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Seismic response factors of reinforced concrete pedestal in elevated water tanks

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ABSTRACT

Reinforced concrete (RC) elevated water tanks are critical structures that are expected to remain functional after severe earthquakes in order to serve the water system networks. Despite this significant role, the number of research studies which investigated the nonlinear seismic response of RC pedestals in elevated water tanks is very limited. In the current codes and standards, the seismic response factors are mainly based on engineering judgement. In this paper, a systematic approach is employed to establish the seismic response factors for a wide range of elevate water tank sizes and RC pedestal dimensions commonly built in industry. In total, forty-eight model configurations (prototypes) are selected and designed based on current codes and standards. The finite element (FE) method is then used for nonlinear static (pushover) analysis of the prototypes. The pushover curve of each prototype is developed and the seismic response factors are determined accordingly. The effect of various parameters such as fundamental period, height to diameter ratio, seismic design category, and tank size on the seismic response factors of elevated water tanks is evaluated. Furthermore, the cracking propagation pattern in RC pedestal is studied. The result of the study shows that the tank size is a critical parameter affecting the seismic response of elevated water tanks. It is recommended not to use the same seismic response factors for all RC elevated water tanks regardless of the tank size. In addition, two different patterns of cracking depending on the height to diameter ratio of the pedestal are detected and discussed.

1. Introduction

Elevated water tank is a water storage facility supported by a tower and constructed at an elevation to provide useful storage and pressure for a water distribution system. These structures rely on hydrostatic pressure produced by elevation of water and hence are able to supply water even during power outages. This feature of elevated water tanks becomes more critical in case of power outage after severe earthquakes.

In general, the tower structure of the elevated water tanks could be classified as four types of reinforced concrete frame, steel frame, masonry pedestal and reinforced concrete (RC) pedestal. This study focuses on the last group in which the tank is mounted on top of a RC pedestal. The tank may be constructed from steel or concrete. As this study only focuses on the nonlinear seismic response behavior of RC pedestals, the type of tank does not affect the results.

Being considered as an important element of lifelines, elevated water tanks are expected to remain functional after severe ground motions to serve as a provider of potable water as well as firefighting operations. Failure or malfunction of these infrastructures disrupts the emergency response and recovery after earthquakes. Elevated water tanks have not performed up to expectations in many earthquakes in the past. The poor performance of these structures in the past earthquakes such as Chile 1960 [1] (due to design deficiency), Manjil-Roudbar 1990 (out of date design standards) [2], Jabalpur 1997 and Gujarat 2001 [3] has been reported in the literature. Extent of damages has been ranging from minor cracks in the pedestal up to complete collapse of the entire structure.

There are many grounds that could explain this undesirable performance. Configuration of these structures which resembles an inverse pendulum, lack of redundancy in RC pedestal, very heavy gravity load (comparing to conventional structures) and poor construction detailing are among the major contributors. Currently ACI 371R-08 [4] is the only guideline in North America that specifically addresses the structural design aspects of elevated water tanks with RC pedestal. This guideline refers to ACI 318-08

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[5] in many occasions for the design and construction of RC pedestal and foundation.

The seismic response of both concrete and steel tanks has been extensively investigated by means of experimental and numerical methods. Such studies date back to as early as 1940s and later by works of Housner [6] and other researchers such as Kianoush and Ghaemmaghami [7], Moslemi and Kianoush [8], El Damatty et al. [9] and Kianoush and Chen [10]. On the other hand, although the RC pedestal is an important part of the elevated water tank structure, their seismic response has been the subject of only a handful of research studies.

In one of the earliest studies on seismic response of elevated water tanks, Shepherd [11] validated the accuracy of the two mass representation of the water tower structures by comparing the theoretical results to the results of a dynamic test on a prestressed concrete elevated water tank. The comparison of the theoretical and experimental tests proved the efficiency and acceptable accuracy of the theoretical two mass modeling of elevated water tanks.

Steinbrugge and Rodrigo [1] investigated the performance of elevated water tanks during the 1960 Chile earthquake. A 4000 m^3 elevated water tank which was empty at the time of earthquake received vertical cracks all over the height of pedestals midway between the fins as shown in Fig. 1(d). The pedestal height and diameter were 30 m and 14.5 m respectively.

Memari and Ahmadi [2] investigated the behavior of two concrete elevated water tanks during the 1990 earthquake of Manjil-Roudbar. They concluded that although the tanks were designed based on the standards of the construction time, the design loads were almost one fifth the design loads of the current standards. They also concluded that the sloshing and P–Δ effect was very minor in elevated water tanks. Fig. 1(c) shows a 1500 m^3 RC elevated water tank that collapsed during this earthquake. There were also two 2500 m^3 elevated water tanks which were empty during this earthquake and only received minor cracks at base of the pedestal above the openings.

Rai [3] studied the performance of elevated tanks in the 1997 Jabalpur and Bhuj earthquake of 2001. It was concluded that with low axial load, small longitudinal steel ratio, and a thick wall, acceptable ductility is gained for RC pedestals. In addition, the concrete jacketing was performed on an RC pedestal as a retrofitting strategy. The RC jacket was shown to enhance lateral strength and ductility of the pedestal by changing the failure mode from the concrete crushing to tension yielding.

Dutta et al. [12] studied the dynamic behavior of elevated water tanks (both RC pedestal and frame) with soil structure interaction by means of finite element analysis and small scale experimentations. This study concluded that generation of axial tension in the tower structure should be commonly expected in the empty-tank condition, while base shear is principally governed by full tank condition. Furthermore, the effect of soil–structure interaction was shown to produce considerable increase in tension at one side of the staging in comparison to fixed support condition.

Moslemi et al. [13] employed the finite element technique to investigate the seismic response of liquid-filled tanks. The free vibration analyses in addition to transient analysis using modal superposition technique were carried out to investigate the fluid–structure interaction problem in elevated water tanks. The computed FE time history results were compared with current practice and very good agreement was observed.

In this study, the finite element (FE) method is employed to investigate the nonlinear seismic response of RC pedestals in elevated water tanks. Multiple prototypes (models of elevated water tanks designed based on provisions of code) in accordance with a number of selection criteria are developed. The prototypes' dimensions and sizes are selected based on the most widely constructed tank sizes and pedestal heights. In total, 48 prototypes are designed and analyzed based on the requirements of ACI371R-08 [4], ASCE/SEI 7-2010 [14] and ACI 350.3-06 [15]. Each prototype is designed for two levels of high and low seismicity. A finite element model is developed for each prototype. Subsequently, pushover analysis is conducted on each FE model. By extracting the load–deformation results of the pushover analysis, the pushover curves are generated and the seismic response factors are determined. Furthermore, the cracking propagation patterns which are developed in the process of pushover analysis will be presented. These patterns are compared and categorized based on the geometry and dimensions of the elevated water tanks.

The main objective of this study is to provide a better understanding of the nonlinear seismic response of RC pedestals. All practical tank sizes and pedestal height and diameters are included in this research in order to develop a comprehensive database for the seismic response factors of RC pedestals in elevated water tanks. Furthermore, studying the cracking patterns helps detect the location of major damages of RC pedestal when subjected to seismic loads. The results of the study show that the tank size has a significant effect on seismic response factors of elevated tanks. In addition, height to diameter ratio of RC pedestal is an important parameter that affects the seismic response behavior of elevated water tanks.

2. Defining the study group

The main criteria for selecting the study group are pedestal height, tank capacity, site seismicity and response modification factor. Generally, the effect of structural plan configuration must also be included as a criterion. This is not required in the case of the elevated water tanks as the plans of all structures are identical in shape (circular RC wall). In addition, due to the symmetrical plan of pedestal, only one direction of applying lateral load is adequate.

According to ACI371R-08 [4] common tank sizes in elevated water tanks range from 0.5 to 3 Mega gallon (Mgal) and RC pedestal heights range from 8 to 60 m (1 Mgal = 3800 m^3). Four pedestal heights of 15, 25, 35 and 45 are determined to be investigated. Majority of the pedestals constructed in industry are in this range. Four tank sizes of 0.5, 1, 2 and 3 Mgal which are considered to be the most widely built tank sizes are selected as well. The pedestal wall thickness and diameter are mainly functions of the tank size.

The site seismicity affects the design response spectrum and therefore the seismic design base shear (V_d). The study group will be investigated for two levels of high and low seismicity. The mapped risk-targeted maximum considered earthquake (MCE_R) spectral response acceleration parameter at short period (S_s) and 1-s period (S_1) are selected based on the upper and lower bounds as required by ASCE/SEI 7-2010 [14] and are employed for determining the design spectral response acceleration (S_a). Accordingly, the selected values are $S_s = 1.25$ and $S_1 = 0.5$ for high seismicity and $S_s = 0.25$ and $S_1 = 0.1$ for low seismicity. The site class "C" is chosen for designing all prototypes. The design earthquake spectral response acceleration parameter at short period (S_{DS}) and 1 s period (S_{D1}) are calculated to be 0.84 and 0.44 respectively for the high seismicity category. These values are determined as $S_{DS} = 0.2$ and $S_{D1} = 0.11$ for the low seismicity. Subsequently, the design base shear (V_d) is calculated based on the equivalent lateral force procedure of ACI371R-08 [4].

According to ASCE/SEI 7-2010 [14], response modification factor (R) of elevated water tanks is either $R = 2$ or $R = 3$ depending on the special seismic detailing provided in the construction of RC pedestals. For the $R = 2$ prototypes no special detailing is required. On the other hand, in the $R = 3$ prototypes, the special detailing according to provisions of ACI 318-08 [5] must be provided which results in more concrete confinement. The prototypes