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SEISMIC DESIGN EVALUATION OF LIQUID-FILLED STIFFENED STEEL CYLINDRICAL TANKS

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This paper aims to estimate dynamic buckling loads of cylindrical liquid storage tanks. Finite element analysis is performed using ANSYS computer program. Twelve different geometries of the cylindrical tanks are analyzed with height to diameter (*H/*D) ratios of 0.5, 1.0, 1.5, and 2.0 and the diameter to thickness (*D*/*t*) ratios of 1000, 1500, and 2000 to cover tall and short cylindrical tanks. The dynamic buckling capacities of cylindrical tanks filled with water up to 90% of their height are investigated in this study. The transient dynamic analysis is performed to find the dynamic buckling loads. Applied dynamic loads in this study are horizontal earthquake excitations in terms of acceleration (g) due to gravity. The transient dynamic analysis results indicate that the dynamic buckling loads decrease when the H/D ratios increase, and the dynamic buckling loads decrease when the D/t ratios increase. Design curves for the cylindrical tanks of various geometries subjected to earthquake accelerations are generated.

Keywords: Finite element, Buckling, Earthquake, Transient analysis, Stability, Shell.

1 INTRODUCTION

Liquid storage tanks are subjected to the horizontal and vertical ground accelerations during the earthquakes. These earthquake ground accelerations may cause damages to the liquid storage tanks. Spillage of toxic liquid from the liquid storage tanks could cause a serious threat to human health and the environment. Additionally, failure of tanks, which contain an inflammable substance such as petroleum has frequently led to an uncontrolled fire which occurred during Niigata and Alaska earthquakes in 1964 (Priestley *et al.* 1986).

The damages of petroleum storage tanks were reported due to earthquakes of 1933 Long Beach, 1952 Kern County, 1964 Alaska, 1971 San Fernando, 1979 Imperial Valley, 1983 Coalinga, 1989 Loma Prieta, 1992 Landers, 1994 Northridge, and 1995 Kobe (Cooper and Wachholz 1999). Damages of cylindrical tanks due to earthquake loading can occur in several forms. The American Lifelines Alliance (ALA) reported the failure modes that have occurred to steel storage tanks (Edinger *et al.* 2001). These failure modes are shell buckling mode, roof, and miscellaneous steel damage, anchorage failure, tank support system failure, foundation failure, hydrodynamic pressure failure, connecting pipe failure, and manhole failure. This study is interested in the shell buckling mode subjected to the horizontal earthquake accelerations. Housner (1963) reported that the hydrodynamic behavior between water and the storage tanks, which are subjected to horizontal accelerations can be distinguished into two kinds. First, impulsive mass, a mass of water is rigidly attached to the tank at the proper height. Second, convective mass, the horizontal accelerations from the tank, excites a mass of water into oscillations. Malhotra *et al.* (2000) presented that the design of fixed-based cylindrical tank is a simple and efficient way to design for the convective component, compulsive component, and shell deformation due to interaction effects from the impulsive component. Sezen *et al.* (2008) used ANSYS computer program to study liquefied gas-structure interaction and a simplified model of three tanks in Turkey that experienced an earthquake on August 17, 1999, and they reported that shear and bending moments are overestimated if the fluid is modeled as a single rigid mass.

2 FINITE ELEMENT MODELS

Twelve different geometries of the tanks are analyzed with height to diameter (H/D) ratios of 0.5, 1.0, 1.5, and 2.0 and the diameter to thickness (D/t) ratios of 1000, 1500, and 2000 to investigate the buckling behavior of various sizes of the cylindrical tanks. These twelve cylindrical tanks are modeled as aboveground storage tanks (AST) that are open at the top. The cylindrical tanks are considered fixed at the bottom and free on the top. Summary of twelve different geometries of the cylindrical tanks adopted in this study is listed in Table 1.

Table 1. Summary of twelve different geometries of the cylindrical tanks.

Model	H (m)	D (m)	t (mm)	H/D	D/t
1	4.573	9.144	9.144	0.5	1,000
2	4.573	9.144	6.096	0.5	1,500
3	4.573	9.144	4.572	0.5	2,000
4	9.144	9.144	9.144	1.0	1,000
5	9.144	9.144	6.096	1.0	1,500
6	9.144	9.144	4.572	1.0	2,000
7	13.716	9.144	9.144	1.5	1,000
8	13.716	9.144	6.096	1.5	1,500
9	13.716	9.144	4.572	1.5	2,000
10	18.288	9.144	9.144	2.0	1,000
11	18.288	9.144	6.096	2.0	1,500
12	18.288	9.144	4.572	2.0	2,000

The material for all cylindrical storage tanks is steel with a modulus of elasticity, E = 200,000 MPa, Poisson's ratio, ν = 0.3, and the mass density, ρ = 7,850 kg/m^3. Bilinear isotropic hardening of the steel is included with the yield stress of 344.74 MPa and the tangent modulus of 13,790 MPa. The liquid filled 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.

The finite element analysis (FEA) computer program, ANSYS, is used to carry all computations. Due to the symmetric geometries, all FEA models are modeled with only half of cylinder to reduce the computation time. From the element types in ANSYS, SHELL181 element is used to be the element for the steel cylindrical tanks. SHELL181 is a four-node element with six degrees of freedom at each node (translation in x, y, and z directions, and rotation about x, y, and z-axes). FLUID80 element is used to be the element for water filled inside the cylindrical tanks. FLUID80 is an eight-node element with three degrees of freedom at each node (translation in x, y, and z directions).

3 TRANSIENT DYNAMIC ANALYSIS

The transient dynamic analysis is the technique for the response of a structure subjected to a time-dependent loading. In addition, inertia and damping effects are considered for the transient dynamic analysis. The equation of motion, Eq. (1), is solved by the transient structure simulation in ANSYS program (ANSYS Inc 2011).

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

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

3.1 Earthquake Accelerations

Earthquake loads of El Centro of May 18, 1940, are used in this study. Numerical values of these earthquakes are in the unit of g, the accelerations due to gravity are presented in Figure 1. Since the PGA is 0.319g at time = 2.02 s, the accelerogram from 0 s to 8 s is used in this study to reduce CPU time-consuming.

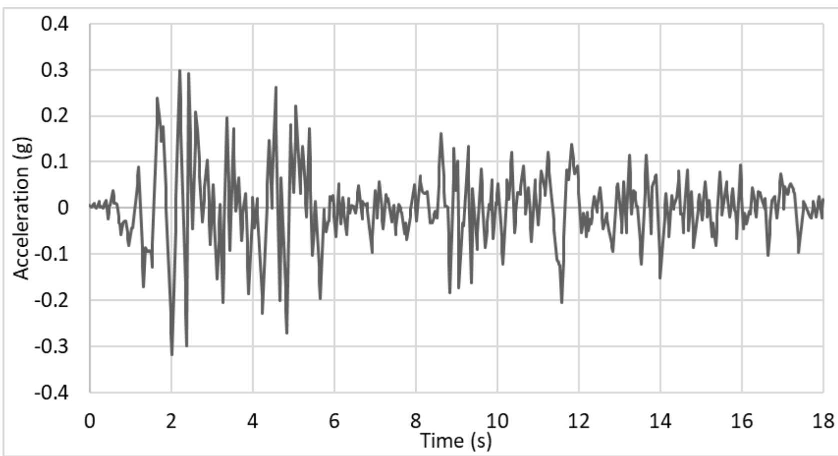

Figure 1. Accelerogram of North-South component of El Centro earthquake, 1940.

4 PSEUDO-EQUILIBRIUM PATHS

Budiansky and Roth's criterion are used to generate pseudo-equilibrium paths in this study. Buckling instability occurs when a small increase in the pulse intensity causes a strong increase rate of the deflection (Budiansky and Roth 1962). The maximum displacements are plotted in as a function of PGA level. These curves have been identified as pseudo-equilibrium paths. The pseudo-equilibrium path is used to indicate the dynamic buckling along the path of transient displacements. Figure 2, 3, 4, and 5 illustrate the deformed shape of model 5, 7, 8, and 10, respectively. Figure 6 and 7 represent pseudo-equilibrium paths for model 5 and 7, respectively.

For von-Mises stresses at the dynamic buckling loads, it is found that von-Mises stresses for all models are less than the yield stress of the steel, which is 344.74 MPa. The highest von-Mises stress occurs with Model 12 at 255.80 MPa.

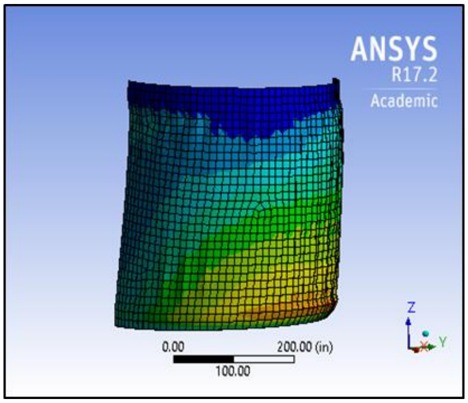

Figure 2. Deformation of model 5.

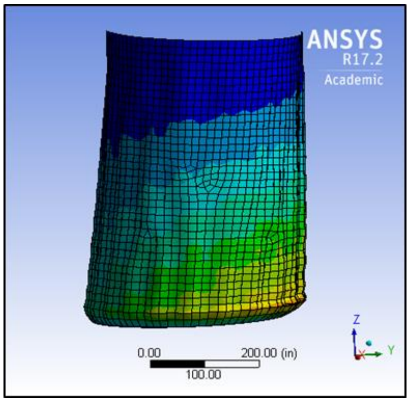

Figure 3. Deformation of model 7.

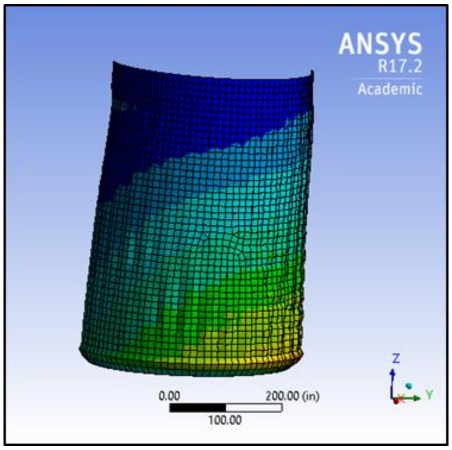

Figure 4. Deformation of model 8.

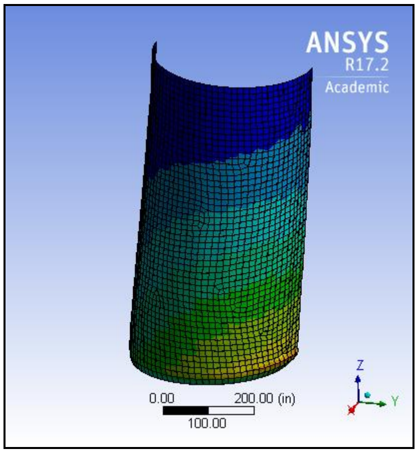

Figure 5. Deformation of model 10.

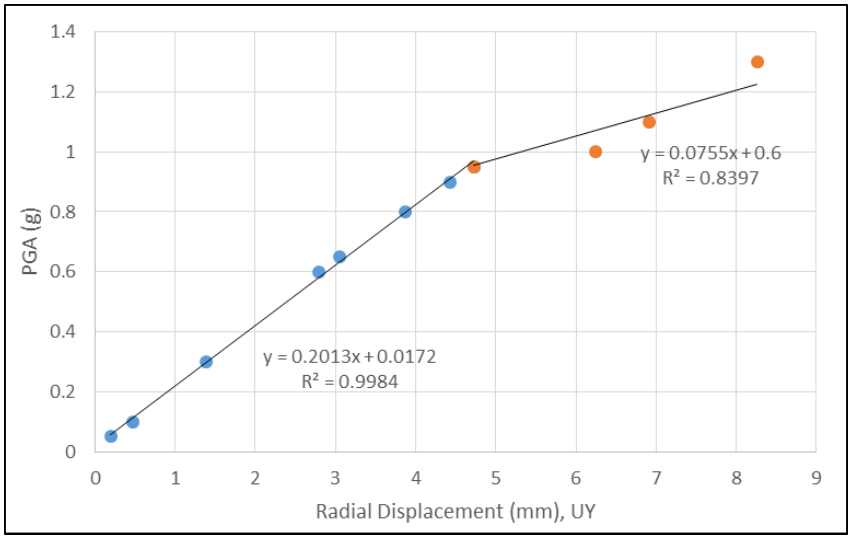

Figure 6. Pseudo-equilibrium paths for model 5.

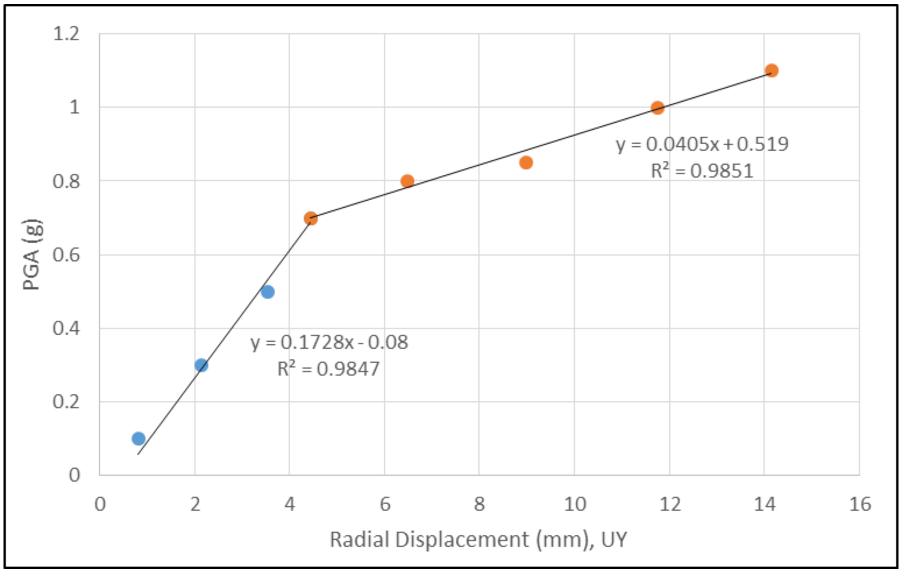

Figure 7. Pseudo-equilibrium paths for model 7.

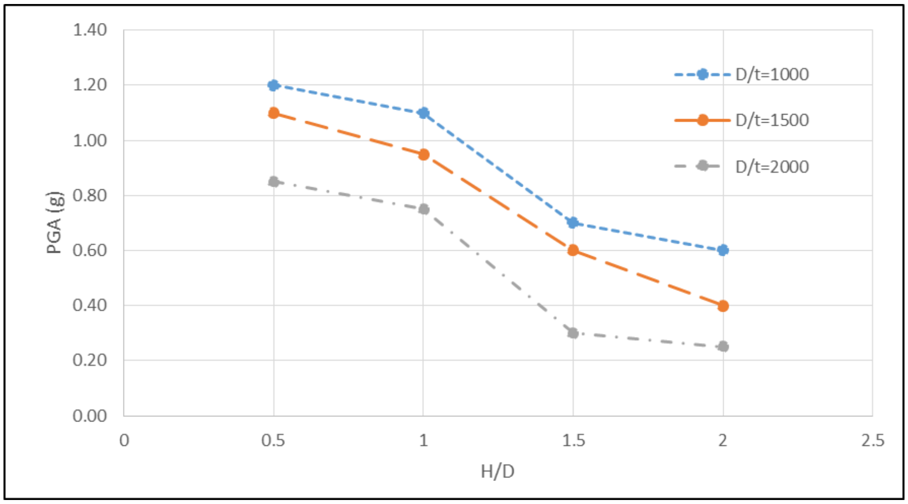

Figure 8. Dynamic buckling capacities.

After different analyses of the structure for several load, levels have been performed, and the value for which there is a significant jump in the response for a small increase in the load indicates that the structure passes from a stable state to a critical state as shown in Figure 6 and 7. In terms of shell buckling for the liquid-filled cylindrical tanks, this study found that the interaction effects between H/D and D/t ratios are significant when the cylindrical tanks are subjected to horizontal accelerations. The dynamic buckling capacities of the cylindrical tanks decrease when H/D ratios increase, and the dynamic buckling capacities decrease when D/t ratios increase. The dynamic buckling capacities of liquid-filled cylindrical tanks can be summarized as illustrated in Figure 8.

5 CONCLUSIONS

This paper dealt with dynamic buckling of steel tanks with fixed support subjected to the horizontal component of the real earthquake. The interaction effects of D/t and H/D ratios on the dynamic buckling were investigated. The buckling loads of the cylindrical tanks filled with water up to 90% of their height subjected to the El Centro earthquake range between 0.25g and 1.20g. The results from the transient analysis show that, for the cylindrical tanks filled with water up to 90% of their height, the dynamic buckling loads decrease when the H/D ratios increase, and the dynamic buckling loads decrease when the D/t ratios increase.

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