Development of Seismic Fragility Curves of Cylindrical Concrete Tanks Using Nonlinear Analysis

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ABSTRACT: Fluid storage tanks are one of the most important components of vital lifelines, especially oil, petrochemical, and water transmission systems. The seismic behavior of liquid tanks in previous earthquakes shows that major damages in water reinforcement concrete tanks are shell cracking and consequential liquid leakage. In the present paper, the dynamic behavior of ground-supported concrete tanks is investigated to develop related fragility curves. The nonlinear numerical simulation is performed for three cases of concrete cylindrical tanks with variable height to diameter ratios. In these simulations cracking of concrete is considered as the damage criteria, and the fragility curves of the tanks for the critical crack width recommended by the Iranian code of 123 are developed. These curves are compared with those recommended by previous researchers and extracted from linear analyses. The results indicate that the three-dimensional iterative cracks and their effect on the total dynamic response of concrete storage tanks can considerably affect the shape of fragility curves which is generally used for mentioned network risk assessment.

1. INTRODUCTION

According to the previous researches, most of the vulnerability studies of tanks are focused on steel tanks. For steel tanks, fragility curves for different failure modes such as shell buckling, roof damage due to the sloshing, etc. One of the most important references in seismic risk assessment of structures is the SYNER-G and HAZUS software in which the lack of concrete tank fragility curves is quite noticeable [1,2]. For evaluating the seismic vulnerability of the water network lifeline, the development of fragility curves of concrete tanks is essential which is the main purpose of this study.

2. METHODOLOGY

The geometric characteristics of the designed tanks are presented in "Table 1".

Using the ACI 350.3, the time of each tank is calculated and is presented in "Table 2" [3,4].

Eqs. (1) and (2) have been used to calculate and distribute the dynamic liquid pressure on the tank shell. In Eq. (1), the dynamic forces caused by liquid in terms of base shear is calculated for a various earthquake based on the simplified mechanical models for each tank. Then, the liquid pressure distribution can be obtained based on the analytical pattern of liquid pressure distribution in radial and circumrenal directions (Eq. (2)).

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Table 1. The aspect ratio of considered concrete tanks.

Tank type		Fluid height (m)	Height (m)	Diameter (m)
Tall	1	9	10	10
Medium	0.5	9	10	20
Short	0.25	4.5	5	20

$$V_{baseshear}(t) = \int_0^{Hw} \int_0^{2\pi} 2.Pd(t).Rd\theta.dh.cos\theta \tag{1}$$

$$Pd(t) = \frac{3}{2\pi.R.H_w}.V_{baseshear}(t).cos\theta.\left(1 - \frac{h^2}{H_w^2}\right) \tag{2}$$

After calculating the liquid pressure, it is exerted on the tank shell. The numerical simulation has been performed in Ansys finite element-based software. According to the tank symmetry parallel to the direction of the earthquake, half of the tanks are considered in the finite element model. The fixed condition is considered for the bottom of the tank shell. SOLID65 element which is known as the concrete element is used to simulate the reinforced concrete considering nonlinear behavior. The rebars are not modeled separately, but as a portion of the concrete element area. Both geometrical and material nonlinearities are considered in numerical analyses. The concrete elements can crack during the load increment

Table 2. The primary parameters used to evaluate the seismic response of a tank.

		Short Tank	Medium Tank	Tall Tank
Impulsive	M_i+M_w **(N.mm)**	752	2154	857
	K_i **(N/mm)**	19821633	27083907	2159453
	T_i **(S)**	0.0387	0.0560	0.1252
	ζ_i **(%)**	5	5	5
Convective	M_c **(N/mm)**	1121	1384	144
	K_c **(N/mm)**	1375	2322	519
	T_c **(S)**	5.67	4.85	3.31
	ζ_c **(%)**	0.5	0.5	0.5

Table 3. Median values and standard deviation for considered tanks.

Tank	*Damage state*	*θ*	*ß*
Short	$CCW = 0.1mm$	1.1	0.16
	$CCW = 0.3mm$	1.3	0.21
Medium	$CCW = 0.1mm$	0.8	0.26
	$CCW = 0.3mm$	1	0.31
Tall	$CCW = 0.1mm$	0.3	0.41
	$CCW = 0.3mm$	0.6	0.54

on the tank shell. Therefore, the stiffness of the tank shell can be changed by pushover analysis. Finally, the value of tensional strain on rebars is extracted from analyses and the crack width is obtained by Eq. (3), suggested by the Iranian code of 123.

$$W = \frac{(4.5\, a_{cr}\, \varepsilon_m)}{(1+2.5((a_{cr}-c)/(h-x)))} \tag{3}$$

ε_m , Rebar strain at the desired level to calculate the crack width taking into account the effect of concrete hardening in the tensile zone,

a_{cr} Parameter related to the cover and the distance between the rebars,

h Overall section height,

x Neutral axis height,

c Net concrete covering

w The crack width is in millimeters.

3. RESULTS AND DISCUSSION

In this section, fragility curves that are extracted for three considered tanks are discussed. A statistical Log-Normal distribution is considered for the Crack Width (CW) as demanded engineering parameter at each Peak Ground Acceleration (PGA). To evaluate the probability of exceeding a certain threshold (here the critical crack width of 0.1 or 0.3 mm), the mean and standard deviation of each crack width caused by various records with different levels of acceleration intensity is calculated. Then, using the cumulative lognormal distribution function, the probability of passing each crack width from the critical crack width is obtained. The relationships used to generate fragility curves with the lognormal cumulative distribution are based on Eqs. (4) to (6) [5].

$$P(C\,|\,IM = x) = \Phi\left(\frac{\ln\left(\frac{x}{\theta}\right)}{\beta}\right) \tag{4}$$

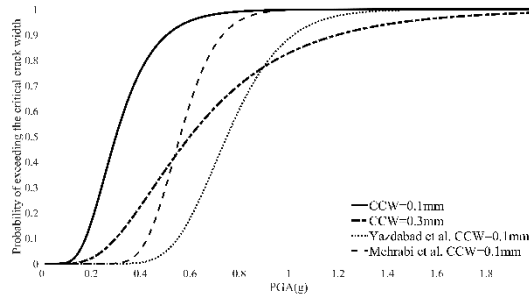$$\ln\theta = \frac{1}{n}\sum_{i=1}^{n}\ln IM_i \tag{5}$$

Fig. 1. Comparison of tall tank fragility curves obtained from nonlinear analyses with previously recommended curves based on linear analyses [5,6].

$$\beta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\ln(IM_i / \theta))^2} \qquad (6)$$

The mean values (θ) and standard deviation (β) of various tanks for two critical crack widths are given in "Table 3". Also, the fragility curves developed here are compared with the curves recommended in previous articles for long tanks is given in "Fig. 1".

4. CONCLUSIONS

In this study, the fragility curves of water concrete tanks have been extracted by considering the geometric and material nonlinearities in a 3D finite element model. In this simulation, the rebars are considered and the possibility of iterative concrete cracking during the nonlinear analysis is also provided. The results of the parametric study in terms of fragility curves are extracted and compared with the previously recommended fragility curves based on the linear analyzes without considering the effect of cracking and rebars modeling. The results indicate that the effect of cracking in the analysis of tanks can significantly change the fragility curves of tanks compared to the linear analysis. For the failure limit proportional to the crack width of 0.3 mm, the standard deviation value is greater than the failure limit proportional to the crack width of 0.1 mm. The results also show that the distribution of cracking area and the percent of its opening is quite different in the nonlinear analyses. For

the tank aspect ratios considered here, it is observed that the probability of tank vulnerability is increased by the increment of aspect ratio from short to medium tanks by 25%, and from medium to long tanks by 50%.

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