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SEISMIC BEHAVIOR OF ANCHORAGE IN DIVERSE LIQUID STORAGE STEEL TANKS BY ADDED-MASS METHOD

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Deformation of liquid storage tanks and the interaction between fluid and structure result in a variety of possible failure mechanisms during earthquakes. Among all failure modes, base-anchor failure is this paper's focus. Three cylindrical steel tanks with different H/D were selected to investigate dynamic loadings on the tank seismic responses. The added-mass method was used in the finite element modeling of the steel tanks and fluid, and numerical analyses were performed. The added-mass method results were compared to conventional method outcomes using two or more lumped-mass and equivalent springs for tank-liquid simulation (Housner method). It was found that the added-mass method results in greater forces on the anchors in comparison to the lumped-mass method.

Keywords: Fluid-structure interaction, Numerical analyses, Lumped-mass, Anchor failure.

1 INTRODUCTION

Seismic behavior of anchored liquid-storage tanks considering hydrodynamic fluid–structure interaction has been researched for years. Many investigations (e.g. Haroun and Housner 1981, Moslem 2011) have analyzed water storage tanks under translational components of the ground motion. Deformation of liquid storage tanks and the fluid-structure interaction result in a wide variety of possible failure mechanisms during earthquakes. Fragility curves for steel tanks as a result of earthquake can be found in O'Rourke (2000) and Salzano (2003). They find that anchor failure plays an important role in damage of the whole structure. This paper focuses on anchor failure as a common failure mode of storage tanks. For this purpose, among all proposed analytical models, two have been studied in this research: 1) the Housner method, which is the fastest and most convenient approach using two or more lumped-mass and equivalent springs for tank-liquid simulation; and 2) the added-mass method, where masses are attributed to pressure distribution of rigid tanks and connected to the tank body. In this study, the added-mass method was used for modeling three cylindrical liquid storage tanks (H/D = 0.8, H/D = 1, and H/D = 2). The resulting anchor bolt forces from response spectrum analyses have been compared to the Housner method.

2 MODELING OF LIQUID STORAGE TANKS BY ADDED-MASS METHOD

Of particular importance is the accurate modelling of liquid storage steel tank by considering the fluid-structure interaction. As far as liquid-containing tanks are concerned, one distinguished simulation method is added-mass models, used in this study and discussed below. The inertia of the portion of the fluid that acts impulsively is lumped in with the inertia of the tank walls, and the added masses are calculated from pressure distributions of rigid tanks (Virella et al. (2006)). The added-mass values are constant during the dynamic simulation. Studies by Haroun and Housner (1981) have shown that the pressure distribution, due to the liquid impulsive component in rigid and flexible tanks, is similar for broad tanks, (Figure 1 (a), (b)). In this figure, η indicates the coordinate along the height of the cylinder, and $C_i(\eta)$ describes the pressure distribution along the tank's height.

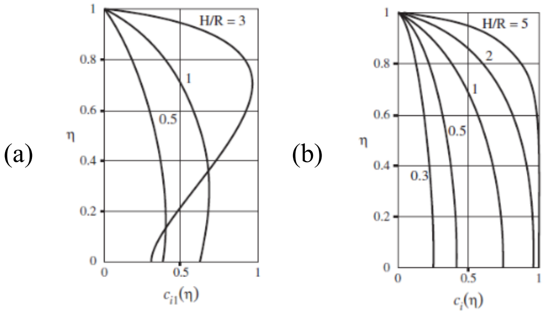

(a) (b)

Figure 1. Pressure distribution along the tank height; (a) Rigid tank. (b) Flexible tank.

3 CASE STUDY OF THREE STEEL TANKS UNDER SEISMIC LOADING

Three tanks with H/D = 0.8, H/D = 1, and H/D = 2 were analyzed. The geometric characteristics of the tanks are illustrated in Figure 2 (a), (b), (c). Tank height, tank diameter (I.D., Interior Diameter, O.D., Outer Diameter), filling level (HHLL), anchor bolt ID (center-to-center anchor bolt distance), and tank thicknesses are indicated in Figure 2. Two have roof structures and one does not.

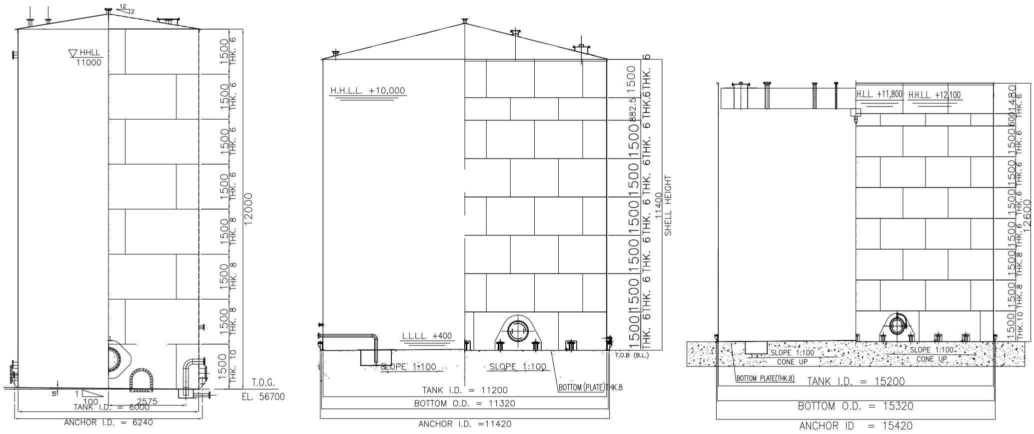
3.1 API code method

According to the Housner theory, the earthquake load, including impulsive and convective components, can be exerted in a defined distance from the tank bottom, as seen in Figure 3(a), (b). Table 1(a) reports assumption to calculate the earthquake loads in accordance with API (2008). According to appendix E of API V, resultant seismic shear force at tank bottom is calculated based on the following equation:

$$V = \sqrt{{V_i}^2 + {V_C}^2} \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where V_C and V_i are base shears for convective and impulsive weights, respectively.

Consequently, M is the resultant moment of a tank by considering Xc and Xi. All tank characteristics including V and M is listed in Table 1(b).



(a) H/D = 2. (b) H/D = 1. (c) H/D = 0.8.

Figure 2. Tank configuration and plates characteristics.

Table 1. (a) Required parameters to calculate tank earthquake. (b) Tank characteristics.

(a)

Parameter	Value
SUG : Seismic Use Group (E.3.1)	Table1(b)
I : Importance Factor Coefficient set by Seismic Use Group (Table E-5)	Table1(b)
Z : Seismic Zone Value (UBC-1997)	Table1(b)
Rwi : Impulsive Reduction Factor	Table1(b)
Rwc : Convective Reduction Factor	Table1(b)
D: Tank Diameter (m)	Table1(b)
H : Tank Height (m)	Table1(b)
Xc, Xi: Distance of convective and impulsive resultant force from bottom of tank, respectively (m)	-
R:D/2	-

(b)

	Tank1	Tank2	Tank3
ρ(ton/m3)	1	1.038	1.032
D(m)	15.4	11.4	6.2
H(m)	12.6	11.4	12
H/D	0.8	1	2
SUG	III	III	IV
I	1.5	1.5	1.25
Z	0.3	0.3	0.4
Rwi	4	4	4
Rwc	2	2	2
Anchor Size	56	48	48
Anchor No.	24	20	16
V(ton)	540	257	99
M (ton.m)	2630	1120	495

3.2 Added-mass method

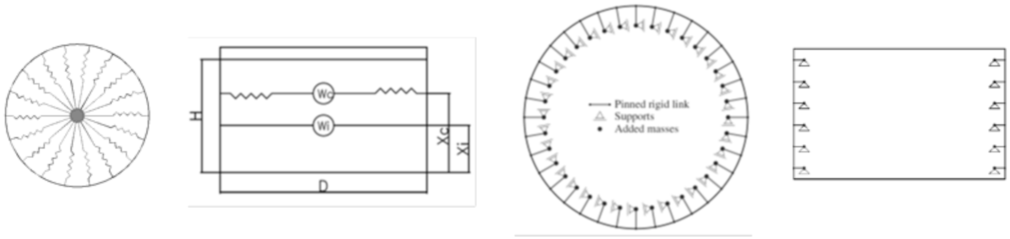
The software SAP 2000 Rev.14.2.4 was used to carry out the analyses. Four-node shell elements were employed to model tank shells. The added-mass approach essentially consists in deriving liquid masses from pressure distributions. From a practical point of view, and to attach the small masses to the shell nodes, a finite element model by means of one-directional elements was used, as shown in Figure 3 (c), (d). The one-directional elements (Pin type frames in SAP) were utilized to constrain the motion of the nodal masses to the normal direction of the shell. The motion of each support was restricted in the global tangential and vertical directions, whereas the support was free in the radial direction. The added-mass model was obtained from pressure distribution for the impulsive mode of tank-liquid system, and the convective component was neglected (Buratti and Tavano 2014). The impulsive pressure distribution was obtained from the horizontal rigid body motion of a rigid tank-liquid system and can be expressed in a cylindrical reference system:

$$P_i(\eta, \theta, t) = C_i(\eta)\ddot{x}_g(t)\rho R cos(\theta) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where θ is the circumferential position, t is the general time, $\ddot{x}_g(t)$ is the ground acceleration time history, and ρ is the water density. $C_i(\eta)$ can be determined from Figure 1(b). The lumped mass at each node of the mesh was computed by multiplying pressure acting on tank walls (Eq. (2)) by the tributary area of the node, and dividing by the reference ground acceleration ($a_n = \ddot{x}_g(t) cos\ \theta$). Therefore, for the general interior node, the expression of the lumped mass is given by Eq. (3).

$$m_i = \frac{p_i E^2_{size}}{a_n} = C_i(\eta)\rho \, . R E^2_{size} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where E^2 is the mesh area of the rectangular finite elements. Pressure distribution along the tank height for each tank is shown in Figure 4(a). The simulation of each tank is depicted in Figure 5.



(a) (b) (c) (d)

Figure 3. API code model according to Housner theory: (a) mass and spring plan, (b) mass and spring view, (c) added-mass model plan, (d) added-mass model view.

4 NUMERICAL ANALYSIS

To study anchor forces, dynamic analyses by means of response spectrum were performed. UBC97 spectrum (Figure 4(b)) with the following characteristics was used, where $C_a = 0.36$, $C_v = 0.54$, Soil type S_d for Seismic Zone III; and $C_a = 0.4$, $C_v = 0.56$, Soil type S_c for Seismic Zone IV. Resulting base shears from UBC spectra were scaled to the static shear of the Housner method. Before the scaling, the importance factor of 1.5 and response modification factor (R) of 3 were applied.

5 NUMERICAL RESULTS

The transfer of the total lateral shear force between the tank and the subgrade will be resisted by friction between the tank bottom and the foundation or subgrade, so no additional lateral anchorage is required for mechanically-anchored steel tanks. In other words, anchors are mainly designed to bear axial loads and they do not contribute to shear loads of the storage tanks. A seismic load was exerted in X direction, and the load of each anchor was determined. Because of the symmetry, similar results were obtained in Y direction. Half the number of anchors in each tank exerted tension force under a seismic load. 500 modes contributed to mass participation of 99.6%.

Figure 6(a), (b), and (c) draw a comparison between anchor forces from the Housner and added-mass methods.

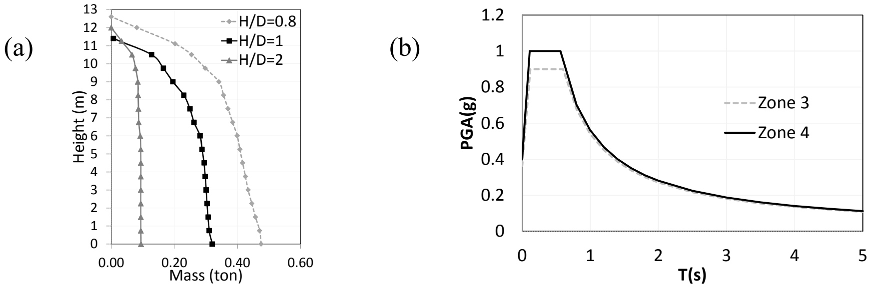


Figure 4.(a) Pressure distribution along the tank height for. (b) UBC97 design spectra.

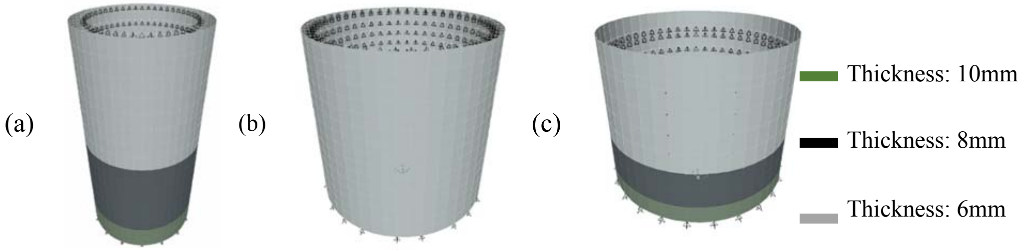


Figure 5. The tank model using added-mass method (a) H/D = 2 (b) H/D = 1 (c) H/D = 0.8.

The horizontal axis in bar charts shows anchor bolts located in the tension side of tanks. Bar chart values represent internal tension force in anchors with the units in tons. As expected, the forces of anchors that were aligned with the seismic load direction had maximum values, and the anchors perpendicular to the seismic load direction had minimum values. Anchor bolts 5, 6 and 7 in tanks with H/D = 2, 1, and 0.8, respectively, were aligned with earthquake load. Anchor bolts 1 and 9 in tank with H/D = 2, bolts 1 and 11 in tank with H/D = 1, and bolts 1 and 13 in tanks with H/D = 0.8, respectively, were perpendicular to earthquake load, so their contribution to the lateral load was zero. The differences between the tensile forces from the two approaches were considerable. To better compare tensile forces from the two methods, the force ratio of the added-mass method to Housner method versus tanks' H/D have been illustrated in

Figure 6(d). As can be observed, all anchor forces from the added-mass method have been around 39%~45% more than those of the Housner method. Moreover, by increasing tank H/D, the added-mass method leads to a higher tensile force. Hence, the greater the H/D, the higher the anchor tension.

6 CONCLUSION

The added-mass approach is a suitable method for study of hydrodynamic effects of the fluid-structure interaction on storage steel tanks subjected to earthquake lateral loading. In addition, the added-mass method represents a good compromise between the accuracy and the computational cost.

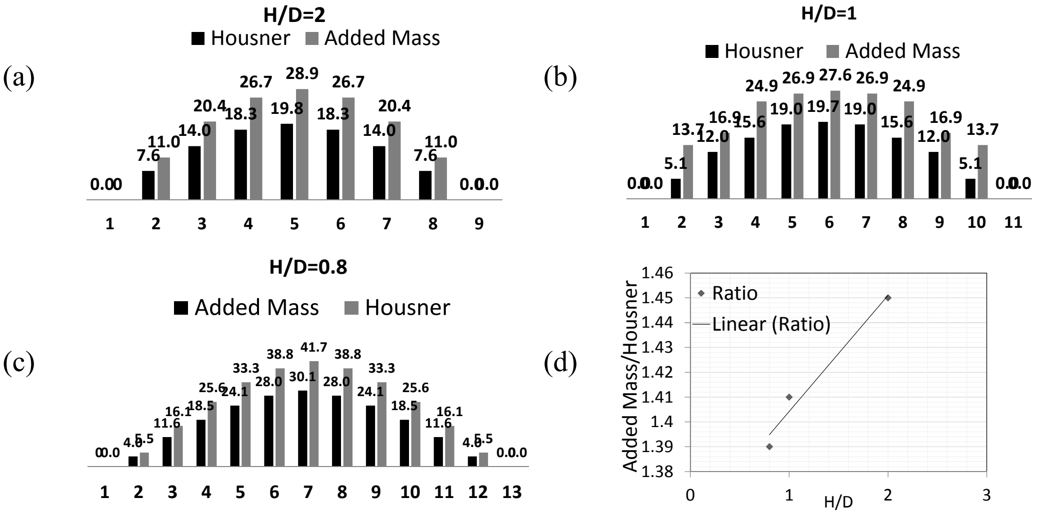


Figure 6.(a), (b), (c) Tensile force in Housner and Added-mass method. (d) Tensile force Ratio.

Comparison between the results of the Housner method and the added-mass method indicates that tanks with higher H/D are more sensitive to the added-mass method. Therefore, the added-mass method can be taken into consideration for the design of anchorage or even other parts of storage steel tanks, particularly those with large H/D in high-risk seismic zones.

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