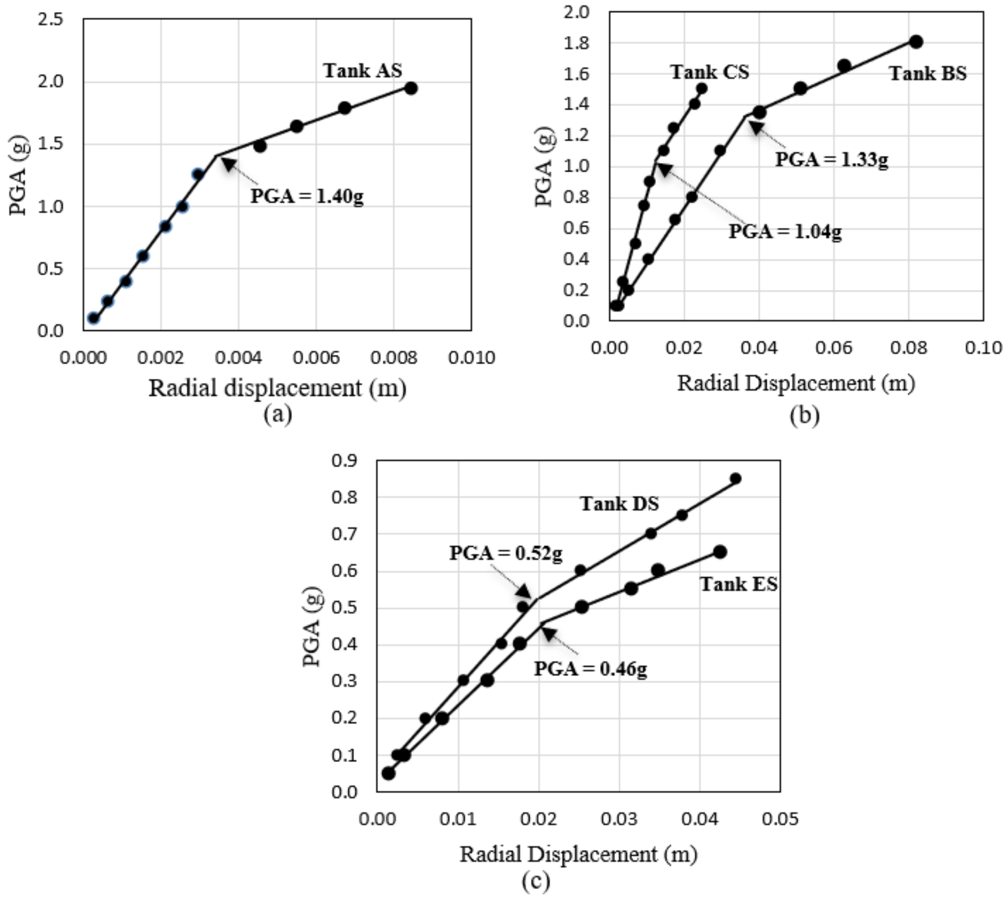


Fig. 7: Pseudo-equilibrium paths under Parkfield earthquake: (a) tank AS; (b) tanks BS and CS; (c) tanks DS and ES

4. Proposed Equation for Seismic Buckling Strength

Table 3 shows that the seismic buckling strengths of stiffened steel cylindrical tanks are higher than the seismic buckling strengths of unstiffened steel cylindrical tanks. Nonlinear regression analysis is used to investigate the interaction effects of D/t ratios, H/D ratios, and vertical stiffeners on seismic buckling strengths. Eq. 3 represents the estimations of seismic buckling strengths based on multiple nonlinear regressors.

$$PGA = -1.53(10^{-5})(D/t)^{1.5} - 0.27\ln(H/D) + 0.11 < Stiffeners > +1.43 \tag{3}$$

In Eq. 3, "*Stiffeners"* is a binary regressor; <*Stiffeners*> = 1 if a tank is stiffened by vertical stiffeners, and <*Stiffeners*> = 0 if a tank is unstiffened. The regression R^2 value of Eq. 3 is 0.71.

The coefficients of D/t and H/D ratios are statistically significant at 95% confident interval, and the coefficient of stiffeners is statistically significant at 80% confident interval. Eq. 3 shows that the critical PGA changes with the exponential rate of the D/t ratio and with the diminishing rate of the H/D ratio. The critical PGA increases when the liquid-filled steel cylindrical tanks are stiffened by vertical stiffeners.

5. Conclusions

The following conclusions are derived from numerical calculations for the liquid-filled steel cylindrical tanks under three different earthquake excitations. This study concludes that the interactions between D/t and H/D ratios can affect the seismic buckling strengths of the liquid-filled steel cylindrical tanks, and the vertical stiffeners can improve the seismic buckling strengths of the cylindrical tanks. The following main observations can be drawn from the current study:

1. The D/t ratio is an important parameter considering the seismic buckling strength of the liquid-filled steel cylindrical tank. The seismic buckling strength of the liquid-filled steel cylindrical tank decreases significantly when the D/t ratio increases. The H/D ratio also affects the seismic buckling strength of liquid-filled steel cylindrical tank; however, its effect is less significant than the D/t ratio.
2. The results from this study indicate that the vertical stiffeners significantly improve the seismic buckling strength of the liquid-filled steel cylindrical tank under earthquake excitations. This improvement is more pronounced for the liquid-filled steel cylindrical tank when the D/t ratio is high.
3. Different characteristics of earthquake excitations also affect the seismic buckling strength of the liquid-filled steel cylindrical tank in terms of critical PGAs. However, the patterns of the interaction effects of the D/t ratio, H/D ratio, and vertical stiffeners on seismic buckling strengths for the steel cylindrical tank are not changed.

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